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Ecological significance and commercial harvesting of drifting and beach-cast macro-algae and seagrasses in Australia: a review

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Abstract

This review provides an overview of aspects of the ecology of drifting and beach-cast macroalgae and marine angiosperms in respect to present and potential commercial use of that resource in Australia. It sets the scene with sections on industries that utilise macro-algae and seagrasses, the ecology of littoral and nearshore sublittoral ecosystems and the processes of deposition of beach-cast macro-algae and seagrasses on beaches. It then describes the major economic macro-algae and seagrasses that occur as beach-cast wrack, with an emphasis on known information on habitat distribution, geographical range, and harvesting issues. Gaps in scientific knowledge are pointed out. The priority areas of future research were found to be:

- The importance of beach accumulations of macro-algae and seagrasses on feeding and nesting shorebirds;
- Whether available resource allows for ecologically and economically sustainable harvesting;
- A survey of present and potential commercial macro-algae and seagrasses: studying biomass, density and annual production rates, interannual variability of recruitment into living stands, the effect of harvesting on trophodynamics and community structure and the stability of the resource base for economically sustainable harvesting;
- An assessment of the importance of wrack in recycling nutrients and detritus to nearshore coastal ecosystems at wider geographical scales than previous work. This research should assess the dependence of offshore production on nutrients and detritus that are broken down in beachwracks.

Introduction

To most people beach-cast algae and seagrass are piles of rotting plant material washed up along the high tide line of many beaches. To a few people these accumulations are a livelihood and represent the raw product of a valuable resource. They also represent a vital link in a complex food chain based on primary production. Collection of beach-cast macrophytes in Australia occurred for scientific purposes and as a human resource since settlement, yet no definitive study has ever modelled the various components nor balanced them. This review illustrates the gaps in knowledge and the various conflicts of interest between harvesters and ecologists in Australia. The existing industries are described.

Harvesting of beach-cast seaweeds and seagrasses is a small, but growing, industry in temperate Australia. Bull kelps are harvested for alginate from King Island, Tasmania. Drifting red algae are used as feed in abalone hatcheries in Tasmania and are being assessed for feed in other states. Seagrass wrack is collected for fertiliser and soil improver in South Australia.

Harvesting can adversely affect the coastal and nearshore environment for beach-cast macroalgae and seagrasses are an important component of these environments. Research on nearshore ecosystem dynamics suggests that wrack accumulations are a source of particulate and dissolved carbon and nutrients (Hansen, 1984; Lavery, 1993). The juveniles of economically important fish use amphipods living in surf-zone accumulations of detached macroalgae as food. It is suggested that the vegetation also provides protection from predators (Robertson & Lenanton, 1984; Lenanton et al., 1982). Amphipods also lived in large numbers in organic matter deposited on a sand beach in New Zealand and their numbers varied with season (Marsden, 1991a, b). Wrack accumulations also contribute to food chain dynamics on beaches including thirteen species of flies (Diptera: Coelopidae) in New South Wales (Blanche, 1992) and at least four species of birds.

The main benefits from harvesting are the production of exportable primary products and in the cleaning of coastal beaches for recreation and tourism. Wrack accumulations can affect human use and enjoyment of beaches when they decompose, producing hydrogen sulphide gas (Hansen, 1984) and plagues of beach flies (Blanche, 1992). The managed harvesting of specific areas, where wracks are seen as problems, can both clean sections of beaches and produce a variety of economic products: fertilisers, soil improvers, stock and mariculture feeds, and such value-added products as alginate and agars. The aim of this review is to examine the impacts (existing and historical) of harvesting beach-cast macroalgae and seagrasses on littoral and nearshore marine environments.

Industries utilising macro-algae and seagrasses in Australia

Macro-algae and seagrasses are or were harvested, in only a few places in temperate Australia (Table 1). Beach-cast and subtidally drifting macro-algae are harvested for such uses as alginate and agar, cattle feed, garden fertilisers, and feed for abalone hatcheries. Seagrasses are harvested for insulation and garden fertiliser.

A major industry based on collecting beach-cast bull kelp (*Durvillaea potatorum*) has developed on King Island, in Bass Strait. Independent collectors collect 15–23 000 t (wet) of *Durvillaea* plants and dry them before selling them to Kelp Industries (KELCO) at AUS $40 t (dry) (F. Cullen, pers. comm., 1995–1996 prices). The company further dries and chips the kelp before shipping it to Alginate Industries, UK, for making into alginates. The supply of dried, chipped *Durvillaea* has not exceeded demand.

The bull kelp harvesting on King Island is unique in Australia in that it is a long established industry that has utilised a single species of macro-algae for 24 years. The island economy is supported partly by the activity. One-third of the harvesting is by full-time professionals, another third from semi-professionals, who work part of the year harvesting bull kelp, and the final third by families, as a social weekend activity. Bull kelp is collected from the swash zone of beaches and placed onto trailers and taken to drying racks supplied by the factory. Bull kelp has to be collected as it washes up because within 2–3 days on the beach the kelp starts to decompose. The kelp thalli are placed on poles on tall stands >4 m above the ground where they are dried for 5–14 days. Harvesters are responsible for the drying kelp until it is prooessed by the factory. Once the kelp is air dried, it is processed by the factory: broken into large pieces by a rubber tyre crusher, taken through a wood-fired oven, and then to another crusher where it is crushed into fingernail and sand grain sized pieces which are shipped directly to KELCO in Scotland. The factory on King Island produces 20% of KELCO's needs for alginates, which is one-fifteenth of known world requirements. Impurities in the dried product are tested regularly by KELCO and the King Island product has never reached the 1% limit for impurities.

There does not appear to be any resource problems and the limits on harvesting have been determined by market needs over 23 years of operation. The resource was surveyed in the 1980s by Cheshire and Hallam 1985, 1988a, 1988b, 1989), who concluded that only 10% bull kelps ripped off reefs find their way to the beach. Approximately 50% bull kelp washed onto beaches is harvested (F. Cullen, pers. comm.). The harvesters believe their industry has had little effect on the populations of bull kelps on King Island, but they are harvesting enough quantity to notioe resource shifts caused by other factors: warm sea temperatures, and decreased frequency of storms from the west (which bring the drifting bull kelps onto the beach) caused by ENSO events in the Pacffic.

It may be possible to harvest bull kelp on the NW Coast of Tasmania, but the main problems to be overcome before a similar industry to that of King Island could be set up are: determining the availability of the resource, building an infrastructure for harvesters, and reducing transport costs back to the King Island factory for processing.

Two byproducts are produced from the King Island factory: smaller grains, which are sold for use in stock feeds, and dust, which is sold for use in soil improvers. Tasbond and Aquasol sell liquid fertiliser made from *Durvillaea* and other drift algae collected from Tasmania and Victoria (Table 1). Kelp Industries on King Island recently made a feasibility study of the harvesting of beach-cast *Gelidium* spp., but found it was

Table 1. Past, present and potential economic Australian macro-algae, their comrnercial products, location where harvested, amount harvested, and method used to harvest.

Species	Commercial products	Where harvested	Amount (t)	Method
Durvillaea potatorum	alginate	King Island (Kelp Ind. Pty.	773-3250 (1975-1993)	harvest wrack
	fertiliser/stock feed	Ltd.) Tasmania Tasbond	unknown	harvest wrack
Ecklonia radiata	alginate	not harvested		
Macrocystis pyrifera and	alginate	Tasmania (Alginate Aust.)	6-13000 (1965-1971)	cut subtidal thalli
angustifolia	abalone feed	Tasmania	unknown	cut subtidal thalli
Sargassum spp.	alginate	not harvested		
Undaria pinnafitida	alginate and food	Tasmania (Tas Wakame P/L)	54 (1993),160 (1993/94)	cut subtidal thalli
Gracilaria spp.	agar	NSW	200-250 (1943)	collect subtidal drift
Gelidium spp. & *Pterocladia* spp.	agar	King Island (Kelp Ind. Pty. Ltd.)	1(1987), 7 (1988-89)	harvest wrack
Posidonia spp.	soil improvers to Japan and within Australia	Kingston, S.A.	unknown, recently operations were closed	bulldoze wrack
Zostera and *Heterozostera* spp.	house insulation soil improver	Western Port Bay, Victoria	early part of 20th Century. recently prohibited	tractors wrack

not profitable (F. Cullen, pers. comm.). Yet, in South Africa, *Gracilaria, Gigartina, Hypnea* and *Gelidium* are harvested mainly from beach-wrack by intertidal pickers (Anderson et al., 1989). Ferguson Wood (1946) suggested *Gracilaria* could be farmed and harvested from many estuaries in Australia, but of interest for this review were his remarks on collecting *Eucheuma*. During World War II, this macro-algae was used for agar production in Western Australia. According to Ferguson Wood (1946), it was collected from the beach in the Abrolhos-Dongarra (*sic*) region, but no extensive subtidal beds of this alga occur in this region today.

The abalone mariculture industry is another user of beach-cast and subtidally drifting macroalgae. Its total use of the resource is small but there is potential, with an increase in the number of mariculture facilities, that it will claim more of the resource. Already, some states have developed regulations to restrict the use of wild macro-algae stocks: in South Australia there is a total ban on taking wild macro-algae stocks, and in Tasmania abalone mariculturalisb are restricted to 5 t (wet) macro-algae per annum (Walker & Clymo, 1995). The general feeling in the industry is that a continuing reliance on wild stocks of macro-algae cannot be sustained (Anon, 1994). At present there is increased research into artificial feeds and mixtures of artificial feeds and dried macro-algae. Therefore, future use of wild stocks should not be any greater than they are at present.

Tasmanian Univalve, one of the largest abalone farms in Australia, annually collects 40 t of the kelp, *Macrocystis pyrifera* and 40 t subtidally drifting red algae (mainly *Rhodymenia* sp.) as feed for abalone (R. Sharkey, pers. comm.). The company collects under a special licence with Tasmanian Department of Primary Industries and Fisheries and the licenoe could be revoked at any time. It used also to collect beach-cast *Macrocystis pyrifera*, but this was not economical.

Annual growth rates of juvenile abalone are less than 5 mm a year (R. Sharkey, pers. comm.) when grown on wild macro-algae, which is not as high as the industry desires and artificial feeds are being developed to replace the macro-algae. Combination feeds that include dried red algae are presently being tested but it is unlikely that the dried red algae required in these feeds can be obtained from the accumulations of mixed species in subtidal drift or beach-wrack, as some red algae contain feeding deterrents to juvenile abalone. The abalone aquaculture industry is also experimenting with *in situ* cages for growing out hatchery juveniles. The cages have a funnel design that collect subtidally drifting macro-algae, which then feed the caged abalone. The cages work well in moderately rough environments. In recent growth trials on Fraser Island, Tasmania, caged abalone were placed *in situ* over naturally occurring accumulations of drifting red algae; their growth rates were similar to those observed in wild populations (C. Sanderson, pers. comm.).

Currently, small quantities of beach-cast seagrass leaves of the genus *Posidonia* are being harvested at Kingston, South Australia. The harvests are mainly for the Japanese soil improvement market and for local sales of soil improvers and growth stimulants through large chain stores. The present legislation for the conservation of seagrasses will discourage expansion of this harvesting. In the particular case of Kingston, the meadows from which these detrital drifts originate are close offshore and extend 20 km along the beach and at least 8.5 km out to sea i.e. there are 170 km^2 of seagrass in Lacepede Bay. If an estimate of 0.6 kg d.wt m^{-2} is used for biomass of seagrass leaves (Kirkman, 1983) there is 102 000 t seagrass leaves in Lacepede Bay, using an estimate of 2.2 g (dry) m^{-2} d^{-1} for productivity of leaves (Kirkman & Manning, 1993), there are 136 500 t seagrass leaves produced in a year. No estimate of the harvest quantities could be given at Kingston. The question is, how much seagrass can be removed from the beach without affecting the nutrient return to the offshore meadows? To confound this calculation, the input of nutrients via agricultural drains which flow to sea in this area must be taken into account. With the balanced equation for input of nutrients with seagrass leaf removal, management can make objective decisions about the amounts of drift that can be removed from beaches, if removal is seen as the only impact on the environment.

Alternatives to harvesting beach-cast algae are extensive harvesting of living stocks and intensive mariculture. Attempts to harvest living stocks over long time periods (e.g. *Macrocystis* in Tasmania, Table 1) have not been successful. In addition, cost recovery for capital investments in a harvesting industry requires a stable resource, but stocks can vary greatly between years. At present, intensive macro-algae mariculture is not economically viable in Australia because of high capital and work-force costs (Sanderson & Bendetto, 1988). Yet, if macro-algae culture can be integrated into fish farms to scrub effluents and act as a food resource, the cost recovery of growing and harvesting the algae may be high enough to be profitable (Sanderson & Bendetto, 1988).

The continued commercial exploitation of beach-cast macro-algae and seagrasses will probably concentrate on a few economically viable products at a few places in Australia.

Ecology of littoral and nearshore sublittoral systems

Large accumulations of beach-cast macro-algae and seagrass occur along the length of the temperate Australian coastline. The accumulations are great benefit to the local ecology of nearshore seagrass meadows and reefs as they are a source of recycled nutrients and detrital material that form the basis for primary production and food chains in nutrient-poor coastal waters (Robertson & Hansen, 1982) (Figure 1).

Nutrient recycling

Surf-zone accumulations of detached vegetation on Australian beaches represent a major area for the processing of offshore primary production. Of the primary production of offshore reefs and seagrass beds in Marmion Lagoon, near Perth Western Australia, 17% ends up in the surfzone and on beaches (Robertson & Hansen, 1982; Hansen, 1984). The concentrations of dissolved nutrients in the water column in the surf-zone, within drifting macro-algae and seagrasses, was extremely high (NO_3: 2.0 to 8.0 μmol L^{-1}; PO_4: 1.0 to 7.0 μmol L^{-1}) compared to coastal areas where plants did not accumulate (NO_3: 0.9 to 2.0 μmol L^{-1}; PO_4: 0.2 to 0.3 μmol L^{-1}) (Hansen, 1984). Coastal Western Australian waters are nutrient-poor, so decomposition of surf zone and beach-cast wrack may be a vital source of recycled nutrients for subtidal communities (Robertson & Hansen, 1982; Walker et al., 1988) (Figure 1).

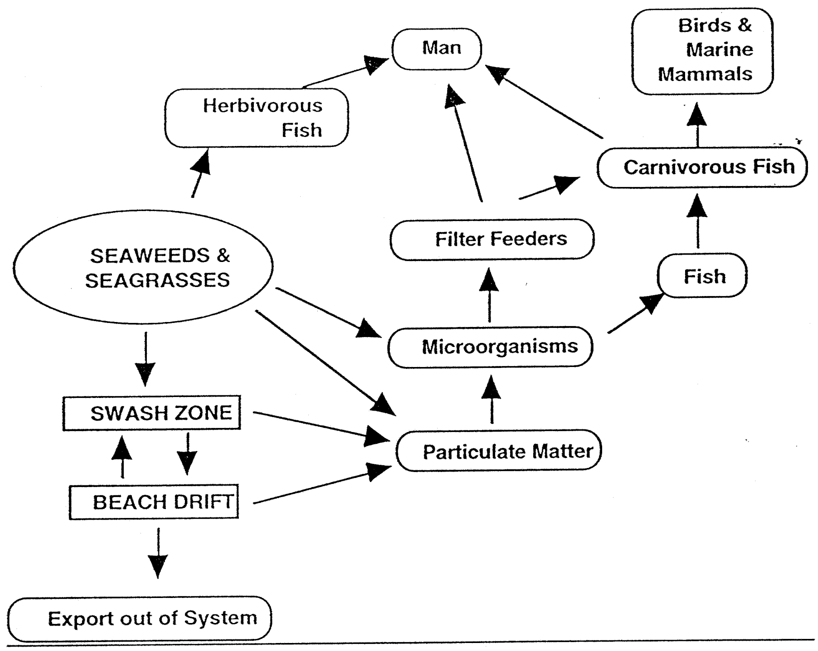

Figure 1. Food web diagram indicating the different pathways of carbon, nutrients and energy flow from the primary producers.

High levels of interstitial nutrients associated with remineralisation of beach-cast wrack have also been recorded at other beaches in Western Australia (McLachlan et al., 1985). This may not be the case in more nutrient-rich coastal marine environments. Beach-wrack in the Cape Peninsula, South Africa, was not a significant source for nutrients to nearshore subtidal communities: only 0.09% of nitrogen requirements of primary production in the nearshore kelp bed, and 0.4% of requirements of surf-zone phytoplankton (Koop & Griffiths, 1982).

Drift macro-algae deposited at high tide levels in a sheltered bay in south eastern Scotland released high concentrations of inorganic phosphate to adjacent pools. Inorganic nitrogen was however always low and much ammonia was lost to the atmosphere (Yelloly & Whitton, 1996). Differences in the importance of surf-zone and beach cast wrack as a source of nutrients for subtidal communities can also occur between beaches and coastlines. For instance, beaches can act as sinks or sources for nutrients, depending on whether they are prograding or eroding (McLachlan & McGwynne, 1986).

Source of particulate carbon

Surf-zone and beach-cast wrack is also a source of particulate carbon for coastal marine environments (Figure 1). This carbon supports detrital-based nearshore foodwebs that include benthic suspension feeders (Duggins et al., 1989), nearshore fishes (Lenanton et al., 1982), seabirds (N. Dunlop, pers. comm.) and beach waders (Bradley & Bradley, 1993; P. Menkorst, pers.comm.). Detrital biomass in the surf-zone can exceed the offshore production by a factor of four (Talbot & Bate, 1988).

Beach-cast wrack is broken down and fragmented by physical processes and detrivores, and remineralised by bacteria. Mineralised components and fragments are dissolved or transported either into the nearshore marine environment, or the atmosphere, or stored *in situ* within the beach. Beach-cast wrack can form a large proportion of the diet of beachliving amphipods and isopods. Grazing amphipods on a South African beach ate 200–300 kg wet kelp m^{-2} yr^{-1} (Griffiths & Stenton-Dozey, 1981). Yet, the role of grazing amphipods and isopods in wrack breakdown – as distinct from consumption – is not clear. Grazer-exclusion experiments on *Macrocystis* and *Durvillaea* wrack in New Zealand indicated that amphipods and isopods had little effect on breakdown of stranded kelps

(Inglis, 1989); microbial decay, physical leaching and fragmentation were more important.

Detritivores

Generally, a species-rich community of detritivores lives in and breaks down beachwrack. The breakdown of detritus on Western Australian beaches was shown to be largely caused by bacteria (Hansen, 1984; McLachlan, 1985). In Western Australia, microbial processes involved in composting wrack were predominantly aerobic, although anaerobic processes did occur in water-saturated sites, and methane and hydrogen sulphide were produced within wracks (Robertson & Hansen, 1982). Bacteria in wracks were also exported from the beach by wave action and were therefore a food resource for nearshore food webs (McLachlan, 1985).

The fauna of beach-cast wrack is generally diverse. In South Africa, 22 species of Coeloptera, 3 Diptera and 2 Amphipoda were identified in kelp wrack 2–3 days after it was washed onto the beach (Griffiths & Stenton-Dozey, 1981). However, in Western Australia the wrack fauna on reflective beaches was species poor and predominantly one amphipod, *Allorchestes compressa* (McLachlan, 1985).

The distribution of some species relies partly on beach-cast wrack. For example, beach flies (Coeloptidae) complete their life cycle in seagrass-algae wrack (Blanche, 1992). The sand-dwelling amphipods *Talorchestia quoyana* and *Allorchestes compressa* were closely associated with beach-cast drift (Marsden, 1991a, b; Robertson & Hansen, 1982). In New Zealand, very high densities of adult *Talorchestia quoyana* (121.750 amphipods m^{-2}) were associated with beach-cast *Macrocystis* kelp wrack, but the juveniles were always found on clean sand away from wrack deposits (Marsden, 1991a, b).

Beach-wrack accumulations can adversely affect infauna, by restricting oxygen exchange. In areas of dense wrack accumulations, sediment infauna did not occur (McLachlan, 1985). Small interstitial fauna (meiofauna) were especially affected by the toxic effects of hydrogen sulphide, low Eh and low oxygen concentrations in porewaters under wracks (McGwynne et al.,1988). There seems to be a balance between organic input and oxygen availability for maximum growth of beach meiofauna (McGwynne et al., 1988).

Offshore consumers

The wrack community is a food resource consisting of fragments of macro-algae and seagrasses, bacteria, meiofauna, and beach macro-fauna. When these sources are washed back into the sea during storms, they provide food for filter feeders, grazing gastropods and fish (Figure 1). In Australia, surf-zone feeding fish and abalone fisheries are, in part, supported by the breakdown of subtidal and beach-cast wrack. In Western Australia, the wrack-inhabiting amphipod, *Allorchestes compressa* was returned to the surf-zone during rough weather, where it was eaten by such fish as mullet, school whiting, herring and cobbler (Lenanton et al., 1982; Robertson & Lenanton, 1984). Large accumulations of wrack in the surf-zone also provide nurseries for juvenile fish (Lenanton et al., 1982). Also in coastal Western Australia, the commercially fished Roes abalone (*Haliotis roeii*) feed almost exclusively on drifting fragments of macro-algae (Wells & Keesing, 1989; Schiebling, 1994) although in South Australia it rasps small micro-algae from reefs (Shepherd, 1973).

Particulate matter from the breakdown of seagrasses and macro-algae also seems to directly effect offshore secondary production. For example, the growth rates of offshore benthic suspension (filter) feeders were greatly increased in the presence of kelp detritus (Duggins et al., 1989). Detritus from breakdown of seagrasses and macro-algae can also be exported far offshore where it can be an important food for demersal fishes (Thresher et al., 1992) and benthos in submarine canyons (Josselyn et al., 1983).

Birds

Wrack-inhabiting organisms are food for shorebirds. On the Palos Verdes Peninsula in California, populations of black and ruddy turnstones increase with increases in the amounts of kelp wrack on beaches (Bradley & Bradley, 1993). The birds are frequently seen feeding on beach-wrack. Wintering ruddy turnstones also feed and shelter on beach-wrack in Victoria, Australia (P. Menkorst, pers. comm.) (Table 2). In southern Australia, another wader, the endemic hooded plover (*Charadrius rubricollis*), also has a close association with wrack accumulations on beaches (Table 2). The hooded plover lives primarily on sandy ocean beaches, and is most abundant where there are large amounts of beach-cast macro-algae. It feeds on crustaceans, molluscs, insects and polychaetes associated

Table 2. Birds known to either, directly forage in beach-cast macro-algae and seagrass wrack, or that inhabit nearby habitat in southern Australia.

Bird	Type	Location	Activity	Conservation Status
Silver gull	seabird	wrack	feeding sheltering	lower risk
Australian raven	opportunist passerine	wrack	feeding sheltering	lower risk
Orange-bellied parrot	parrot	dunes	feeding	vulnerable
Hooded plover	shorebird	dunes, wrack, beach	feeding nesting	vulnerable
Ruddy turnstone	shorebird	wrack, beach feeding	data deficient	

with wrack (Schulz & Bamford, 1987). Plovers nest on the uppermost sections of beaches or in primary sand dunes, making a small depression in the sand next to vegetation or macro-algae wrack (Schulz, 1992). Their nesting requirements bring them into conflict with people using ocean beaches in the Coorong region of South Australia (Buick & Paton, 1989) and at Phillip Island, Victoria (Schulz & Bamford, 1987). Silver gulls (*Larus novaehollandiae*) in Western Australia also use beach-cast wrack: they feed on kelp fly larvae and amphipods during winter (N. Dunlop, pers. comm.) (Table 2).

Beach harvesting can also affect species that do not feed directly on wrack (Table 2). The orange-bellied parrot (*Neophema chrystgaster*), a vulnerable and threatened native parrot, migrates from a narrow coastal strip in south-west Tasmania, where it breeds, through the islands of Bass Strait, to coastal dunes and saltmarshes in Victoria and South Australia (Brown & Wilson, 1984).

Coastal geomorphological scales – dune formation

Seagrass wrack accumulations on the coastline enhanced dune formation in Mauritania (Hemminga & Nieuwenuize, 1990) and Cervantes, Western Australia (Hesp, 1984), in the stable beach areas. At Kingston, South Australia, there are *Posidonia* remains at the base of coastal dunes suggesting that they are also involved in dune formation through trapping and binding drifting sand.

Processes of deposition of algae on beaches of Western Australia – A case study

We will now present a case-study from Marmion Lagoon near Perth, Western Australia, in which biomass and production of the offshore plants are compared with subtidal drifting and surf-zone and beach-cast macro-algae and seagrasses. The case-study highlights the weaknesses in knowledge of sources and sinks of drifting macro-algae. We use both published and unpublished research in Marmion Lagoon between 1979 and 1985 to investigate the relationship between the source, living subtidal macrophyte beds, and the amount of beach-cast macro-algae and seagrasses over a relatively broad spatial scale and over seasonal and daily time scales (Lenanton et al., 1982; Robertson & Hansen, 1982; Kirkman, 1983; Robertson & Lenanton, 1984; McLachlan, 1985).

At Marmion, beach and surf-zone accumulations of macrophytes often occur at the same site, forming a continuous band from the beach through the surf, and are highly variable in distribution and abundance in time and place. Drift macro-algae frequently move between surfzone and beach (Hansen, 1984). There is also long-shore movement of surf-zone accumulations although persistent accumulations are often found at cuspate forelands and groynes (Hansen, 1984).

Transport from offshore beds During summer 1982 and winter 1983, bottom drifters and surface driftcards were released over Whitfords Reef, a limestone reef which runs parallel with the coast about 2 km offshore of Marmion and Whitfords. The plastic bottom drifters, designed to mimic subsurface drifffng kelp (*Ecklonia radiata*), were mushroom-shaped and negatively buoyant. Surface drift cards, which mimicked surface drifting seagrass leaves and macro-algae, like *Sargassum*, were rectangular pieces of plastic that floated on the surface. Both drifters and cards were released at Whitfords Reef about 3 times a week. Returns were not high (e.g. in winter 1983, 48% of bottom drifters and 31% of drift cards were returned). The bottom drifters travelled predominantly in a north-easterly direction in summer and winter (Figure 2), suggesting the submerged algae drifted predominantly to the south-west. The surface drifters moved mainly in a northerly direction in summer and a south-easterly direction in winter (Figure 2), suggesting the buoyant seagrass leaves and floating macro-algae, like *Sargassum*, were from a larger geographic area than bottom-drifting macro-algae like kelps. This interpretation is supported by comparisons of the average distances travelled by the drifters and cards: the bottom drifters travelled an average distance of 4.6 km (range 0.8 to 29.6 km); surface drift cards averaged 9.3 km (range 1.8 to 40.8 km). These results suggest that floating seagrass and *Sargassum* would travel further than the negatively to neutrally buoyant kelp.

In July (winter) 1985, 5000 tagged kelps (*Ecklonia radiata*) were cut from Whitfords Reef and left to drift. Of the 53 tagged plants recovered from 15 to 23 days later 78% were >2km NE of the release site on adjacent beaches. The kelps had drifted in the same direction as the bottom drifters released in winter in 1983 (Figure 2). Only 1% of the total tagged, released kelps reached the beach. It took between 15 and 23 days for kelp to wash onshore. What happened to the detached kelp over that time?

Relationship between detached macrophytes and living attached plants

The sources of beach-cast wrack are offshore beds of living macro-algae and seagrasses. The size of these wracks and drifting plants is difficult to measure, due to the vagaries of winds and nearshore currents over a range of spatial scales and over time scales from hours to weeks. The drifter and tagged kelp studies indicated that drifting times, distances and directions for bottom and surface drifting macrophytes were variable. Here we look at the annual production of subtidal kelps, other reef macro-algae and seagrasses (from Kirkman, 1983; Kirkman & Manning, 1993) in 55.6 km^2 of coastal reef and seagrass meadow near Marmion, (Ottaway & Simpson, 1986), and compare this to the amount drifting in the subtidal (unpublished data) and found in beach-cast wrack (Hansen, 1984).

Within the study area, kelp beds covered 9.6 km^2, seagrass meadows covered 24.6 km^2, and sand habitats covered 20.7 km^2 (Ottaway & Simpson, 1986). Annual production for *Ecklonia radiata* was 3500 t d.wt km^{-2} (Kirkman, 1983, 1984), which constituted 99% of the algal biomass. The remaining 1% was made up of other algae, which produced 4 t d.wt km^{-2} year^{-1}. Seagrasses had an annual production of 2192 t d.wt km^{-2} (Kirkman, 1983; Kirkman & Manning, 1993). The amount of submerged drifting macro-algae and seagrass in the study area was estimated over three days in July 1985. Divers sampled between the offshore reefs and the shore on bottom types consisting of seagrass and sand. On the beach the collections were separated into three categories: seagrass, kelp and other algae, and weighed. Kelp and seagrass accounted for 93.5% of the total biomass of submerged drifting macrophytes, and were in quantities of 3200 and 1056 t d.wt km^{-2}, respectively. Other algae weighed 303 t d.wt km^{-2}. This large subtidally drifting biomass could have come from north or south of the nearby reefs and could have been in the water as detached drift for months (Hansen, 1984).

The amount of beach-cast macro-algae and seagrass on the 16 km coastline fringing the 55.6 km^2 study area was determined in 1981 and 1982 by Hansen (1984). *Ecklonia radiata* and seagrass were 1270–7800 and 4600–9600 t d.wt km^{-2}, respectively. Other macro-algae accounted for 1000–7000 t d.wt km^{-2}. This is a much larger total than is produced annually within the study area. Presumably either the source for beach-cast wrack is greater than the study area, or macro-algae and seagrasses survive for a long time as subtidally drifting and beach-cast wrack.

The apparent lack of a direct relationship between submerged and beach drift and attached marine vegetation in Marmion Lagoon could partly be due to differenoes in the collection of the data. The data on the living kelps and seagrasses were collected between 1979 and 1981; the seasonality of wracks between 1981 and 1983 (Hansen, 1984; Kirkman, 1983); the subtidal drift in 1985.

Time scales of presence of beach-cast wrack

Both the amount and distribution of beach-cast macro-algae and seagrasses fluctuates seasonally on a 46 km section near Perth (Hansen, 1984). Beach-wrack was not uniformly distributed but often accumulated at specific sites and at specific times (Hansen, 1984). Averaged biomass over a length of coastline probably over-

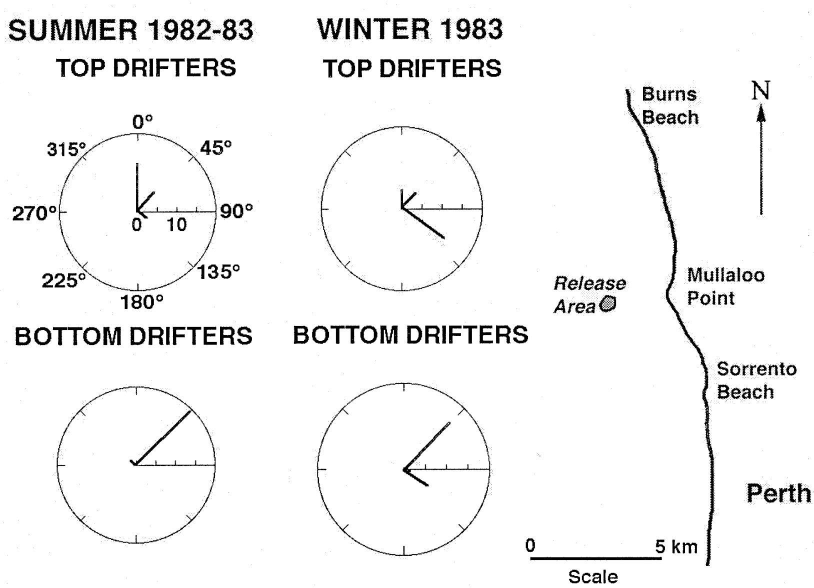

Figure 2. Maps showing release area and beaches near Marmion, W. A. and compass roses showing numbers of returned drift cards or bottom drifters (scale = O to 20) in each of 8 compass directions.

estimates the biomass of wrack, and would affect calculations of the proportions of living biomass that can be found in beach-wracks.

Waves carrying wrack back into the subtidal, combined with longshore transport, change the biomass of beach-cast wrack daily or weekly. Photographs taken at two beaches (Figure 3) between 10 and 18 June 1981 illustrate the magnitude of these changes. At Marmion Angling Club, a large wrack bed was carried back into the subtidal and moved alongshore over the nine days. At Whitfords Point, 3–4 km further north, the amount of beach-cast drift varied dramatically between days. A few isolated clumps of beach-cast algae were visible on 10 June; fewer larger clumps were visible on 16 June; and an almost continuous cover of a thick bed was observed on 18 June.

The complete breakdown of kelps and seagrasses in static wrack accumulations has been estimated. In the persistent wrack accumulations at cuspate headlands, the kelp *Ecklonia radiata* takes 20–23 days to decompose while seagrasses can take up to 414 days (Hansen, 1984). How the rates of decomposition are affected by frequent offshore transport by waves and redeposition is unknown. Mechanical fragmentation would increase breakdown, but would slow decomposition.

Summary

The case study demonstrates that the standing biomass and production of offshore macro-algae and seagrasses can be determined, as can the biomass of these groups in the beach-cast wrack. However, the relationship between the biomass of macro-algae and seagrasses found in these habitats is tenuous, because the direction, distance and time over which detached macrophytes drift are unknown. Generally, surface-drifting seagrasses and macro-algae, drifted with the prevailing winds, whereas bottom-drifting macro-algae were more influenced by currents. Yet, only a small proportion of artificial drifters and released kelps were actually cast onto beaches, and they had spent many days offshore before becoming beach-wrack. The biomass of drifting and beach-cast seagrass and kelps was much greater than was annually produced. This again emphasises the dynamic nature of subtidally drifting and beach-cast macro-algae and seagrasses. There were also strong seasonal and spatial distributions of beach-cast wrack, yet photographs of beaches taken over periods of days showed these wrack accumulations were dynamic and often resuspended.

Figure 3. Variation in the amount of beach-cast macro-algae and seagrasses at Marmion Angling Club and Whitfords Point, Western Australia over a week in winter, 1981.

Principal macro-algae and seagrasses of past, present and potential economic importance

Durvillaea potatorum (Labillardière) Areschoug

Durvillaea potatorum is an endemic species growing in temperate south-eastem Australia from Margaret Brock Reef off Cape Jaffa, South Australia, to Bermagui, NSW and the west, south and eastern coasts of Tasmania. It grows predominantly in the intertidal and shallow subtidal, but also to 30 m depth in SE Tasmania (Womersley, 1987). Beach-cast *D. potatorum* plants are older thalli that have either broken off the reef because they have grown too large to survive wave action, or are senescent. Harvesting of living shnds of *Durvillaea antarctica* was not found be sustainable in New Zealand (Hay & South, 1979).

Ecklonia radiata (C. Agardh) J. Agardh

Ecklonia radiata thalli are generally less than 2 m long. *E. radiata* is found from Kalbarri and the Abrolhos Islands, Western Australia, around southern Australia and Tasmania to Caloundra, Queensland. It is found in New Zealand and South Africa (Womersley, 1987). It is dominant in the upper sublittoral on moderately wave-exposed shores and deeper (44 m) on rough water coasts (Womersley, 1987). *Ecklonia radiata* beach-cast wrack is locally important to detrital-based food chains (Lenanton et al., 1982; Robertson & Hansen, 1982; Robertson & Lucas, 1983; Hansen, 1984; Robertson &Lenanton, 1984), and a source of nitrogen to coastal waters (Hansen, 1984; Paling, 1988; Paling, 1991; Lavery, 1993). Harvesting beach-cast *E. radiata* would require some assessment of the loss of secondary production to the nearshore marine environment. *Ecklonia radiata* is not at present harvested in Australia. Other species of *Ecklonia (E. cava* and *E. stolonifera*) are collected in Japan, China and Korea for food and alginate (Sanderson & Benedetto, 1988). In a recent survey of potential, commercial macro-algae products, *E. radiata* was valued at $250 t (dry) as an alginate producer, whereas *Durvillaea potatorum* for the same year was $400 t (dry) (Sanderson & Benedetto, 1988).

Macrocystis pyrifera (L.) C. Agardh *and Macrocystis angustifolia* Bory

Macrocystis pyrifera and *M. angustifolia* are the two species found in Australia (Womersley, 1987), they are larger than *Ecklonia*, growing to between 3 and 30 m long. *Macrocystis pyrifera* is found in southern Australia, on the east and south-east coast of Tasmania (Womersley, 1987). It is also found in New Zealand, the Cape Province, South Africa, Peru, Chile, Argentina, and sub-Antarctic islands as well as western North America. *Macrocystis angustifolia* is distributed from Margaret Brock Reef off Cape Jaffa, South Australia, to Walkerville, Victoria and the north and NW coasts of Tasmania (Womersley, 1987). *Macrocystis pyrifera* grows mainly in deeper water (8 to 22 m) whereas *M. angustifolia* is found from the intertidal to 10 m depth (Womersley, 1987). *M. pyrifera* community structure in Californian kelp beds has been studied in detail (e.g. Dayton et al., 1984). Some community studies are underway in Tasmania at present, but results are yet to be published (C. Sanderson pers. comm.).

Living stands of *Macrocystis pyrifera* were harvested for alginates in Tasmania between 1964 and 1973 by Alginates (Australia) Co. The total tonnage collected by Alginates (Australia) Co. increased from 6 tonnes per annum in 1965 to 13 000 tonnes per annum in 1971. Shortages of the alga in the early 1970s led to the demise of the industry. *M. pyrifera* stock have since increased to their former levels (Sanderson, 1987;1994), but there is no intention to permit commercial harvesting in Tasmania in the future (W. Zacharin, pers. comm.). The effect of warm waters on the growth of this kelp is partly to blame for the collapse of the wild harvest industry in 1973. In late 1988 the total biomass of *M. pyrifera* beds was one hundredth of that recorded 2 years before, and the decline in biomass was correlated to higher sea temperatures in 1987 and 1988. Since then, *M. pyrifera* has recovered to pre-1988 levels. However, populations in areas north of Bicheno, Tasmania, have still not recovered (C. Sanderson, pers. comm.). Therefore, *M. pyrifera* seems to be at the northern extreme of its range in Australia. The abalone aquaculture industry harvests a small amount on *Macrocystis*, but it is not harvested as beach-cast wrack, as the reliability of collecting enough is poor.

Harvesting *Macrocystis* can result in shifts in abundance of understorey algae and subtidal drifting fragments of kelps, which changes the foraging base of kelp-associated herbivores (Druehl & Breen, 1986). Further research is needed in Australia to assess the impact of harvesting on kelp community and trophic structure.

Sargassum C. Agardh

Sargassum is similar to *Durvillaea* in its life history and reproduction (Womersley, 1987). *Sargassum* species are canopy-forming algae, common on subtidal reefs in tropical and temperate Australia generally growing in sheltered to semi-exposed habitats from the intertidal to 30 m depths (Lewis, 1985; Womersley, 1987).

Recent studies of tropical and temperate *Sargassum* have concentrated on seasonal patterns of growth and reproduction (Kendrick, 1993; Kendrick & Walker, 1994; Martin-Smith, 1994; Vuki & Price, 1994), associated epifauna (Martin-Smith, 1994), and recruitment dynamics (Kendrick & Walker, 1991; 1995; Kendrick, 1992; 1994). *Sargassum* floats and drifting thalli are habitat for juvenile fishes (Lenanton et al., 1982) and may form the base for the food chain for pelagic seabirds. Bridled terns along the Western Australian coastline feed exclusively on organisms associated with surfaoe drifting *Sargassum* (N. Dunlop, pers. comm.). It is not known what amount of beach-cast *Sargassum* is resuspended by wave action, and how this is related to the total amount of surface-drifting *Sargassum* in coastal waters of Australia.

Sargassum is a seasonal component of beach-wrack in Western Australia (Hansen, 1984) thus harvesting on beaches would need to be seasonal. Sargassum species are at present collected commercially in Japan, Korea, China, Philippines, SE Asia and Hawaii for food and for alginate extraction (Sanderson & Bendetto, 1988).

Undaria pinnatifida (Harvey) Suringer

Undaria pinnatifida is closely related to *Ecklonia radiata*. It is native to Japan, Korea and parts of China where it is an important cultivated macro-algae (Hay, 1990). It was introduced to Tasmania, New Zealand and France in the early 1980s, probably from Japanese ships. It was found to survive attached to hulls of commercial and pleasure craft over voyages of 100s of km in New Zealand (Hay, 1990), fouling aquaculture cages and fishing nets and attached to abalone shells (Shaap, 1992). Recently, *Undaria* was found at an isolated patch in Port Phillip Bay, Victoria. Once established, it is difficult to eradicate (Hay, 1990; Sanderson, 1990). It grows between Rheban and Woodchip Mill, Port of Triabunna, eastern Tasmania (Sanderson & Barrett, 1989; Sanderson, 1990).

Undaria pinnatifida grows in the subtidal from 2 to 12 m depths in sheltered to moderately exposed rocky habitats (Sanderson & Barrett, 1989). It is very abundant in subtidal urchin barrens where growth of other macro-algae was controlled by high densities of grazing urchins: *Undaria* grows faster than the grazing rates of the urchins (Sanderson & Barrett, 1989). *Undaria* can also grow in habitats now or previously colonised by *Macrocystis*. To assess the potential impact to nearshore commercial and recreational fisheries, future research should determine the community shifts associated with the change from a *Macrocystis* dominated to an *Undaria* dominated kelp forest. Since 1988, the distribution of *Undaria* in Tasmania has been annually monitored by the Department of Sea Fisheries (Schaap, 1992; Anon, 1993a). Transport of live thalli out of the invaded area should be discouraged.

Live stands of *Undaria pinnatifida* are being harvested and packaged as food for the Japanese market by Tasmanian Wakame Pty. Ltd (Graham Hills, manager) in Tasmania. The first harvest was in November 1992. In 1993, 54 t of blanched and salted *Undaria* were shipped overseas (Anon., 1993b). Harvesting of subtidally drifting and beach-cast Undaria may also contain its geographical spread.

Gracilaria spp. Greville

Gracilaria has a world-wide distribution in temperate and tropical waters between the latitudes of 50° N and 50° S (Lüning 1990) and grows throughout Australia. *Gracilaria* species grow on subtidal, semi-exposed to sheltered shores and in estuaries of temperate and tropical Australia (Withell et al., 1994). They are either attached to reef or free-living, drifting with currents, and appear to photosynthesise and grow as detached algae in estuaries and shallow and deep coastal embayments. In estuaries, *Gracilaria* often grows attached to shells, small pebbles or becomes entwined in algal mats. Fish and invertebrate grazing can cause large shifts in biomass of the alga at any one location. Grazing pressure resulted in the loss of *Gracilaria* and the collapse of the wild-harvesting industry in South Africa (Anderson et al., 1989).

During the 2nd World War, *Gracilaria verrucosa* was harvested from estuaries in New South Wales (1943 – 200–250 dry tonnes per year). In 1945, 20.3 t of agar was produced from *Gracilaria* harvested in New South Wales (Chapman & Chapman, 1980). Ferguson Wood (1947) recommended investigations into the use of *Gracilaria* for food agar. Any potential harvesting of wild stocks should assess the effects of harvesting on habitat loss in estuaries.

Gelidium Lamouroux and *Pterocladia* J. Agardh

Gelidium and *Pterocladia* are widely distributed in temperate oceans of the world and in southern Australia there are 4 and 3 species, respectively (Womersley & Guiry, 1994). *Gelidium asperum. G. australe* and *Pterocladia lucida* are predominantly subtidal from 3 to 30 m depths. *P. capillaceae* and *P. rectangularis* are common to the upper subtidal and rock pools in the intertidal (0–3 m depths). *G. crinale* and *G. pusillum* are common in the intertidal (Womersley & Guiry, 1994).

Pterocladia lucida is gathered commercially from the intertidal in New Zealand. *Gelidium* was collected from drift at King Island by harvesters for Kelp Industries. Preliminary trials suggested that the industry was viable, but after 3 years this venture failed due to variable supplies of beach drift (F. Cullen, pers. comm.). How stable this resource is over time needs further investigation.

Posidonia sinuosa Cambridge and Kuo, *P. australis* (L.) Hooker and *P. angustifolia* Cambridge and Kuo

The seagrass genus *Posidonia* has eight species in Australia but two (*P. sinuosa* and *P. angustifolia*), form large (square km) beds. The plants grow on sandy or silty substrate and form a thick, fibrous mat underground. The fibres from *Posidonia* rhizomes may be hundreds of years old as they consist of pure cellulose which is resistant to bacterial breakdown in anaerobic conditions. *Posidonia* meadows are extensive along southern Western Australia, Shark Bay, the large bays and the gulfs of South Australia and diminish in extent east to Port Stevens in NSW. *Posidonia sinuosa* and *P. angustifolia* are distributed from Geraldton in southern Western Australia to Lacepede Bay in South Australia. *Posidonia australis* has a wider distribution but is not as abundant and occurs in different ecological habitats than *P. sinuosa* and *P. angustifolia*.

Posidonia grows from the intertidal to depths of 40 m depending on the amount of photosynthetic active light that it receives. *Posidonia* spp. appear to be poor colonisers: they have been shown to colonise only areas of a few square meters over 10 to 50 years (Kirkman, 1985; Kirkman & Kuo, 1990; Hastings et al., 1995).

The removal of living beds of *Posidonia* is not ecologically sustainable and should not be encouraged. Beach-cast wrack may be harvested although the effect of harvesting on the nearshore trophodynamics should be considered. Soil improver, mulch and compost are the main current uses of *Posidonia* leaves. In the past *Posidonia* was mined from meadows in South Australia and used, with wool, as suiting material and as an insulator for steam pipes, cool rooms and houses. Between 1910 and 1915 up to 100 leases totalling 96 000 ha were held in Spencer Gulf, Gulf St Vincent and Kangaroo Island. The miners collected a small residue of fibre estimated at about 3.6 kg m^{-3} from the substrate underlying the living Posidonia (Winterbottom, 1917). Later, *Posidonia* leaves, harvested from beaches, were used as house insulation. Ceilings of some of the old government buildings in Adelaide are lined with *Posidonia* leaves (D. Fotheringham, pers. comm.).

Zostera spp. L. and *Heterozostera tasmanica* (Martens ex Aschers.) den Hartog

The Zosteraceae is represented in Australia by the three species of the genus *Zostera: Z. capricorni*, *Z. muelleri* and *Z. mucronata* and *Heterozostera tasmanica*. In Australia, they are considered temperate plants but *Zostera capricorni* has a distribution along the east coast from Jervis Bay in New South Wales to Trinity Inlet at Cairns north Queensland. Meadows of Zosteraceae are not extensive where *Posidonia* is the main meadow-forming genus but in Western Port Bay, Victoria, Moreton Bay, near Brisbane in Queensland, the Gippsland Lakes in Victoria and other sheltered estuaries considerable areas are taken up by the Zosteraceae.

Harvesters of beach-cast Zosteraceae should not damage beaches and shorelines. Beachcast *Zostera muelleri* and *Heterozostera tasmanica* were harvested in Western Port Bay, Victoria for house insulation, sound proofing and for soil improver. As an insulator, the leaves do not readily burn and the high cellulose content ensures good insulation properties. A survey of the industry by the Victorian Ministry of Conservation estimated 5% of beach-cast *Zostera muelleri* leaves were harvested from beaches using tractors and trailers. Forty five to 50 subcontractors worked for two companies (J. H. Rudd and Co. and Seafibre Insulation) that sold the fibre as housing insulation. Removal of seagrass was not important in removing nutrients from Western Port Bay. Only 270 kg of phosphorus was removed with the 134,000 kg of seagrasses harvested annually. There was a dramatic decline in *H. tasmanica* in Western Port Bay in the 1970s and harvesting closed soon afterwards. Pollution was implicated in the decline of *Heterozostera*. Incidentally, the quilts and sleeping bags of the first US expedition to the Antarctic were lined with leaves of *Zostera marina* from northeastern USA (Cabot, 1986).

Potential threats

The main potential threats of harvesting beach-cast macro-algae and seagrasses are disturbance associated with the harvesting activity, the dependability of the resource and the long-term effect of exporting nutrients and detrital carbon from the nearshore coastal region. Disturbance associated with harvesting beach-cast macro-algae and seagrasses has not been assessed. The main concern, as already expressed by the Victorian government, is that extensive harvesting of drift wrack would disturb vulnerable or threatened species, especially shorebirds and species that use adjacent habitat in sand dunes and inter-dunal depressions. Proposals for harvesting beach-cast macro-algae and seagrasses should be assessed on their potential impact to threatened and vulnerable species. It should also be noted that the existing industries that harvest beach-cast macro-algae and seagrasses concentrate on areas where beach-wrack accumulates, so management protocols that restrict general access to beaches and dunes would suffice.

The biomass of beach-cast macro-algae or seagrasses may not give any indication of the biomass nor health of living resources offshore. The attempt to clarify connections between the available living resource on offshore reefs and the amount of macro-algae and seagrasses cast upon beaches in a case study indicated there was not a direct link between offshore annual production on a 16 km long coastal reef and the amount of subtidally drifting and beach-cast macrophytes. Partly, this was due to the dynamic nature of currents and winds and their influence on transport of surface and submerged drifting macro-algae and seagrasses to and from the beach. The amount of beach-cast macrophytes overestimated subtidal resources. Therefore, care should be taken when determining the sustainable harvest from beach-wrack.

There is a possibility that harvesting of beach-cast macro-algae and seagrasses will result in loss of production of other commercial species dependent on nutrients, detritus or species associated with beach-cast macro-algae and seagrasses. As shown throughout this review, the connections between offshore attached macro-algae and seagrass resources and beach-wrack are not clear. Yet, the nutrients and detrital particles released from beachwrack account for a percentage of overall nearshore coastal productivity. Any large scale harvesting should be assessed on the potential impacts to other fisheries dependent on nearshore productivity.

Priority areas for future research

Much of the research into beach-cast macro-algae and seagrasses has been process-based, restricted in geographical scale and concentrated on single ecosystem components. Throughout this review some areas have repeatedly surfaced as requiring immediate research effort. We need to study the importance of beach accumulations of macro-algae and seagrasses on feeding and nesting shorebirds. The survey of present and potential commercial macro-algae and seagrasses showed data deficiencies common to most, if not all species. These deficiencies suggest that research in the following areas is required for any commercial species:

- Assessment of biomass, density and annual production rates of living stands for each location where harvesting is occurring or is proposed.
- Assessment of the the relationship between offshore attached and beach-cast macro-algae and seagrass resources.
- Determination of the interannual variability of recruitment into living stands.
- Assessment of the effect of harvesting on trophodynamics and community structure.
- Assessment of the stability of the resource base for economically sustainable harvesting.
- Assessment of the relative importance of wrack in recycling nutrients and detritus to nearshore coastal ecosystems.

The study should include sampling at wider geographical scales than previous work at locations that offer potential for harvesting beach-cast macro-algae and seagrasses. Also, past research has concentrated on oligotrophic waters where wrack decomposition can account for 15–19% of nutrient recycling. Further research should look at locations in less oligotrophic waters.

Beach-cast macro-algae and seagrasses are resources that are patchily distributed on beaches and their biomass highly variable over all time scales, thus they do not generally represent a dependable resource base for a harvesting industry. In exceptional locations, like Kingston, South Australia, and King Island, Tasmania, where ocean conditions and the aspect of the coastline result in dependable long-term harvesting, these industries should be fostered, and aided through research and management for sustainability.

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