CHAPTER EIGHT: GENERAL DISCUSSION

Summary of main findings

Mean wrack cover on the 17 study beaches, spanning 3 biogeographical regions of South Australia, ranged between 1 and 95%. It also varied greatly between visits to individual beaches (maximum range on any beach 80%), particularly on beaches with high mean wrack cover. Wrack cover thus varied both spatially (between beaches and regions) and temporally (at scales of months or less). South Australian wrack deposits contain a diverse mix (total of 242 categories) of algal and seagrass material, as well as small amounts of other material including dune vegetation, animal carcasses and anthropogenic debris. Thus, these wrack deposits are spatially variable and dynamic in composition. Compared to conventional methods such as transects, the photopoint method provides an accurate, simple and rapid method for estimating the cover of wrack on a range of sandy beaches.

Beaches that were more Dissipative in nature (i.e. gentle beach-face slope, fine sands and low energy) had higher wrack cover than Reflective beaches (i.e. steep beach-face slope, coarse sands and high energy). Beaches with higher wrack cover had a higher organic-matter (OM) content within their sediments compared to beaches with low wrack cover, and the driftline and below-driftline areas had higher OM content than sediments above the driftline. Compared to Metropolitan Adelaide or Fleurieu Peninsula beaches, beaches in the SE region of SA tended to have higher wrack cover, more diverse species composition and higher proportions of algal biomass in the wrack deposits, and higher OM content in the sediments.

The beach macrofauna encountered in this study were diverse, representing 72 species from 19 Orders in total including Coleoptera, Diptera, Araneae, Amphipoda and Isopoda. Representatives from multiple trophic levels (herbivores/detritivores and predators) were present and the fauna were dominated by terrestrial, rather than marine, forms. The abundance, species richness and macrofaunal community structure were variable in time (among visits) and space (among beaches and between positions on the beach). Macrofaunal abundances were higher within the driftline than away from the driftline, and the identity of those species differed from those found in wrack deposits away from the DL. Within the driftline itself, there were fewer differences between bare sand and wrack-covered areas, suggesting that the entire driftline area is equally important as a habitat.

Cusp bays accumulated a greater cover and larger pieces of wrack than cusp horns, regardless of differences in cusp morphology. There were no differences in the mean particle size of sediments between bays and horns but sediment OM content was higher on horns than in bays. Macrofaunal communities were more diverse and there were more individuals (excluding the ubiquitous beach pill-bug *Actaecia pallida*) in bays than on horns. This pattern was explained by the greater cover of wrack in bays than on horns. Thus, although higher wrack cover in bays was linked to a greater abundance and diversity of macrofauna, the opposite effect was seen for OM, i.e. OM was higher on horns despite the more sparse wrack cover there.

In litterbag experiments, the seagrass *Posidonia sinuosa* and the algae *Ecklonia radiata* and *Sargassum* spp. showed rapid initial loss of mass, followed by very slow or no further decomposition over 85 days. The seagrass *Posidonia coriacea*, did not show this pattern and exhibited very slow but relatively steady loss of mass throughout the study. Rates of decomposition of wrack may be taxon- (i.e. algae vs. seagrass) and species-specific, and may vary depending on the structure and chemical composition of the material, weather, wetting/drying by tides and the initial state of the wrack. The rapid initial mass loss shown by three of the four species tested is most likely due to cell lysis (through wetting and then drying) and leaching, similar to wrack first being deposited on the shore and then drying. Thus, after the initial deposition of wrack onto the beach causes cell lysis and leaching, there may be only a slow and small release of nutrients from wrack into the beach. Percent C, C:N ratios and $\delta^{13}C$ of wrack in litterbags did not differ over time. Percent N varied due to the interaction of Species (nested in Wrack type) and Time and $\delta^{15}N$ differed with the age of wrack, showing slight increases as wrack ages. These results were likely due to the processes affecting %N differing among species and during decomposition, and may be due to colonisation of the wrack by microbial communities. Given that $\delta^{15}N$ is used as an indicator of trophic level in trophic web studies, the difference in $\delta^{15}N$ over time may confound estimates of trophic level for potential consumers.

Seven species of fish and three species of macro-invertebrates were captured in the nearshore zone and their abundance, species richness and aspects of community structure were variable in time and space. The cover of wrack on the beach and amount of wrack in the surf zone did not affect the abundance and species richness of fish and invertebrates.

Both $\delta^{13}C$ and $\delta^{15}N$ values for individual species of seagrass, algae, invertebrates and fish differed in both time and space. Seagrasses were isotopically distinct from algae due to their more enriched $\delta^{13}C$ values but there was little separation amongst algal taxa (i.e. red, green, kelps and other brown algae). Beach invertebrates spanned multiple trophic levels including likely detritivores and/or herbivores and predators. Crabs, fish and predatory staphylinid beetles had higher $\delta^{15}N$ values, reflecting their relatively high trophic levels compared to other beach and nearshore invertebrates. Brown algae and kelps are likely sources of nutrition for consumers but seagrasses do not appear to contribute much, if any, organic matter to these trophic webs.

The raking experiments performed here to assess the effects of wrack removal did not identify any effects on macroinvertebrates, likely due to the small scale of the wrack removals. An opportune sampling at Kingston, SE, demonstrated that a 'Cleared' area of beach (where large, refractory banks of seagrass wrack had occurred and were cleared from the beach) had a much lower diversity and abundance of macrofauna compared to 'Natural' areas of beach. Whilst the conclusion of this experiment is limited due to the lack of data prior to clearing, it is clear that such large-scale wrack removal can affect macrofaunal communities. The scale of experiments to assess the effects of wrack removal is clearly an important factor that should be considered in future studies, and removal experiments should be performed at ecologically-relevant spatial scales. Experiments may be improved by timing sampling to coincide with wrack clearing activities (before and after wrack removals) and utilising the identical method of wrack removal (equipment, volume of wrack removed). To achieve this, co-operation with organisations (whether government or private-sector) who perform wrack removal may be necessary.

Estimates of the quantity of sand removed during wrack removal indicated that a large proportion of the material removed is sand (81% of the DW or 0.57 kgDW per m^2 of beach cleares) rather than wrack. Wrack removals may thus constitute large losses of sand from beaches and may contribute to beach erosion.

Synthesis of findings

Photopoint method

After testing the photopoint method (Chapter 2) on a range of beaches with varying wrack cover, I concluded that photopoints, i.e. photographs, taken parallel to the dune at the driftline, gave similar results for % wrack cover as more time-consuming, conventionally used transects. The accuracy of the photopoint method proposed by McKechnie and Fairweather (2003) was improved by scoring photos into 20 classes, with a finer scale used for beaches with low wrack cover (0-10%). The photopoint method can thus be used to accurately and rapidly estimate wrack cover on a range of sandy beaches. This method was used throughout the remainder of this thesis to assess the cover of wrack at the scale of the whole beach and for general beach descriptions. Conventional transects and quadrats were still used to assess wrack cover at smaller scales (e.g. in Chapters 4, 5 and 7) because the photopoint method is only useful for assessing wrack cover at the scale of beaches, or sites separated by several hundred metres to ensure independence of samples.

The photopoint method provides a useful tool for researchers, natural resource managers (e.g. Primary Industries and Resource South Australia and the Coast Protection Board, which is a branch of the Department for Environment and Heritage) and community groups. Its use allows researchers to expend their efforts to answer more complex questions rather than using up time and funds performing routine surveys of the size of wrack deposits. Many previous studies have quantified the size of wrack deposits as the volume of wrack per square metre (i.e. units of measurement m^3m^{-2}, e.g. Ince *et al*. 2007) or the mass of wrack per linear metre of shoreline (i.e. units of measurement $kgWWm^{-1}$, e.g. Orr *et al*. 2005, or $kgDWm^{-1}$, e.g. Ochieng and Erftemeijer 1999). The photopoint method could also be used in conjunction with measurements of the depth of piles to estimate volume or mass of wrack to provide a more accurate description of the size and distribution of wrack deposits. It is thus a useful tool for researchers to perform rapid surveys of wrack deposits and provide a general description of the beach.

Wrack cover and composition

This study provides important survey and baseline data on the state (both cover and composition) of the wrack deposits in South Australia (Chapter 2). Other studies have also reported high variability in the amount of wrack present on beaches in South Australia (McKechnie & Fairweather 2003) and elsewhere in both Australia (Ince *et al.* 2007) and overseas (ZoBell 1971; Ochieng & Erftemeijer 1999; Yatsuya *et al.* 2007). Conversely, I am not aware on any other studies that have reported such a high diversity of species in wrack deposits. This may, in part, be indicative of the high diversity of algae and seagrasses which occurs within South Australia (Womersley 1984; 1987; 1994a; b; c) but may also reflect the comprehensive sampling regime and sorting of wrack samples in this study. This study exceeds many others in terms of its scope; the number of sampling events, the geographical range, the range of beach types sampled and the number of beaches sampled.

Unlike other studies, there was no overall trend for higher wrack cover to occur seasonally (i.e. in winter as reported by Robertson & Hansen 1982; McKechnie & Fairweather 2003; Yatsuya *et al.* 2007). There may in fact be such a trend on some South Australian beaches but only one visit was made to each beach every 2 months, and given that wrack deposits are highly influenced by tides, currents and winds, such patterns may have been missed. Seasonal trends in wrack cover may also occur in some years but not others. McKechnie and Fairweather (2003) found that in one year, the cover of wrack was higher in winter than in summer, in the same regions of South Australia. Thus, I recommend that additional surveys of South Australian beaches be carried out (using the photopoint method), to survey the cover of wrack on beaches at the scale of days to weeks and throughout the lunar cycle and on a day-to-day basis. Surveys should be carried out in all 4 seasons, with multiple visits within each season, to assess whether seasonal trends in cover or composition occur.

In most cases the species found in the wrack deposits reflected those growing in nearby algal and seagrass beds, and thus represents the transfer of organic matter and nutrients between offshore habitats and the nearshore, beach and terrestrial habitats. The one notable exception to this was the kelp *Macrocystis angustifolia*, which is reported to grow only in the far southeast but was found, in small quantities (i.e. single blades) with floats attached, at beaches spanning the entire SE region and into the Fleurieu and Metro regions. The congener *M. pyrifera* has also been reported to float long distances, likely due to the presence of floats (Edgar 1987; Harrold & Lisin 1989; Hobday 2000). Thus, the export of *M. angustifolia* wrack out of the area in which it grows is a pathway for the transfer of organic material into distant habitats (i.e. separated by up to hundreds of kilometres). Whilst not all of the material that arrives on a beach is incorporated into the beach ecosystem, some proportion may be retained and interact with sediments, leach organic matter and/or nutrients, or be incorporated into trophic webs. Upwelling events, which bring nutrient-rich waters to the surface, occur along the Bonney coast in the SE region. Export of material from upwelling areas, where productivity is high, has been reported for other habitats (Bustamante & Branch 1996; Vetter & Dayton 1999). Movement of wrack out of these upwelling areas, either on to the beach or out of the region, may thus disperse the upwelled nutrients into other habitats. Further research should be carried out to investigate the movement of wrack from the source(s) of the epiphytes to beaches, and the exchange of wrack between the beach and nearshore zone. Previously this has been achieved for large kelps (tag-recapture and radio tracking, Harrold & Lisin 1989) and mesh bags containing wrack (Piriz *et al.* 2003) but this has not been attempted for small species of algae or seagrass.

Wrack provides habitat and food

A diverse and abundant macrofaunal community was associated with the wrack deposits sampled in this study. Many studies utilise coring (McLachlan 1985; Dugan *et al*. 2003; McLachlan & Dorvlo 2005), rather than pit-fall trapping as in this study, and these methods differ in that pit-fall trapping captures surface-active, nocturnal fauna rather than those within the sediments. The advantage of this is that mobile fauna, which may move to and from wrack deposits are sampled. My study appears to under-represent larval forms and macrofauna which do not emerge from the sediment (e.g. worms), compared with other studies of the fauna of wrack deposits (Egglishaw 1965) but in comparison I have captured more Diptera (McLachlan 1985), which are highly mobile and tend to escape when coring sediments (pers.

obs.). Yet other studies have recognised that the wrack itself may harbour macrofauna, rather than just the underlying sediments, and thus also sampled the fauna among the wrack (Lavoie 1985; Olabarria *et al.* 2007). For future research I would recommend a combination of these sampling strategies, with coring and direct collections of wrack to sample non-mobile fauna, as well as pit-fall trapping to capture mobile and nocturnal species.

Many studies of sandy-beach macrofauna do not explicitly consider whether the driftline or other, smaller wrack patches as habitats are separate from bare sand areas on the beach (e.g. McLachlan & Dorvlo 2005). It is often, therefore, difficult to determine the role of wrack in providing habitat for macrofauna. The relative distributions of macrofauna and wrack may be particularly important when assessing zonation of sandy beach macrofauna, since wrack tends to form driftlines running parallel to the beach. In this study (Chapter 4), I found that the entire driftline area, rather than just the wrack patches themselves, provides habitat for macrofauna, with increased abundance and diversity of fauna, and different communities when compared to bare sand areas. Smaller wrack patches are also colonised by macrofauna but the importance of these patches may be less than that of the driftline, with lower diversity and numbers of fauna occurring here. This result is similar to other studies that have found that large wrack banks have more abundant and diverse macrofaunal communities (Olabarria *et al.* 2007). Studies of sandy-beach macrofauna should then consider, if not explicitly incorporate into their study design, the role of wrack as a habitat. At the minimum, this could be achieved by routinely recording the cover and/or type of wrack present where any samples are taken. For example, the cover of wrack and percent algal vs. seagrass wrack in the square metre surrounding a core sample could easily be recorded. Alternatively, studies could explicitly include sampling within versus outside of the driftline or under versus away from small patches of wrack. In any case, wrack should not be ignored when sampling sandy-beach macrofauna.

Future research could also incorporate large-scale and long-term removals of wrack from beaches to assess the role of wrack as both a habitat and a food source for macrofauna. By removing wrack, we may expect to see a reduction in the abundance and diversity of macrofauna. Alternatively there may be a shift to other species on the beach that either do not rely on wrack, or may be adversely affected by wrack deposits (e.g. bivalves may be smothered by large quantities of wrack and may not be able to filter feed or may be affected by anoxia, which can be induced by high wrack cover, McGwynne *et al.* 1988). This work could also be performed on beaches that are ‘cleaned’ of wrack but the effects of no wrack may be confounded with other effects of beach cleaning such as compaction of sediments by vehicles and increased sand erosion due to any loosening of surface sediments. These experimental removals of wrack should thus be performed with minimal disturbance to the beach, e.g. by collecting wrack by hand rather than raking it as in Chapter 7.

Although mass loss from litterbags was minimal over weeks in my litterbag experiments (Chapter 6), in the initial stages of decay there was a rapid loss of mass. This likely corresponds to the deposition of wrack followed by drying, cell lysis and leaching of organic matter and nutrients. Freshly-deposited wrack or wrack wetted by rain is thus more likely than old, dry wrack, to contribute OM or nutrients via decomposition. Leached OM may be incorporated in trophic webs on the beach through consumption by meiofauna, or may be washed into the nearshore zone where it may be available to filter-feeding invertebrates. Nutrients may also be available to algae and seagrasses but the importance of these nutrient inputs is likely to depend on the proximity of the beach to the source of the macrophytes. Robust species (e.g. seagrasses and, in particular, *Posidonia coriacea*) decompose more slowly (Chapter 6), probably due to the high proportion of lignin in their tissues. These species may thus play a greater role in the formation of dunes (Hemminga & Nieuwenhuize 1990; Sanderson *et al.* 1998) rather than in providing food or nutrients.

I suggest that further research into the rate and processes involved in the decomposition of wrack be carried out, particularly to investigate the effects of wetting/drying regimes and the size of wrack deposits (since larger deposits tend to dry out more slowly, pers. obs.). I also suggest that these experiments could be performed with concurrent investigations of the OM content of underlying sediments to assess leaching and inputs of OM.

Algae, but not seagrasses, provide a food source and are incorporated into the beach and nearshore ecosystem through trophic transfer. Direct consumption of algae by beach macrofauna appears likely based on stable isotope analysis (Chapter 6). Wrack also indirectly provides food for higher consumers through the provision of prey among this microhabitat, with their stable-isotope signatures also reflecting those of algal wrack. This finding supports previous studies which have reported the presence of higher-level consumers within wrack deposits (Egglishaw 1965; Griffiths & Stenton-Dozey 1981; Lavoie 1985; Olabarria *et al.* 2007) and furthermore demonstrates that predatory species derive nutrition indirectly from wrack.

Stable-isotope analyses on wrack and nearshore crabs and fish suggested that algal wrack may also provide a basal food source for these consumers (Chapter 6). Only preliminary analyses of these data were performed due to time constraints and thus these conclusions are tentative. It was clear, however, that fish and invertebrate consumers occupied broad trophic niches and consumed a variety of prey items. Wrack deposits thus support multiple trophic levels and provide a basis for a food web linking marine and terrestrial habitats. Furthermore, wrack provides a pathway for the transfer of nutrients and organic matter between habitats including seagrass meadows, algae on reefs, nearshore waters, sandy beaches and terrestrial habitats (Fairweather & Quinn 1992; Polis & Hurd 1996).

One constraint of this study was that a limited number and type of primary producers and consumers were sampled. In terms of primary producers, only wrack (from the beach and nearshore) was sampled and for consumers only invertebrates for which sufficient biomass could be collected were processed. There are thus many potential food sources, both in the nearshore zone and in other marine habitats nearby that were not sampled. Future studies should attempt to sample a broader range of materials including living seagrass and algae, epiphytes, phytoplankton and benthic invertebrates. This would be a quite large undertaking for any study and was beyond the scope of thus project.

There was no relationship between the cover of wrack on the beach and the amount of wrack collected in the seine net, nor were there any relationships between these two measures of wrack and the abundance or species richness of fish and invertebrates. These results contrasted with other studies, which found positive relationships between the amount of wrack present and the abundance and species richness of fish and invertebrates (Kingsford & Choat 1985; Lenanton & Caputi 1989; Crawley *et al.* 2006). I propose that constraints on the methods used in this study were, in part, the cause of this. In other studies, boats were used to deploy and retrieve seine nets (Kingsford & Choat 1985; Lenanton & Caputi 1989) and in some cases floating wrack patches were targeted for sampling (Kingsford & Choat 1985). Seining by hand (as in this study) rather than using a boat to deploy and retrieve the net imposes limitations on the beaches that can be sampled (due to wave height), the maximum (safe) water depth, the size of the net that can be used and hence the volume of water/wrack sampled per haul, and the speed at which the net can be pursed (probably affecting the success of capture). In addition, at beaches with large quantities of wrack in the surf zone, seining is difficult and can be dangerous due to the weight of the net. In future studies, I suggest the use of a boat to deploy and retrieve the net (which consequently can be larger than the one used in this study), particularly if beaches with large quantities of surf-zone wrack (e.g. Kingston SE) or if wrack patches (e.g. individual kelp plants) in the surf zone are targeted.

Interactions between beach morphology and sediments and wrack, and implications for macrofauna

There was no relationship between the cover of wrack and the organic matter (OM) content in the underlying sediments (Chapter 3). This result is supported by my litterbag experiments (Chapter 6), which suggested that loss of mass and nutrients from litterbags was minimal over weeks in my litterbag experiments. In contrast, in Chapter 3 higher wrack cover at the scale of the whole beach was linked to increased OM content of beach sediments, i.e. the OM content of sediments was higher in the SE region of the state, which had the greatest cover of wrack on its beaches (Chapter 2). Thus, wrack deposits may increase the organic matter content of sediments, but the effect is at the scale of the whole beach rather than only in the driftline. This supposition is supported by the finding that sediments from below the driftline also had relatively high OM content (Chapter 3). This may be caused by leaching of OM from wrack in the driftline, which may then slowly wash back down the beach. This is supported by my observations at beaches with high wrack cover, where pools of brown liquid accumulated around driftline wrack and trickled in small rivulets into the low shore. Increased OM content in sediments may benefit meiofauna living within the beach (McGwynne *et al.* 1988) and filter-feeding invertebrates living in the low shore and nearshore zones (Bustamante & Branch 1996) through the provision of food. Wrack on beaches in the far southeast of the state was dominated by algae, particularly kelps (Chapter 3). In my litterbag experiments, I found that, in some cases, algal wrack decomposes faster than seagrass wrack (Chapter 6). The combined effects of greater wrack cover and a higher proportion of algal rather than seagrass wrack, may result in the trend for higher sediment OM content in the SE region.

The cover of wrack on beaches increased as beaches tended towards more dissipative states (i.e. a flatter profile with less energy reaching the high shore) (Chapter 3). Since wrack provides both habitat (Chapter 4) and food (Chapter 6) for macrofauna, this may be an important, yet largely ignored, factor driving the higher abundance, species richness and biomass of macrofauna on dissipative compared to reflective beaches (McLachlan & Dorvlo 2005; 2007). Furthermore, morphological features such as cusps affect the distribution of wrack on the beach (Chapter 5), accumulating wrack into bays and thus concentrating resources in the alongshore direction. In my study of the distribution of macrofauna within cusps, I also found that bays had higher species richness and abundance of macrofauna. This pattern may be caused by physical processes such as redistribution by swash, or may be a response of the fauna directly to the beach morphology or the distribution of food and habitat resources (i.e. wrack). Beach morphology can then, affect the amount and distribution of wrack on sandy beaches, which may also have possible flow-on effects for beach macrofauna.

In Chapter 3, high wrack cover was correlated with increased sediment OM content. In the investigation of the effects of cusp morphology on wrack deposits and sediment characteristics (including organic matter content) (Chapter 5); however, the opposite result was found i.e. bays had higher wrack cover but lower sediment organic matter content compared to horns. This may be because high swash backwash (in the form of a mini-rip along the centre of the bay) (Russel & McIntire 1965; Masselink *et al.* 1997) may wash particulate OM from the beach and into the nearshore zone. Thus, there is another interaction between beach morphology, sediments and wrack, with one influencing the other and vice versa.

Future research could focus on assessing whether wrack cover differs due to other morphological features. In this study, I sampled only one site on each beach and sites were chosen so that they were at least 100m from any hard structure in the nearshore zone or on the beach. My observations suggest, however, that wrack accumulates on one side of headlands, rock walls and groynes (e.g. at Stinky Bay near Nora Creina, Kingston and North Haven), depending on the prevailing current and wind directions. This may be due to longshore drift, which moves sediments in the direction of current movements. For example, along the Adelaide metropolitan coast, currents tend to move from south to north (Pattiaratchi *et al.* 2007) and move large quantities of sand towards the northern beaches (Pattiaratchi *et al.* 2007). At North Haven, where man-made rock walls extend into the sea at both ends of the beach, large accumulations of wrack are trapped by the rock wall at the northern end of the beach but the wrack cover at the other end of the beach is not as high (pers. obs.). I suggest a study investigating the distribution of wrack along beaches with sampling performed at a range of distances in both directions alongshore from structures (both natural and man-made) on the beach and in the nearshore zone. Such information could also be used to assess whether building new structures on the beach will result in large wrack accumulations, which may be an undesirable ecological outcome and/or offensive or undesirable for beach users. This information would allow better planning of beach engineering solutions (in terms of locations, orientations and designs) for these structures to create flow-through situations rather than effectively wrack traps.

Another direction for future research may involve sampling additional beaches, in particular beaches at either end of the morphodynamic range (Dissipative and Reflective types). The range of beach morphological types sampled in this study was limited because few truly Dissipative or Reflective beaches exist within the three bio-geographical regions of South Australia that were studied. Thus, to assess whether my conclusion that more wrack occurs on more Dissipative beaches holds at the morphodynamic extremes, I recommend sampling additional beaches across the state, ranging from Dissipative through to Reflective. Additional sampling on Dissipative and Reflective beaches should also be carried out to test my conclusions regarding the role of wrack as a habitat and food source for macrofauna, since the abundance, biomass and species richness of macrofauna differs between morphodynamic types (McLachlan & Dorvlo 2005; Langley 2006; McLachlan & Dorvlo 2007). In addition, further testing of my findings about the effects of cusps on wrack accumulations, sediments and macrofauna should be carried out on more Reflective beaches with cusps, to sample a wider range of cusp sizes and morphologies. This additional sampling will require sampling outside of the three biogeographical regions studied here, in other regions of SA, interstate and globally.

Effects of wrack removal

Due to the small number of beaches that are 'cleaned' or have wrack harvesting activities, formal analyses comparing these beaches with control beaches were not performed. At Kingston in the SE region wrack harvesting occurs only once or twice a year. Harvesting of algal wrack also occurs at Beachport in the SE but this occurs infrequently and only in small quantities (Susan Mills, pers. comm.). In the Metro region, beach cleaning and sand replenishment occurs at Glenelg and Seacliff respectively, and beach cleaning occurs mainly in summer. To assess the effects of wrack removal on these beaches, I will compare these beaches to the control beaches in this study to assess whether there is a marked difference in terms of the cover of wrack (Chapter 2) and sediment characteristics (Chapter 3). I also compare Glenelg and Seacliff to control beaches to assess effects on fish and nearshore invertebrates (Chapter 6) but such sampling was not performed at Kingston or Beachport. Macrofaunal communities at Kingston were sampled on one occasion following the harvest of wrack from an area of this beach. These results are also discussed here.

Kingston had the highest wrack cover of any beach (Chapter 2) but the cover of wrack also varied greatly between visits. My observations suggest that this was mostly due to the harvest of wrack but there was also some natural variation in cover due to deposition and removal of wrack by tides. The wrack deposits there are dominated by aged (brown) and fragmented seagrass material, predominantly *Posidonia sinuosa*, with smaller amounts of the seagrass *Amphibolis antarctica* and a variety of red, brown and green algae. My assessment of Kingston is that the 'natural' state for the beach is for large deposits of wrack, covering most of the high shore with over a metre of wrack to be present. The deposit forms a bank (Mateo *et al.* 2003), in front of which the wrack cover is more patchy and may or may not extend to the swash, depending on tidal movements of wrack on and off the beach. The large accumulation of wrack is likely a result of the offshore seagrass beds, which are some of the largest in this state. The situation is exacerbated by the man-made rock wall at the northern end of the beach, which traps wrack and prevents its further longshore movement with the prevailing current. Clearing of wrack by the licenced harvesters reduces the cover and depth of wrack to a noticeable extent (Figure 8.1). The rate at which the wrack re-accumulates on the beach is currently unknown but could be investigated with a series of photopoints, closely spaced in time, following the wrack harvest.

The massive wrack deposits at Kingston appear to prevent seawater from reaching the high shore and buffer wave action (pers. obs.) in calm conditions. Whether these wrack banks can withstand heavy swell and storms has not been investigated but their presence may provide some protection for the beach and reduce erosion of sediments by water or winds. The large wrack deposits at Kingston also appear to form a compost-like substance, which is dark coloured, spongy and has high organic matter content (over 20%, Chapter 3) and is found under the wrack deposit in the high-shore zone. The layer of this material is at least 30cm deep (pers. obs.) and is likely to contain high proportions of refractory seagrass as well as sand. Similar deposits, which form layers within sand dunes, have been reported by other authors (Short & Hesp 1982; Hemminga & Nieuwenhuize 1990).

Seine netting could not be performed in the nearshore zone at Kingston due to the extremely large volume of wrack in the nearshore making it unsafe. Beaches in Western Australia, which also have large surf-zone wrack accumulations, have been studied by other authors (Lenanton *et al.* 1982; Kingsford & Choat 1985); these beaches had diverse and abundant of fish communities. Further research on the nearshore fish and macroinvertebrate communities at Kingston should be carried out with improvements (of a larger net and a boat to deploy and retrieve the net) incorporated (see above).

The effects of wrack removal on the macrofaunal community at Kingston were assessed in a pit-fall trapping study. This study was carried out after a fortuitous co-incidence- on one visit to Kingston the licence holder was harvesting wrack from the beach. I sampled a 'cleared' area of beach that had been covered in a deep, uniform layer of old *P. sinuosa* wrack which was then partially cleared (leaving a layer of wrack approximately 10cm deep) for commercial harvest. This situation is thus unique, in that the 'cleared' section of beach still had very high wrack cover. A 'natural' area of beach was also sampled as a control. The faunal community in the 'cleared' area was depauperate in both the number of individuals and the number of species. Comparatively, the 'natural' area had both high diversity and high abundance of macrofauna. Sampling on one other visit to Kingston, in an area of beach similar to what may have been present before the wrack harvest, also yielded low faunal abundance and diversity. Thus, there may be few fauna present in the old, refractory *P. sinuosa* wrack deposits at Kingston, and by removing the wrack it is possible that few fauna are removed and that the removal of this wrack does not constitute a loss of habitat or food for macrofauna. In fact, removal of old wrack deposits could potentially clear the beach so that new wrack deposits, which are more suitable for macrofauna, can occur. Comparison of these results to other studies is difficult given this unique situation. To my knowledge there have been no previous studies on beaches where wrack was removed in a commercial harvest, nor where such a large quantity of wrack remained on the beach after the wrack removal activities. Overall the findings were similar to those of other studies; the abundance and diversity of macrofauna was lower in the 'cleared' area of beach (Llewellyn & Shackley 1996; Engelhard & Withers 1998). This result may be confounded by the lack of before-removal data and thus the results should be interpreted cautiously. Thus, additional sampling of the macrofauna at Kingston should be carried out, with sampling performed at various times of the year, in areas of varying wrack cover and type, and both before and after wrack harvesting.

Over the course of 3 years I made over 15 visits to Beachport in the South East region. During that time, I did not see any evidence of wrack removal activities on this beach. This is not surprising since wrack removal activities on this beach are only carried out infrequently and involve one or two people collecting wrack by hand (Susan Mills, pers. comm.). My estimates of wrack cover on this beach (Chapter 2) were similar to other SA beaches in both their cover and the variation among visits. Beach width, fall and slope and sediment characteristics were also similar to the other beaches sampled. Although pit-fall trapping and coring were not carried out at

Beachport, I observed macrofauna (mostly amphipods and flies) on the beach and in the wrack samples collected for composition estimates (Chapter 2), suggesting that the wrack on this beach provides habitat and/of food for beach macrofauna. Seine netting was not carried out here due to the high waves and steeply-sloping benthos in the nearshore zone.

Glenelg and Seacliff both had relatively low wrack cover (Chapter 2), although other beaches had similar wrack cover and so this cannot be attributed solely as an effect of beach cleaning or the sand replenishment program. On one occasion, I observed the beach cleaning operation at Glenelg; a small tractor was used to tow a raking machine that had cleaned the beach from the rock wall at the back of the beach to the freshest driftline approximately half way between the rock wall and the swash. In the wake of the tractor and rake, all of the large (> 2cm long) pieces of wrack were removed from the beach but small fragments of wrack, mostly seagrass, remained mixed with the sand. The top layer of sand (approximately 3cm deep) was very loose and showed clear raking marks. Thus, the machine appears to be efficient at removing wrack but clearly affected the beach sediments by loosening them and potentially making them more vulnerable to erosion by wind and waves. At Seacliff, where the trucks drove on the beach the sediments were compacted so that wrack was deposited on the surface but did not become buried into it as it did at other beaches (pers. obs.). In the high shore, the sediments were similar to those at other beaches, although I did not sample in the sand pile where trucks dump their sand loads.

Few fauna were ever observed on the beach at either Glenelg or Seacliff and insufficient numbers were captured in sediment cores, so none were sampled for stable isotope analysis in Chapter 6. Sampling of macrofauna at these beaches should be carried out (using a combination of sampling techniques as described above). Pit-fall trapping at these beaches will be a difficult task due to the large number of people using the beach, even at night and during winter. These experiments will require researchers to mind the traps until after dark and probably will only be able to be done in off-peak usage times at Glenelg (i.e. not in summer). I expect that low diversities and abundances of fauna will be found, especially at Glenelg, which has no dune system, and thus provides no refuge or recruitment pool for beach macrofauna.

Glenelg and Seacliff had comparable (or even relatively high) species richness and abundance of fish and invertebrates to other beaches sampled (Chapter 6). Both beaches appear to support fish communities that are similar to those elsewhere. On one visit to Seacliff (August 2007) there was a large accumulation of wrack in the nearshore zone. This was likely caused by strong winds pushing wrack into that end of the bay, where it was trapped by the headland and rocks. Thus, despite the low wrack cover on the beach, the amount of wrack in the surf zone was large. This suggests that the amount of wrack in the nearshore zone is not necessarily determined by the amount on the beach or vice versa (although there is often exchange between the two) since the cover of wrack at Seacliff is usually low and was low on that day. This observation is supported by the lack of a relationship between these two measures of the amount of wrack shown in Chapter 6. Other factors such as currents and wind directions may also have an effect on wrack accumulations and may move wrack between beaches, from the nearshore into the offshore and vice versa. Fish and macrofauna may also be associated with the drifting wrack, rather than a specific beach, and move with the wrack. For example, on the visit to Seacliff when there was a large amount of wrack in the nearshore zone, there were large numbers of the smooth toadfish (*Tetractenos glaber*) and sand crabs (*Ovalipes australiensis*) present. Such high abundances were not recorded on the other visit to Seacliff, when the volume of wrack in the surf-zone was lower. Conversely, I did not find a general relationship between the amount of wrack in each seine haul, the abundance or diversity of fish, but I recommend further investigation of this.

The generally low wrack cover at Glenelg and Seacliff (even in winter when cleaning does not occur) may mean that the wrack that is present is more important for macrofauna, compared to on beaches with high wrack cover (i.e. per unit of wrack the effect is greater). This low wrack cover may mean that the removal of the small amount of wrack present is more detrimental to beach macrofauna, as it removes their only habitat and food. In Chapter 3 there was a significant difference in the species richness of macrofaunal communities among the 4 visits made but because only one visit was made in each season I did not assess which visit had the most diverse community (i.e. Visit was a random factor and post-hoc tests were not performed). Visual inspection of the data (Figures 4.5a and b) showed that species richness was lowest in summer and winter compared with autumn and spring, which may be due to the more extreme environmental conditions in the temperate summer and winter of South Australia. There was no trend for higher or lower wrack cover on any of the seven visits made to the 17 study beaches in Chapter 2. I would therefore suggest that environmental conditions are more likely causes of this variation in species richness between seasons.

By cleaning beaches only in summer, sediment erosion may be avoided in winter, when erosion of the beach is usually greatest due to higher wave energy. In addition, previous studies have demonstrated that the beach (sediment OM content, meiofaunal and macrofaunal communities) can recover from beach cleaning after a period of a few weeks to months (Engelhard & Withers 1998; Lavery *et al.* 1999; Malm *et al.* 2004). Thus, while the desirable outcome of a clean beach is achieved in summer during peak usage times, during winter beach cleaning is less frequent, so the beach may have a chance to recover from the summer cleanings.

My experimental removal of wrack had no measurable effect on the abundance, diversity or macrofaunal community structure. This result contrasts with other studies, which have reported immediate reductions in faunal abundance following experimental removals (Engelhard & Withers 1998). I propose that scale (size of the raked areas and number of raking events) was insufficient. I was only able to clear small plots (approximately $25m^2$) within the driftline because of the effort required to remove wrack by hand raking. I therefore propose that a mechanical rake, preferably of the same type used by local councils, be used to remove wrack and that the scale of the removal be increased to better simulate actual beach cleaning activities. Larger plots, which cover a greater alongshore distance (at least 10s of metres) and extend from the base of the high shore to at least the most recent driftline, should be used. Replicate beaches and cleared versus control plots should be used if possible. This study was also only able to assess the effects of wrack removal immediately following the experimental removal. In future studies, I recommend that repeated clearings (of the same plots if possible) be performed to assess the long-term impacts of repeated wrack removal. Multiple clearing events will also allow assessment of any temporal variation in the effects of wrack removal, which may be caused by variation in the cover and/or composition of the wrack, weather and environmental conditions, or the timing of activities of macrofauna such as recruitment events. Alternatively, sampling of actual harvested and cleared areas could be performed. BACI designs with multiple ‘after’ samplings could be used; however this would require close consultation and cooperation with councils and contractors to time sampling activities around beach cleaning and harvesting activities. In practice this may be difficult to arrange.

My experimental removal of wrack did indicate that large quantities of sand are removed with the wrack that is raked off the beach. I found that 62% WW and 81% DW of the material removed is sand, which is similar to the value reported by (Ochieng & Erftemeijer 1999). This may have direct consequences for beach sand budgets; if large volumes of wrack are removed from the beach the loss of sand may be considerable. On many beaches around the world, erosion of the beach and dune is of ecological and social concern (Schlacher *et al.* 2008; Williams *et al.* 2008). At some of these beaches, particularly urbanised beaches, wrack removal occurs and so may contribute to this loss of sand. Where beach nourishment or beach armouring also occurs, these beach management strategies may be working counter-productively, in that one results in the loss of sand whilst the other tries to prevent it. My estimates of the proportion of sand in the material removed are based on my experimental clearing and may not represent either ‘cleaned’ or ‘harvested’ material. I recommend that sub-sampling of both ‘cleaned’ and ‘harvested’ material to assess the quantity of sand removed. This again will require the assistance of councils and licensed wrack harvesters.

Further research into other possible effects of wrack removal could also be carried out concurrently with the above experiments. Other effects to investigate include:

- Long-term effects of wrack removal on sediment OM;
- Effects of raking and/or harvesting wrack on the erosion and loss of beach sands into the nearshore zone;

- The rate of wrack accumulation after beach cleaning and harvesting (i.e. how long does the beach stay 'clean'?);
- Effects on nearshore fish and invertebrates (e.g. does removal of wrack from the beach reduce the amount of wrack in the nearshore zone? Does the availability of invertebrate prey which is washed from the beach decrease?); and
- Comparison of the methods and effects of wrack removal via beach 'cleaning' versus wrack 'harvesting'.

Management implications

The photopoint method is a rapid and accurate technique which can be applied by managers of wrack deposits. Photopoints could be used to inform managers of wrack cleaning and harvest activities, as well as assessing wrack stocks around the state and possibly identify unknown or unused resources. Primary Industries and Resources South Australia (PIRSA), in their capacity as managers of the wrack harvest, require that licence holders provide data on wrack volume/cover before and after harvest (PIRSA 2003). Prior to now, there was no feasible way to do so; however, photopoints provide a rapid tool to monitor the activities and check the compliance of licensed harvesters.

I recommend that PIRSA make it a requirement of licences to harvest wrack that they are notified of when wrack removal activities will occur. This will allow improved monitoring of compliance and will allow future researchers the opportunity to conduct targeted sampling around the activities. Currently PIRSA require that a layer of at least 10cm depth of seagrass wrack remains on the beach after harvesting wrack. This licence condition is crucial, as it may provide some protection from erosion, reduce the amount of sand removed, and leave some wrack available as faunal habitat on the beach and in the nearshore zone.

I propose that the current level of wrack removal at Kingston is acceptable based on the following:

- The cover of wrack at Kingston is probably un-naturally high due to the breakwater at the northern end of the beach acting as a wrack trap;
- Macrofaunal abundance and diversity in the wrack banks is low;

- The wrack is mostly old, refractory seagrass which does not input nutrients into the beach ecosystem via either decomposition or incorporation into trophic webs;
- PIRSA requires that a layer of at least 10cm of seagrass wrack remain on the beach, and the licence holder appears to comply with this; and
- Wrack harvest occurs only once or twice a year.

The effects of beach cleaning at Glenelg and the sand replenishment program at Seacliff are unclear. These beaches are highly urbanised and are also affected by a number of natural and anthropogenic processes, making interpretation of my results difficult. Cleaning is carried out mostly in summer for the amenity of beachgoers. The frequency and extent of this cleaning are largely driven by subjective decisions on how much wrack and what type (i.e. if there are harmful materials such as glass or syringes) is present. It seems likely that with such reasons, beach cleaning will continue at Glenelg. The sand replenishment scheme along the Adelaide metropolitan coast will soon be modified and so that trucks may no longer be driven onto a number of beaches and sand piles such as the one at Seacliff may no longer be required. Further research into they effects of vehicles on the beach will be required and is currently being undertaken by members of my supervisor’s research group.

Conclusions

This thesis aimed to increase our understanding of the role of wrack in the beach and nearshore ecosystem. Wrack deposits on sandy beaches throughout three biogeographical regions of South Australia were studied, as well as their associated sediments, macrofaunal communities, and the incorporation of wrack into beach and nearshore ecosystems via decomposition and trophic transfer. Survey and experimental methods were developed, improved and tested, and can now be applied to benefit the study, management and protection of wrack deposits and sandy beaches throughout Australia and globally.

The wrack deposits on South Australian sandy beaches were composed of a diverse mix of algal, seagrass and other material and varied, in terms of their cover and composition, both spatially and temporally. They are thus a dynamic and variable resource. Wrack cover was also affected by beach morphology; higher wrack cover occurred on beaches which were more dissipative in nature, and morphological features such as cusps affected the distribution of wrack on the beach, creating areas of high and low wrack cover. Decomposition of wrack was initially rapid and then slowed following initial leaching, suggesting that the input of organic matter and nutrients to the beach would occur shortly after the deposition of wrack. Organic matter content of sediments was higher in the SE region of the state, which has higher wrack cover on its beaches. The SE region also had the highest proportion of algal wrack, which may decompose to a greater extent and release more nutrients and organic matter to the ecosystem than seagrass wrack. Macrofaunal communities within the driftline were diverse and abundant, and these communities differed from the fauna found in wrack deposits elsewhere on the beach, both in bare sand and under isolated wrack deposits. Thus, wrack deposits of varying sizes (i.e. the driftline and wrack patches elsewhere) are important as they provide habitat niches for beach macrofauna. Wrack deposits, particularly algae, act as a food source for beach and nearshore macrofauna and fish, providing a pathway for the transfer of nutrients and energy from offshore habitats into beach and nearshore habitats.

The second aim of this thesis was to assess the effects of wrack removal on aspects of beach and nearshore ecosystems. My experimental removal of wrack to simulate beach ‘cleaning’ had little effect on macrofauna but demonstrated that large proportions of the material removed (81%DW) is sand. Macrofaunal communities at Kingston Beach, where commercial harvest of wrack occurs, were very different between a ‘cleared’ and ‘natural’ area of beach. This was likely due to a combined effect of the size and type of wrack present in the ‘cleared’ area (old, refractory seagrass *Posidonia sinuosa*), and the wrack harvest. I recommend that future investigations into the effects of wrack removal be carried out on large spatial scales and investigate both short- and long-term effects.

Wrack provides an important link between offshore habitat and nearshore, beach and terrestrial habitats via the transfer of organic matter and nutrients. Wrack interacts with beach morphology and sediments, provides habitat for macrofauna, remineralises nutrients through its decomposition, and provides the basis of a complex trophic web. It is thus a key component in beach ecosystems and requires further study.

List of Figures

Figure 8.1