

**Conservation, Monitoring &  
Recovery of Threatened  
Giant Kelp (*Macrocystis pyrifera*)  
Beds in Tasmania –  
Final Report**

**Report to Environment Australia (Marine Species Protection  
Program)**

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## HOW TO USE THIS REPORT

This report on the conservation, monitoring and recovery of threatened Giant Kelp (*Macrocystis pyrifera*) beds in Tasmania is divided into 5 major sections:

- **Data Review & Kelp Mapping** – this section provides a comprehensive overview of all the historic and current Giant Kelp datasets for Tasmania. Appendices of all the datasets (and time-series inventories of individual kelp beds) are included in the accompanying CD to this report.
- **Temporal Analysis of Giant Kelp Distribution** – this section primarily deals with a discussion on current distribution and regional patterns of kelp distribution, loss and persistence needs to be read in concert with the accompanying GIS-based colour maps of kelp distribution (contained in the accompanying CD to this report). This includes:
  - Maps of the current distribution of *Macrocystis pyrifera* for the east and south coast of Tasmania (Cape Portland to Prion Bay).
  - Maps of regional kelp distribution, kelp loss and 'persistence' for regions subject to detailed temporal analysis (ie. Southport to Recherche Bay, Bruny Island, Port Arthur, Eaglehawk Neck – Fortescue Bay, Maria Island and Mercury Passage, Freycinet Peninsula and Schouten Island, and Binalong Bay and Gardens). These maps include time-series maps of kelp distribution, and also, maps of kelp loss and persistence.
- **Inshore Oceanographic and Meteorological Analyses** – this section provides a preliminary historical analysis of the major oceanographic and meteorological variables that are known to affect Giant Kelp distribution and abundance. Full-colour, time-series of sea surface temperatures are provided for the coast and east coast of Tasmania (1990-2001) and time series of sea temperatures and nitrates for Maria Island (1944-2000) are included in the accompanying CD to this report.
- **Conservation and Threat Assessment** – this section deals with the formal threat analysis of *Macrocystis pyrifera*, as required under the *Threatened Species Protection Act 1995* and using the guidelines prepared by the Scientific Advisory Committee.
- **Monitoring and Recovery Program** – this section provides an overview of international and Australian kelp monitoring protocols and recovery programs, and potential methods and approaches for monitoring and recovery of kelp populations in Tasmania.

# EXECUTIVE SUMMARY

## REVIEW

- Giant Kelp is a short-lived, perennial temperate macroalgae, which shows pronounced inter-annual population fluctuations.
- Unlike many perennial temperate macroalgae, reproduction in Giant Kelp is aseasonal and closely linked with resource availability and environmental conditions.
- Reproductive allocation is negatively correlated with seawater temperature and positively correlated with the nitrogen content of adult plants.
- Aseasonality in the onset of reproduction allows individuals to respond more readily to unpredictable fluctuations in resource availability and environmental conditions, and to adjust their reproductive investment accordingly.
- Major declines in Giant Kelp have been observed overseas (ie. California), due to El Niño events, storm events and predator-prey interactions (ie. sea urchins, otters, seals).

## KELP MAPPING

- Kelp mapping was undertaken using a wide range of data sources, including early navigational charts, aerial photography, aerial survey information (1986, 1999), and recent Landsat TM imagery (Sept 1999).
- Additional field data obtained for surface and sub-surface records of Giant Kelp in the Bruny Bioregion provided verification and 'ground-truthing' of kelp beds.
- Recent marine habitat mapping provided critical information on the known extent of reefal habitat (and hence, potential kelp habitat).
- Current aerial photography and Landsat TM, together, estimated a total kelp area of 770 ha (comprising 254 beds), from Cape Naturaliste – Prion Bay. Aerial photographic mapping alone estimated a total kelp area of 558 ha (68 beds), from Cape Naturaliste to Pelican Island (Southport). Recent (1999) Landsat TM estimated a total area of 351 ha (comprising 239 beds), but was only available for the south-east (Great Oyster Bay to Prion Bay).
- Current aerial survey data (1999) estimated a total kelp area of 2,562 ha (comprising 164 beds), from Cape Naturaliste to Recherche Bay.
- Using all current data sources (aerial photography, Landsat, aerial surveys), a total area of 1,311 ha (comprising 345 beds) is recorded.
- Kelp mapping by Olsen (1965) in the Mercury Passage – Maria Island region was more accurate and correlated well with other contemporaneous data sources (ie. aerial photography).
- Data from the commercial kelp harvesting industry (ie. Alginates Australia) provided detailed field survey information for the kelp beds on east and south coast for 1971-73, and also, regional and seasonal estimates of standing stock (biomass) for 1970-71.
- The original mapping of kelp beds in 1950-52 by Cribb (1954) was accurate in identifying kelp beds, but the areal extent of beds (ie. 11,986 ha) was over-estimated (due to the difficulty in mapping the seaward boundaries of beds). Subsequent field surveys conducted by Alginates Australia 1965-72, estimated a total kelp area of 1,215 ha.
- The large difference (ie. 10 X) in estimates by Cribb (1954) and Alginates Australia (1965-72) is probably also the result of the time of mapping. Cribb (1954) undertook kelp mapping in 1950 (ie. the largest La Niña event in history), while Alginates Australia undertook mapping in 1965-73 (during the El Niño's of 1965 and 1972). Severe storms in March 1972 resulted in a catastrophic loss of kelp on the east and south coast. Field notes indicate that north-eastern kelp beds, in particular, failed to recover from this event.
- Aerial survey information was accurate in identifying kelp beds, including many previously unrecorded beds in the St Helens to Bicheno and Great Oyster Bay region (where recent aerial photography and/or Landsat coverage was poor). Estimates of areal extent of kelp beds was accurate for small, defined beds, but inconsistent (cf. with other data sources) for extensive coastlines and larger offshore beds (ie. Acteon Islands).
- Mapping resolution and accuracy were compared for aerial photography, Landsat and aerial survey mapping methods.

- Landsat TM provided an accurate, large-scale, method of mapping. However, the relatively coarse scale of resolution (25 m per pixel) resulted in predictable, but consistent, under-estimates of areal extent. As such, correction factors can be applied to improve accuracy.

## TEMPORAL ANALYSIS

- The historical decline of Giant Kelp (*Macrocystis pyrifera*) was investigated using a detailed GIS-based analysis based of 7 regions of major kelp distribution (Binalong, Freycinet, Maria Island, Eaglehawk Neck-Fortescue Bay, Port Arthur, Bruny Island, Southport – Recherche Bay).
- Rates of loss over the 1944-99 period varied from 18% (Port Arthur) to >90% (Maria, South Bruny and Southport).
- Major kelp loss episodes coincided with the 1972 El Niño, the 1982-83 El Niño and the 1987 El Niño (all of which were strong events), for all regions. The extent of recovery after these events, however, varied. In all regions, kelp forests have been unable to fully recover to their original historical extent.
- All regions generally showed a consistent decline over the 1944-99 period, however, Port Arthur showed an increase of 33% using 1999 Landsat TM. Over the last 20 years, all regions showed loss apart from Fortescue (61% increase) and North Bruny (2% increase). Over the last 10 years, all areas showed a decline, apart from Binalong (9% increase).
- Aerial survey data indicated an overall increase in area of kelp (42%) between 1986-1999.
- Greatest losses have occurred in the north-eastern region of the distribution range (under the influence of the EAC) (ie. Freycinet, Maria Island). Smallest losses have occurred in areas under the influence of colder waters (ie. Bruny Island, Port Arthur).
- “Persistent” populations have been identified as a result of GIS-based temporal analysis.

## INSHORE OCEANOGRAPHIC AND METEOROLOGICAL ANALYSIS

- Long-term sea temperature data for Maria Island over the period 1944-1999, reveals an increase in annual minimum temperatures (and to a lesser extent, average temperatures) of 1.5-2°C. This rise however, is largely due to increases in annual minimum temperatures. Further, inter-annual variability in maximum sea temperatures is correlated with the southerly extension of the EAC and with ENSO events at least until the mid-1970s (Harris *et al.* 1987). This study however, has shown significant correlation between ENSO events and inter-annual variability in sea temperatures, both in El Niños during the 1980s (1982, 1987) and during the 1990s (1991, 1997). In addition, the prevalence of strong El Niños post-1975, has been accompanied by declines of ~ 1.0 °C in annual maximum summer-autumn and winter-spring sea temperatures after the mid-1970s.
- Examination of sea surface temperatures (SSTs) over the past decade (1990-2001) also indicate a warming of waters (ie. annual minimum SSTs) off the east coast (particularly the northeast) after 1992, and a decrease in maximum SSTs, resulting in a significant decline in seasonal variability. These trends correlate with prevalence of El Niño conditions over the past decade, and the increased southerly penetration of the warm water Eastern Australian Current (EAC) along the east coast. This has been accompanied by the southerly penetration of subtropical, nutrient-poor water off the Tasman Peninsula, and a declining influence of subantarctic waters in southerly locations (particularly after 1996). This tends to suggest that the East Australian Current has penetrated farther south in the 1990s, since the work of Harris *et al.* (1987) in 1984 and 1985.
- This pattern of warming, particularly on the northeast coast, correlates with major losses of *Macrocystis pyrifera*, along the northeast coast (ie. Binalong Bay and the Gardens, Freycinet Peninsula, Schouten Island and Maria Island). Unfortunately, these northern regions were also major areas of kelp abundance on the east coast.
- Overall, mean annual nitrate levels off Maria Island have increased over the period 1945-1999 (and particularly since the mid-1980s). In particular, there is a trend toward larger peaks in mean annual nitrates over time. However, against this background of nutrient increase, there is strong inter-annual fluctuations, corresponding to prevailing climatic and oceanographic conditions. Peaks in the annual mean and maximum nitrate correspond to strong El Niño years (ie. 1953, 1963, 1969, 1976, 1987, 1992-93) and also, some strong La Niña years (ie. 1971, 1973). La Niña conditions in Tasmania result in “above average” rainfall and these may well have resulted in increased nutrients from coastal run-off. Conversely, El Niño conditions results in an increase in

the zonal westerly winds, bringing gales and cold, wet weather to Tasmania. These strong westerlies also drive colder, nutrient-rich subantarctic waters up the east coast of Tasmania in summer (Harris *et al.* 1987). Increases in extreme rainfall events over the past decade (due to climatic influences) may also explain the larger peaks in mean annual nitrates over time.

- Reproduction and growth in *Macrocystis pyrifera* is strongly coupled with environmental fluctuations (particularly sea temperatures and nutrients). As such, cold, nutrient-rich spring waters provide optimal conditions for kelp growth and reproduction. In California, some of the largest populations of *M. pyrifera* occur where seasonal change among warm, cool-mixed, and cool-upwelling periods is highly pronounced. In Tasmania, the rise in minimum temperatures, the declining influence of subantarctic waters (and increased southerly penetration of subtropical waters), and the reduction in seasonal (and inter-annual) variability in sea temperatures on the east coast of Tasmania, are all factors that have probably combined to dampen reproductive success in *Macrocystis pyrifera*.
- Along with the increase in the frequency and strength of El Niños in the 1980s and 1990s, rainfall since the mid-late 1970s in Tasmania (particularly eastern Tasmania), has been decreasing (BOM). This reduction in rainfall has been strongest along the north-east coast. To this extent, north-east Tasmania shows a La Niña response (ie. a tendency towards wet conditions in La Niña years), similar in strength to the El Niño response (a tendency towards dry conditions in El Niño years).
- The 'mismatch' between increasing nitrate levels, yet decreasing rainfall, suggests that anthropogenic factors (increased coastal and stormwater runoff) may be the result of increasing nutrient levels at Maria Island. Alternatively, the increasing incidence and strength of El Niño events (ie. increased upwelling from zonal westerlies), particularly since the mid-1980s, may also account for increases in nitrates.
- Storm events are also a major source of mortality of kelp forests on the east and south coast of Tasmania. As such, a storm event or episodes can have major large-scale, catastrophic effects on distribution and abundance of kelp. This is clearly evidenced by the major storm event of 25 March 1972 (under the strong El Niño conditions), documented by Alginates Australia, which resulted in major loss of many kelp beds on the east and south coasts. El Niño conditions in Tasmania result in an increase in the zonal westerly winds (Harris *et al.* 1988) – resulting in increased frequency and severity of storms. This has, no doubt, contributed significantly to kelp loss during El Niño episodes off the east and south coasts of Tasmania.

## CONSERVATION AND THREAT ANALYSIS

- Extent of historical decline of Giant Kelp sufficient for formal listing of species under the *Threatened Species Protection Act 1995*.
- Biology of the plant, past and current rates of loss, past and current threats, sufficient for listing as 'endangered' based on 3 criteria:
  - An observed, estimated, inferred or suspected reduction of at least 50% over the last 10 years in area of occupancy (Criteria A1).
  - Continuing decline, inferred, observed or projected in area of occupancy, number of locations or populations, number of mature individuals (Criteria B2).
  - Extreme fluctuations in number of populations, number of mature individuals (Criteria B3).
- Threat analysis used aerial photography and recent Landsat data. Potential threats include:
  - increased sea temperatures – due to greater southerly penetration of the EAC
  - increased mortality from storms due to increased frequency (and severity) of El Niño episodes, due to long-term climate change
  - increase in urchin populations, particularly *Centrostephanus rodgersii*
  - spread of the Japanese Sea Kelp (*Undaria pinnatifida*) in habitat previously occupied by Giant Kelp
- Urchin barrens (particularly *Centrostephanus rodgersii*) have become established along the east coast. Barrens now occupy much of the former kelp habitat of north-east Tasmania, south to Maria Island – Mercury Passage. Urchins can switch from passive detritivores in kelp forests to active (and destructive) kelp grazers under conditions of high recruitment and/or low algal drift availability. Management intervention in California has shown that urchin fisheries can enhance the ability of kelp forests to recover from catastrophic-scale disturbance.
- Importantly, over-exploitation of commercial abalone (*Haliotis rubra*) and lobster (*Jasus edwardsii*) can also contribute to the establishment of 'urchin barrens' (ie. areas denuded of seaweed). In NSW (where barrens occur over approximately 50% of nearshore reefs between Port

Stephens and the Victorian border), reduction in abalone have possibly contributed to increases in the distribution and abundance of sea urchins, particularly *Centrostephanus rodgersii*. Further, *C.rodgersii* effectively prevents re-colonisation by abalone, with very few abalone found in 'barrens' habitats. Reducing densities of *Centrostephanus* can modify 'barrens' habitats however, to alternative habitats that can enhance the recruitment, survival and growth of abalone. Such a strong negative interaction between an established high-value fishery (abalone), and an under-exploited resource with considerable potential for development (sea urchins), offers a rare opportunity to develop complimentary fishery management plans.

- To this end, commercial abalone and lobster fisheries management in Tasmania needs to recognise that the persistence and conservation of *M.pyrifera* habitat is fundamentally linked to the complementary management of urchin resources, as well as the sustainable management of the abalone and rock lobster resource. Conservation of *M.pyrifera* habitat is also essential to the sustainability of these fisheries. As loss of kelp standing stock can result in the creation of barrens, through decreasing drift algal availability (which can trigger a switch from passive drift feeding to destructive urchin grazing).
- *Undaria pinnatifida* is unlikely to be displacing *Macrocystis pyrifera* habitat on the east coast of Tasmania. While *U.pinnatifida* is highly invasive and opportunistic, it is disturbance-dependent, colonising reefs after sea urchins have removed native algae. Without ongoing disturbance or sedimentation, *Macrocystis* can establish and recover within *Undaria* forests.
- "Persistent" populations should be priority areas for formal conservation assessment (ie. Marine Protected Areas) – as they show signs of temporal stability and may potentially act as "source" populations in a recovery program.
- Effective conservation management of *Macrocystis pyrifera* in Tasmania requires greater understanding of the inter-relationship between the standing stock and persistence of *Macrocystis pyrifera* forests and large-scale environmental anomalies (ie. temperature, current flow, productivity), and the dynamics of herbivorous grazers (such as urchins).

## MONITORING AND RECOVERY

- Comprehensive database and GIS system has been developed for monitoring of Giant Kelp beds.
- Database provides information on individual kelp beds and their history.
- Landsat is an ideal tool for State-wide assessment of Giant Kelp beds (3 yearly) – however the scale of resolution is too coarse for impact assessment purposes.
- Smaller scale monitoring of targeted beds using aerial photography is required on an annual basis for early change detection. In addition, regular subsurface monitoring of plant biomass, density, size and carrying capacity of selected kelp beds can provide more sensitive information on the long-term trends of selected beds and would assist in early change detection.
- Air-borne cameras (infra-red) should also be investigated as they may provide a much more accurate and cost-effective method of fine-scale monitoring of targeted beds.
- Optical mapping studies are required to define the relationship between kelp canopy area and density of beds, and better refine ongoing monitoring methods.
- Field 'ground-truthing' is required for verification and assessment, and also, to assist with the development of biomass and density estimates of kelp forests.
- Oceanographic monitoring (particularly of SSTs) of the shelf waters of Tasmania is required to complement kelp monitoring.
- "Persistent" and "non-persistent" populations need to be monitored annually for signs of species recovery.
- Current reforestation efforts of *Macrocystis pyrifera* in Tasmania need to be supported and integrated within a broader conservation, recovery and monitoring program.
- Management intervention in southern California (ie. sea urchin control, kelp restoration, and improvements in sewage disposal practices) have assisted the recovery of kelp forests from catastrophic-scale disturbance.
- In light of the large-scale losses of kelp on the east and south coast, these approaches need to be trialed in Tasmania.
- GIS-based methodologies have become an important tool in marine management, monitoring of *M.pyrifera* overseas and also, in the design of Marine Protected Areas. Significantly, GIS overlay methods can be used to assess the geographic relationship between observed kelp distributions, kelp persistence, and key physical (ie. depth, coastal aspect, slope, bottom relief or topography) and ecological variables (ie. disturbance regimes, urchin densities), that permit kelp to

resist or recover. Considerable potential exists in Tasmania to develop such an integrated research, monitoring and management tool in Tasmania.

# 'Forests of the Sea'

*“There is one marine production, which from its importance is worthy of a particular history. It is the kelp, Macrocystis pyrifera. This plant grows on every rock, from low-water mark to a great depth, both on the outer coast and within the channels...The number of living creatures of all Orders, whose existence intimately depends on the kelp is wonderful. A great volume might be written, describing the inhabitants of one of these beds of seaweed....I can only compare these great aquatic forests of the southern hemisphere, with the terrestrial ones in the inter-tropical regions.” (Charles Darwin 1845)*

## 1 INTRODUCTION

Giant Kelp (genus *Macrocystis*) or 'String Kelp' are large, canopy forming plants which grow in dense beds along the inshore subtidal reefs of south-east South Australia, Victoria and Tasmania. Kelp forests occur in cold, nutrient-rich waters and are among the most beautiful and biologically productive habitats in the marine environment. Individual plants can grow up to 30m tall, forming tall spectacular forests with the fronds providing a dense canopy which shade and modify understorey reef communities.

Giant Kelp forests are species/habitats of outstanding ecological and economic significance, representing areas of high biodiversity and productivity; and providing key habitats for the recruitment of economic shellfish species (ie. abalone, rocklobster). In addition, the large kelp plants themselves represent a major ecological keystone species, influencing the hydrological and light environment, and also, the recruitment of rocky inshore fish and invertebrates. Drift plants are important as food and for the dispersal of invertebrates, while, on shore, beach wrack plants represent an important nesting and foraging habitat for shorebirds (particularly migratory species). Giant Kelp forests are also of very high recreational and tourism value, providing one of the greatest diving experiences in temperate waters.

Giant Kelp or *Macrocystis* forests represent one of the most spectacular marine habitats in temperate Australia, and are of immense ecological, economic, recreational and social significance. *Macrocystis pyrifera* (one of the two species of *Macrocystis* which occur in Australia), is confined to south-eastern Tasmania and is likely threatened with extinction, with potentially large-scale ecological and economic consequences. As a major structural component of habitats, loss of *Macrocystis* is likely to have significant downstream effects on marine biodiversity and also, commercial fisheries, particularly reef fisheries such as lobster and abalone, which live in kelp habitats. For instance, recent field studies in Tasmania indicate that structural complexity and surface area significantly enhance lobster recruitment (Frusher *et al.* 1999).

Previous surveys of *M.pyrifera* conducted in 1952 (Cribb 1954) and 1986 (Sanderson 1987), indicate that the size and number of beds of *M.pyrifera* has dramatically declined over the past 30 years, to perhaps only 5% of the original area (Edgar 1997). A number of possible causes or factors have been identified: large scale oceanographic changes; the effects of marine pollution; and/or the introduction of the Japanese Kelp (*Undaria pinnatifida*).

### 1.1 Australia's Southern Temperate Marine Flora

The diversity and endemism of the marine macroflora in the temperate regions of Australia, including Tasmania, are among the highest in the world with about 125 species of Chlorophyta (green algae), 225 of Phaeophyta (brown algae) and 800 of Rhodophyta (red algae). This is

largely due to the length of the southerly-facing rocky coastline (i.e. the longest, ice-free, temperate coastline in the world) and the long period of geological isolation (Edyvane 1996). While other regions around the world, such as Japan and Pacific North America have more macroalgal species (1,452 and 1,254 species, respectively), their coastal waters encompass a wider range of climates (Womersley 1990).

Within Australia, the diversity of temperate species of macroalgae is three times that of tropical species (Womersley 1990). The most remarkable aspect of the southern temperate macroalgal flora is the diversity of red and brown algae, particularly the large number of genera recorded only from southern Australia.

Although the Tasmanian flora remains poorly known because of a lack of professional algal workers, the southeastern Tasmanian region includes probably the highest level of localised endemic species in Australia (Edgar *et al.* 1997, Edgar 1999). Shallow reefs around eastern, southern and western Tasmania are more thickly vegetated by macroalgae than reefs elsewhere in Australia, presumably because of the relatively high nutrient levels and cool water temperatures (Crawford *et al.* in press). The macroalgal flora of Tasmania is typically cold temperate, with a small element of colder water (sub-Antarctic) species. However, many of the recorded species of macroalgae in Tasmania also extend along the southern Australian coast into South Australian and southern Western Australian waters, encompassing a biogeographic region known as the Flindersian Province (Bennett & Pope 1960, Knox 1963, Edgar 1984a). The macroalgal flora of Tasmania, and to a lesser extent Victoria, is considered cold temperate, while the rest of the Flindersian flora is considered transitional warm to cool temperate (Womersley 1981a, 1990).

The cold temperate species of Tasmania include the largest Australian seaweeds, most notably giant kelp *Macrocystis pyrifera*, bull kelp *Durvillaea potatorum*, strap kelp *Lessonia corrugata*, common kelp *Ecklonia radiata* and other large brown algae such as crayweed (*Phyllospora comosa*), *Xiphophora gladiata*, *Desmarestia ligulata* and numerous *Sargassum* and *Cystophora* species (Womersley 1981b, Edgar 1984a, Womersley & King 1990). *Durvillaea*, *Desmarestia*, *Lessonia* and *Macrocystis* possess close relatives throughout southern latitudes, including New Zealand, South America and the sub-Antarctic islands, and require cold nutrient-rich waters to thrive. Tasmanian waters are also characterised by the presence of several sub-Antarctic macroalgal species which are not recorded elsewhere in Australia (i.e. *Urospora pencilliformis*, *Myrionema incommodum* and *Gononema ramosum*) (Edgar *et al.* 1997).

The cool waters of Tasmania have provided ideal conditions for some of the largest areas of subtidal kelp habitat in Australia. In particular, *Macrocystis pyrifera* forms large forests on inshore reefs to 30 m depth, and provides a key habitat for several of the State's commercial shellfish species, including abalone and rock lobster. Although the extensive kelp forests are an important marine community off the State's coasts, some along the east coast have been in decline in recent years (Sanderson 1987).

## 1.2 What are Kelps ?

Kelps are large brown seaweeds or algae (Class Phaeophyceae) which belong to the Order Laminariales. The Order Laminariales is characterised by individuals with a heteromorphic alternation of generations, comprising 2 free-living life phases (a macroscopic sporophyte generation and a microscopic gametophyte generations. The sporophytes are typically differentiated into a holdfast, stipe and one or more blades. Growth is by intercalary meristems that are primarily active at the base of the blades. As each strand of kelp grows, new blades are added by splitting of the blade at the very tip of the strand.

Members of the Laminariales are typically cold-water species, richly developed in the cold temperate and Arctic waters of the northern hemisphere, less so in the southern hemisphere and absent from the Antarctic. Four families are recognised worldwide (Alariaceae, Chordaceae, Laminariaceae and Lessoniaceae), two of which occur on southern Australian coasts (Lessoniaceae and Alariaceae), where they are often conspicuous elements of the mid to upper sublittoral zones.

### 1.2.1 Kelps in Australia

In Australia, 3 genera (and 4 species) of Laminariales occur: *Macrocystis* and *Lessonia* (Order Lessoniaceae) and *Ecklonia* (Order Alariaceae) (Womersley 1987). In the genus *Macrocystis*, 2 species are recognised: *M.pyrifera* and *M.angustifolia*. Only one species of *Lessonia* (*L.corrugata*) and *Ecklonia* (*E.radiata*) occur in Australia. *Macrocystis angustifolia* and *Lessonia corrugata* are endemic to Tasmania.

Bull Kelp (*Durvilleae potatorum*) which is found in the sublittoral fringe, along much of the cold temperate waters of southern Australia, is not a 'true' kelp (ie. a member of the Laminariales), but rather is a member of the Order Fucales. The Fucales is a diverse group of large brown seaweed, which have only one life stage (compared with two in true kelps). The Fucales is particularly species rich in southern Australia, particularly in the genera *Sargassum* and *Cystophora*.

*Macrocystis* is in the family Lessoniaceae. The characteristics of the family include branched stipes, each branch terminating in a single blade, and blades that split at an intercalary meristem. Some of the genera, like *Macrocystis*, have gas-filled floats called pneumatocysts that hold the plant erect in the water. Other genera in the Lessoniaceae include *Lessonia*, *Postelsia*, *Pelagophycus* and *Nereocystis*.

### 1.2.2 Distribution and Taxonomy of *Macrocystis* C. Agardh (Giant Kelp)

Kelp forests occur in cold, nutrient-rich waters and are among the most spectacular and biologically productive habitats in the marine environment. They are found throughout the world in shallow open coastal waters, and the larger forests are restricted to temperatures less than 20°C, extending to the Antarctic and Arctic Circles. A dependence upon light for photosynthesis restricts them to clear shallow water and they rarely occur much deeper than 15-40m.

Species of *Macrocystis* have traditionally been described based on morphological traits. One of the earliest studies by Skottsberg (1907) described the high degree of morphological diversity in *Macrocystis* (and the numerous species that were described to reflect this diversity), but recognised only a single species, *M.pyrifera*. However, later studies recognised three species (*M.pyrifera*, *M.angustifolia* and *M.integrifolia*), based on holdfast morphology (Womersley 1954, 1987). Since then, a fourth species, *M.laevis* has been described from Marion Island in the southern Indian Ocean, based on the characteristic of smooth blades (Hay 1986).

*Macrocystis* has a disjunct, bipolar geographic distribution: it has a circumpolar cold-temperate distribution in the Southern Hemisphere and is limited to the eastern North Pacific Ocean in the Northern Hemisphere (Lewis & Neushul 1994). All three (four including *M.laevis*) species occur in the Southern Hemisphere, whereas only *M.pyrifera* and *M.integrifolia* occur in the Northern Hemisphere.

*Macrocystis pyrifera* has a more southerly distribution in the Northern Hemisphere, whereas *M.integrifolia* occurs from the Monterey Peninsula north to Sitka, Alaska (Womersley 1954).

*Macrocystis pyrifera* occurs in the subantarctic region; New Zealand; South America north to Callao, Peru, and to about 50°S on the east coast; Pacific North America from Magdalena Bay, Baja California, Mexico to the Monterey Peninsula, California.

However, more recent morphometric, transplant and genetic studies indicate that *M.pyrifera*, *M.angustifolia* and *M.integrifolia* are conspecific (Lewis *et al.* 1986, Brostoff 1988, Lewis & Neushul 1994). Studies on *M.pyrifera* populations in southern California (which show both *M.angustifolia*-type and *M.pyrifera*-type holdfasts), indicate that the morphological differences in holdfast morphology (ie. based on basal stipe length) is genetically determined. However, intergrades of the holdfast types can also be found, indicating ecotypic differentiation but not separation into species (Brostoff 1988). In hybridization experiments of these southern California populations, both of these holdfast types of *M.pyrifera* (as well as *M.integrifolia*) were able to interbreed and form fully viable hybrid progeny (Lewis *et al.* 1986). This has also been supported in molecular and phylogenetic studies of the Laminariales, using restriction analysis of chloroplast DNA (ct DNA), which has revealed that the restriction fragment patterns of Northern Hemisphere *M.integrifolia* and *M.pyrifera* are identical (Fain 1989). However, Northern and Southern Hemisphere *M.integrifolia* differed.

In a latter comprehensive hybridization experiment involving gametophyte isolates of *M.pyrifera* and *M.integrifolia* from the extremes of their Northern Hemisphere ranges along the Pacific Coast of North America and *M.pyrifera* and *M.angustifolia* from the Southern Hemisphere (Tasmania, Australia) - all combinations of individuals of *Macrocystis pyrifera* (L.) C. Agardh, *M.integrifolia* Bory, and *M.angustifolia* Bory hybridized. Although all 3 species of *Macrocystis* may be considered conspecific according to the biological species concept, Lewis & Neushul (1994) recommended that they continue to be recognized as separate species based on their morphological differences.

Recent taxonomic studies suggest that while most Australian specimens of *Macrocystis* can be distinguished as either *M.pyrifera* or *M.angustifolia* on the basis of morphological characters, some from northern and sheltered south-eastern Tasmanian coasts show intermediate characters and are difficult to place (Womersley 1987). Field studies in Australia suggest that *M.pyrifera* is confined to south east Tasmania, occurring mainly in deeper water, where it is dominant in depths of 8-22 m, while *M.angustifolia* occurs along the coast of South Australia (east of Cape Jaffa), Victoria and the northern and north-western coast of Tasmania, from low tide level to 10 m depth (Edgar 1984a).

The bipolar or disjunct distribution of *Macrocystis* (and the Lessoniaceae) have been explained by migration out of a "centre of origin" and across the tropics by means of dispersal. Controversy centres however on which sector is the true centre of origin (Lewis & Neushul 1994). Chin *et al.* (1991) however, has suggested a process of vicariant differentiation out of a Pacific Ocean/Southern Ocean ancestral complex, based on biological, palaeo-oceanographic and geological evidence.

### **1.2.3 *Macrocystis* (Giant Kelp) in Australia**

In Australia, two species of *Macrocystis* occur: *M.pyrifera* (Linnaeus) C.Agardh and *M.angustifolia* Bory. *Macrocystis angustifolia*, occurs from Cape Jaffa (South Australia), along the coast of Victoria, to the sheltered north and north-west coast of Tasmania, from low tide level to 10m deep (Womersley 1987), while *M.pyrifera* appears to be confined to the south-east and east coasts of Tasmania, occurring submaximally or moderately exposed regions with horizontal substrata, mainly in deeper water, where it is dominant in depths of 8-22m (Edgar 1984a) (see Figure 1.1).

Tasmania has the largest and most extensive beds of *Macrocystis* in Australia.



**Figure 1.1** Distribution of Giant Kelp (or *Macrocystis*) in Australia.

### 1.3 Biology and Ecology of Giant Kelp

The distribution of Giant Kelp is greatly influenced by physical factors, particularly the influence of nutrients, currents (which provide cool, nutrient rich waters), water temperature and the frequency of storm events. Specifically, Giant Kelp require a hard surface for attachment, high nutrient concentration, moderate water motion, and cool, clear and clean ocean water for growth. World-wide, Giant Kelp (*Macrocystis pyrifera*) is found in the cooler waters of North America (Alaska to Baja California), south Africa southern Australia, and the west coast of South America (Womersley 1987).

#### 1.3.1 Morphology and Growth

Giant Kelp (or *Macrocystis*) has the distinction of being the largest marine plant (and seaweed) in the world; with the largest attached plant recorded being 65m long. The kelp plant has a root-like **holdfast** that fixes to rocky surfaces; a long slender stalk or **stipe**; and long, leaf-like blades or **fronds**, which are the major site of photosynthetic activity. The kelp plant is supported in the water by gas-filled bladders on each frond called **pneumatocysts**. The holdfast is cone-shaped and can grow up to 60 cm in diameter in large plants.

*Macrocystis pyrifera*, the world's largest alga, produces a surface canopy of numerous vegetative fronds that arise from a single holdfast. Vegetative fronds constitute most of the biomass of the plant and account for approximately 95% of the organic production (Neushul 1963, Towle & Pearse 1973).

Fronn sizes, node initiation and elongation rate fluctuate according to the seasonal pattern of light or water temperature (Van Tussenbroek 1989b). However, fronn growth rates are generally higher in deeper beds than those recorded in the coastal zone (van-Tussenbroek 1989b). In the Falkland Islands, the maximum life-span of *Macrocystis pyrifera* fronds was calculated to be 1 year, independent of the time of the year in which the fronds were formed (Van Tussenbroek 1989a). In shallow, coastal waters the half-life of the fronn population was estimated to be 2 to 3 months. In contrast, fronds in deeper beds, had an estimated half-life of 5 to 6 months. Fronn losses were probably mainly caused by water movements and abrasion.

Seasonal fluctuations in lamina wet weight, density and form as well as pneumatocyst wet weight form and stipe density (ie. wet weight per unit length) parallel fluctuations in fronn wet weight (Van Tussenbroek 1989c). Studies in the Falkland Islands have shown that fronn morphological differences between canopies of *M.pyrifera* in relatively sheltered coastal and offshore beds exposed to swells are probably mainly due to differences in water movement

and depth (Van Tussenbroek 1989c). However, laminae and pneumatocysts of submersed-fronds had different shapes than those of canopy-forming portions of fronds at the same sites, and had longer internodes.

Kelp forests undergo regular seasonal growth, with peak growth in spring and regular dieback of plants during the winter months. Sporophylls (reproductive blades bearing sporangia that release motile spores) grow from the base of each frond near the holdfast, and the number of sporophylls per frond and the number of fronds per plant are highly variable (Lobban 1978, Reed 1987), some plants can have >200 sporophylls (Reed *et al.* 1996). Plants containing fertile sori can be found year-round and bear as many as  $3 \times 10^{11}$  spores at a time (Neushul 1959, Anderson & North 1967). Sporophylls can bear fertile sori that cover nearly all of the blade within 2 months of blade initiation.

Individual plants mature in the 1<sup>st</sup> year (Neushul 1963) and rarely live more than a few years (Rosenthal *et al.* 1974, Barrales & Lobban 1975). Individual Giant Kelp plants can live up to seven years, however they may be shorter lived and removed in environments of high water motion associated with winter storms. The average life-span of an adult *Macrocystis* plant on exposed coasts is about one to two years (Dayton *et al.* 1984, Dean *et al.* 1989). The half-life of adult plants in southern California is approximately 8 months (Dayton *et al.* 1984, Dayton *et al.* 1992).

Although much is known about the growth and survivorship of adult kelp sporophytes, relatively little is known about the ecology of their microscopic gametophytic stages. These stages are probably highly vulnerable to grazing and sedimentation, such as that from sewage discharges. Studies on microscopic stages of Giant Kelp suggest they are also sensitive to the toxins associated with municipal and industrial waste discharges.

### 1.3.2 Reproduction & Dispersal

The life history of *Macrocystis pyrifera* (like all members of the Laminariales) consists of a heteromorphic alternation of generations, comprising 2 free-living stages: a macroscopic, diploid (2n) sporophyte generation (which forms the large leafy plants), which produces spores that develop into the microscopic haploid (n) gametophyte generation (comprising male and female gametophytes). These microscopic plants on the seafloor fertilise to give rise to the diploid, leafy sporophyte.

The spores are found in sori located on the blades, within special blades (sporophylls), located at the base of the plant (branching off the stipes just above the holdfast). A single adult plant can produce many sporophylls, each sporophyll containing billions of zoospores. *Macrocystis pyrifera* is capable of producing sporophylls from spring to fall, continuously releasing zoospores throughout that time. Studies on sporophyll production in California indicate that vegetative biomass greatly influences sporophyll production (and zoospore production) (Reed 1987). Sporophyll biomass is closely correlated with zoospore production. The removal of 75% of vegetative fronds led to a drastic decrease in sporophyll production.

After the zoospores are released they settle to the seafloor and begin to germinate. Each zoospore forms a germination tube and the contents of the zoospore move through the tube to a new cell (the gametophyte). Among the zoospores, the male:female gametophyte ratio is approximately 50:50. Female gametophytes tend to be one or two cells in size, while the male gametophytes show a branching, filamentous type of growth. After a period of growth, the females develop an egg and the males develop antheridia containing sperm (both through mitotic divisions). The egg releases a pheromone, lamoxirene, that attracts sperm to it, however the sperm are so small that a male and female gametophyte have to be located within one square millimeter of each other for fertilization to occur (Reed 1990).

After fertilization, the egg becomes diploid and is called a zygote. The zygote begins dividing into a young sporophyte, which grows directly out of (and eventually over), the female gametophyte. The sporophyte eventually begins to differentiate into a holdfast with stipes and blades as it matures to adulthood. The new sporophyte is termed a 'recruit' when first seen in the field. The recruit grows into a non-reproductive juvenile, and eventually into an adult with sporophylls. In California, germination and recruitment occur in the spring.

## Recruitment

Studies in southern California have shown that recruitment of sporophytes is greatest during periods of low temperatures and high nutrients, called 'recruitment windows'. These conditions are evident during spring upwelling when light is also high because of canopy thinning and the creation of 'gaps in the canopy' by winter storms (Reed & Foster 1984, Dean *et al.* 1989). New sporophytes grow from the substrate to the surface where they may form very dense surface canopies. Kelp canopies can reduce the amount of light reaching the substrate to less than 1% of surface irradiance (Reed & Foster 1984).

Irradiance and temperature are key factors controlling sporophyte recruitment or production in *Macrocystis pyrifera* (Deysher & Dean 1986a). Temperatures between 11°C and 20°C have little effect on sporophyte production, while gametophyte cultures have significantly lower fertility at 20°C than at lower temperatures, with a trend toward lower fertility at temperatures > 15 °C in cultures (at lower irradiances). These differences are also reflected in the development time for female gametophytes, with lower temperatures (ie. 11°C) reaching 50% fertility slightly faster (Deysher & Dean 1986a). Laboratory studies on the dispersal potential of *M.pyrifera* also indicate that under photosynthetically saturating irradiance no spores of *M.pyrifera* swim longer than 120 h; but when placed in the dark, < 10% remain swimming after 48 h (Reed *et al.*1992). More importantly, spores do not die after they stopped swimming; but rather germinate in the water column, retaining their capacity to produce viable sporophyte recruits.

The distribution of kelp forests is dependent on dispersal of spores and the successful fertilization of settled gametophytes. *Macrocystis pyrifera* is constrained in its ability to disperse over long distances by two life history characteristics: (1) high spore densities (2 per mm<sup>2</sup>) must settle into an area for successful fertilization and sporophyte recruitment to occur (Dayton 1985, Reed 1990, Reed *et al.* 1991); and (2) sporophylls are located at the bottom of kelp plants. Data on the diffusion of spores indicates that on average, >90% settle within 1.5 m of the parent plant (Anderson & North 1967). In addition, long distance dispersal has been found to occur during episodic storm events and has been suggested as a contributing process to recolonization of disturbed or cleared areas (Reed *et al.* 1988).

Recruitment from newly settled propagules is an important process in the population dynamics of many species, especially those living in highly disturbed areas and subjected to frequent local extinctions. For many primitive plants such as kelps, the process of recruitment is quite complex and requires the successful completion of an alternate microscopic free-living sexual stage. Field studies on the effects of variable zoospore settlement and early (ie. prerecruit) competition on patterns of kelp recruitment, indicate that a minimum density of at least 1 zoospore/mm<sup>2</sup> is needed for successful recruitment (Reed 1990).

Overall recruitment density of *Macrocystis pyrifera* declines with increasing distance from the adult stand; significantly lower recruitment was observed as little as 3 m from the stand (Reed *et al.* 1988). In contrast, dispersal of understorey, filamentous brown algae (ie. *Ectocarpus siliculosus*) was much greater; no significant decrease in recruitment density was observed out to 500 m.

Field studies off southern California have also confirmed the importance of episodic events (such as storms) in the dispersal and recruitment in *M. pyrifera*. Although the density of zoospores decreases with distance from the source, winter storms can result in substantial long distance dispersal of kelps via zoospores, out to at least 500 m (Reed *et al.* 1988). Recruitment out to 4000 m always coincided with recruitment at the source as well at all intermediate distances.

Laboratory and field studies on kelp gametophyte competition and sporophyte recruitment indicate that sporophyte recruitment density in *M. pyrifera* is highly variable over time (Reed 1988). The effect of settlement density on sporophyte recruitment density was most pronounced when recruitment was high. In mixed-species treatments, interspecific competition of microscopic stages was asymmetrical: the kelp, *Pterygophora* had a negative effect on *Macrocystis* recruitment while the presence of *Macrocystis* had no effect on *Pterygophora*.

### **Reproductive Success**

Generally, reproduction among plants is closely tied to environmental conditions and the availability of resources, and thus typically varies with season. Consequently, perennial organisms that reproduce continuously are generally restricted to tropical regions with relatively aseasonal climates. *Macrocystis pyrifera* is a rare among many perennial temperate marine plants, as most individuals produce spores throughout the year in a seasonally variable habitat (Neushul 1963, Anderson & North 1967, Reed *et al.* 1996). In fact, some of the largest populations of *M. pyrifera* occur in southern California where seasonal change among warm, cool-mixed, and cool-upwelling periods is highly pronounced (Lynn & Simpson 1987), and resources (ie. light and nutrients) and environmental conditions (temperature and water motion) most likely to influence marine plant reproduction vary greatly throughout the year (Jackson 1977, Gerard 1984, Zimmerman & Kremer 1984, Deysher & Dean 1986b). Such aseasonality in the onset of reproduction in *Macrocystis* allows individuals to respond more readily to unpredictable fluctuations in resource availability and environmental conditions, and to adjust their reproductive investment accordingly (Reed *et al.* 1996). For this reason, it follows that the adaptive value of reproducing throughout the year in *Macrocystis* more likely resides in a mechanism that maximises propagule production (ie. fecundity) rather than in one that maximises the proportion of offspring that survive (Reed *et al.* 1996).

In *Macrocystis pyrifera*, reproduction is closely linked with resource availability and environmental conditions (Reed *et al.* 1996). Reproductive allocation and spore standing stock in *Macrocystis* are negatively correlated with seawater temperature and positively correlated with the nitrogen content of adult plants. Although reproductive allocation varied greatly with season and year, the majority of the adult population bear fertile sori year-round (Reed *et al.* 1996). *Macrocystis* generally displays two seasonally distinct peaks (with intervening trough) in spore production per year (winter and spring), indicating that most plants make a concerted output followed by a rapid regeneration of spores when conditions are favourable. However, this seasonal pattern can be disrupted during warmwater El Niño events, when spore allocation can be relatively low and variable throughout the year (Reed *et al.* 1996). Spore C/N ratios remained relatively constant over time in *Macrocystis*, despite large seasonal fluctuations in C/N ratios of vegetative tissue of adults plants. Nonetheless, spore C/N ratios were positively correlated with seawater temperature in *Macrocystis*. Spore viability (swimming and germination) varied considerably, and often unpredictably, over time for both species.

The strong relationship between increasing seawater temperature (nutrient depletion) and decreasing reproductive output is indicated by the poor reproductive response of *Macrocystis* to extended El Niño episodes of warm nutrient-poor water (Reed *et al.* 1996).

*Macrocystis* is relatively short lived and may "hedge its bets" by reproducing continuously rather than risk delaying reproduction (Reed *et al.* 1996). Conversely, in other kelp plants that live longer and exhibit a strict seasonal reproduction (such as the sympatric species, *Pterygophora californica*), plants can afford to release spores only during times when the chances for reproductive success are predictably greatest because these plants are likely to reproduce again in subsequent years.

### 1.3.3 Kelp Forests as Habitat

#### Biodiversity

Kelp forests world-wide support very high levels of marine biodiversity. This is because of their unique three dimensional nature and the complex structure of these forests. Like trees in a forest, Giant Kelp plants provide shelter and habitat for an enormous number and diversity of animals, including, fish, molluscs (sea snails), bryozoans (lace corals), polychaetes (worms), crustaceans (crabs, isopods, amphipods), echinoderms (sea urchins, seastars) and sponges. Kelp forests provide habitat in several ways: as settlement habitat for larvae, and as food and shelter for adults either living among the kelp fronds, or living directly on the kelp plant itself. On the seafloor, a wide range of plants and animals occur in the low-light, sheltered environment created beneath the kelp canopy.

The rootlike holdfast of Giant Kelp, particularly the decaying portions, shelter an entire community of animals, including small crustaceans (isopods, amphipods), crabs, sea urchins, polychaetes, ophiuroids (brittle stars), small fish and eels, hydroids, bryozoans, gastropods (molluscs) and sponges. In California, about 770 animal species have been recorded living in kelp forests. Of these, more than 150 different species shelter in the kelp's holdfast alone. Approximately 23,000 individuals (from 9 invertebrate phyla) have been recorded living in 5 Giant Kelp holdfasts alone.

Outside the holdfast, on the seafloor, sponges, tunicates, anemones, cup corals and bryozoans are probably the most commonly occurring sessile animals with kelp forests. Low turfing fleshy algae and encrusting and articulated coralline algae also dominate due to their high tolerance to low light and high wave energies conditions. Like forests on land, the growth of understory plants and turf algae and the germination of new plants, is suppressed by the low light beneath the dense kelp canopy. However, when a gap is created in the canopy (ie. through storms removing plants), the increased light stimulates the vigorous growth of understory plants (including juvenile *Macrocystis*). Mobile organisms which live on the seafloor, include Blacklip Abalone (*Haliotis rubra*) and lobster (*Jasus edwardsii*) which live in rocky crevices. Small abalone feed on encrusting algae while large abalone and lobsters feed on drift algae. Echinoderms also commonly live and feed on the seafloor under kelp forests and include, sea urchins, such as Rodgers Sea Urchin (*Centrostephanus rogersi*) and *Heliocidaris erythrogramma*, the Feather Star (*Cenolia sp.*), sea stars (*Pateriella regularis*, *P. calcar*, *Uniophora sp.*), the Eleven-armed Sea Star (*Coscinasterias calamaria*), and Biscuit Stars (*Tosia sp.*).

In addition to the bottom dwelling species, a large number of animals occur within the kelp canopy. Some live on the kelp plant itself, such as isopods, seastars, sea urchins, sea snails and bryozoans. While other species reside in the water column of the kelp forest, closely associated with kelp plants. These species include octopus, cuttlefish, seahorses and fish, and diverse assemblages of planktonic species such as jellyfish, crustaceans and fish larvae. Common fish species include wrasse (*Notolabrus tetricus*, *N. fucicola*, *Pictilabrus laticlavus*, *Pseudolabrus psittaculus*), Bridled Leatherjacket (*Acanthaluteres spilomelanurus*), Shaws Cowfish (*Aracana aurita*), Butterfly Perch (*Caesioperca lepidoptera*), Blotch Tailed

Trachinops (*Trachinops caudimaculatus*), the Common Bullseye (*Pempheris multiradiata*) and the Weedy Sea Dragon (*Phyllopteryx taeniolatus*).

Many commercially important fish and invertebrates find shelter and food within the Giant Kelp forest. Lobsters and abalone live and feed on the rocky reefs under the kelp canopy. Fishes such as Stripey Trumpeter (*Latris lineata*), Bastard Trumpeter (*Latridopsis forsteri*), bream (*Acanthopagurus australis*), blackfish (*Girella tricuspidata*) and snapper (*Pagrus auratus*), feed on the algae and small crustaceans on the reef beneath the kelp.

Seastars and soft-spined urchins make their home climbing among the kelp fronds. The sea urchin, *Holopneustes purpureus*, lives in 'nests' which it makes by pulling the fronds of the kelp plants around itself. The nests provide protection and shelter from predators, as the urchin has very small spines. The nests also provide shelter to the herbivorous snail, *Phasianotrochus eximius*, which would be vulnerable to predation on the open surface of the kelp.

Another animal commonly found on kelp plants is the lace coral or bryozoan, *Membranipora membranacea*, whose coral skeleton forms large, white, lacy patches on the kelp frond. *Membranipora* also provides both shelter and food for nudibranchs (sea slugs) from the family Coramidae, which have evolved an effective camouflage against predators – a white network pattern on their bodies to exactly match the pattern of the bryozoan skeleton.

The kelp canopy is also a major habitat for marine life. When growth is vigorous, the kelp forest is crowned by a dense surface canopy. The canopy acts as a nursery for juvenile fishes, attracting swirling schools of small bait fish and predatory fish. The buoyant kelp canopy also provides a resting place for seabirds and seals. Beneath the canopy, the kelp forest also provides seals with shelter from predators.

The Giant Kelp plant is not only an important habitat, but an essential source of nutrients for many animals. For example, limpets ingest broken pieces of kelp from offshore beds and detritivores ingest microscopic pieces of kelp after it has broken down in the surf. On the seafloor, large numbers of filter-feeders or suspension feeders (such as sponges), feed on kelp detritus. This abundance is also probably due to the concentrated settlement of planktonic larvae beneath the kelp canopy, which has accumulated because of the reduced water flow (compared to more exposed hard substrata).

## **Biogeography**

The structure and composition of Giant Kelp (*Macrocystis pyrifera*) forests is strongly influenced by environmental variables, such as water movement. For instance, exposure to wave-generated water motion, through its influence on the surface canopy and therefore on the amount of light reaching the bottom, may be responsible for significant between-site differences. For instance, studies of kelp forests along a 8.5 km wave exposure gradient in central California found consistent between-site differences in the three major structural elements - the surface canopy, the understory assemblage, and the ground cover/turf assemblage - of kelp forest communities (Harrold *et al.* 1988). *Macrocystis pyrifera* was found at all sites, *Nereocystis luetkeana* only at the most exposed site. The understory kelps *Laminaria setchellii* and *Pterygophora californica* were also characteristic of exposed sites. Articulated coralline algae were more abundant at exposed sites than protected, while fleshy red algae showed the opposite pattern.

Density-dependent effects on Giant Kelp, *Macrocystis pyrifera* biomass and architecture (eg. plant height and structural complexity), common among both macrophytes and terrestrial plants, can greatly influence the relationship between plant density and recruitment of other species (Carr 1994). For organisms with dispersive life stages whose local recruitment is

influenced by the occurrence of living habitat structure, spatial and temporal variability characteristic of such biogenic habitats can be a major source of variation in their recruitment.

## **Recruitment of Fish**

As a major habitat in temperate environments, the dynamics of Giant Kelp forests can profoundly influence the local abundances of substrate-oriented species of fish (Carr 1994). Forests of Giant Kelp undergo substantial spatial and temporal variation, which in turn, can influence the local (among-reef) abundance of substrate-oriented fishes (Holbrook *et al.* 1990). For organisms with dispersive life stages whose local recruitment is influenced by the occurrence of living habitat structure, spatial and temporal variability characteristic of such biogenic habitats can be a major source of variation in their recruitment.

In southern California, extensive studies have shown that the size and structure of populations of many rocky inshore fishes, can be profoundly influenced by the canopy-forming *Macrocystis pyrifera* (Holbrook *et al.* 1990a). Experimental kelp removal studies in California indicate that the presence of a giant kelp forest may increase the abundance and species diversity of the fish assemblages over a high relief structurally complex rocky reefs (Bodkin 1988). The abundance of seven species of fish, of which five were considered midwater species, significantly declined after the kelp was removed. In other experimental manipulation kelp studies, the presence of *Macrocystis* enhanced local abundance for some species and reduced the abundance of others (Carr 1989).

Giant Kelp has a positive, direct effect on local abundances of species that use it as a nursery ground and/or adult habitat (Holbrook *et al.* 1990a). The effects of kelp are strongly related to the resources required by different life history stages of fishes. For some species that were positively affected, the magnitude of the kelp effect was stronger for recently settled recruits than older juvenile and adult stages (Carr 1989). For some inshore temperate rocky reef fish, such as surfperch, the 'natural' establishment of Giant Kelp at sites, resulted in the predicted dynamical responses of the species (based on an understanding of how particular reef resources influence abundances of the surfperch and of the effect of giant kelp on those resources) (Schmitt & Holbrook 1990). *Macrocystis* adversely affected populations of striped surfperch (*Embiotoca lateralis*), but enhanced those of black surfperch (*E. jacksoni*). Reef fishes with similar ontogenetic resource requirements appear to share a common relationship with the presence and density of kelp (Holbrook, Carr, Schmitt, Coyer 1990). In individual rockfish species (*Sebastes*), variation in substratum type in a kelp forest contribute to spatial patterns of recruitment, while the temporal dynamics of algal abundance, especially *M. pyrifera*, may strongly influence temporal, as well as spatial variability of rockfish recruitment (Carr 1991). Variation in timing of peak recruitment among species corresponded to the sequential parturition of pelagic larvae. Recruits of each rockfish species exhibited strong and significantly distinct habitat selection based on substratum type and relief, algal type, and vertical position in the water column (Carr 1991).

Kelp can also indirectly affect abundances of fish. These indirect effects, which can be positive or negative, result from the shading of understory algae by kelp (Holbrook *et al.* 1990a). As such, the occurrence and relative abundance of canopy and understory algae can explain much of the local spatial variation in the species composition of fish recruitment among temperate rocky reefs. In experimental manipulations of kelp, the reduced recruitment of two benthic species of fish was probably related to their affinity for understory algae, the cover of which is inversely related to the abundance of *Macrocystis* (Carr 1989).

Despite the affinities to particular algal substrates by many individual species of fish, assemblages of non-cryptic, substrate-oriented species of fish generally do not vary according to biogenic habitat structure and the presence of Giant Kelp (Holbrook *et al.* 1990b). In southern Californian studies, no differences in fish species richness and only weak differences

in species composition were detected among reefs of different habitat types (ie. dense beds of *M.pyrifera* with turf understorey; sparse beds of giant kelp with foliose algae understorey; foliose algae < 1 m in height; and open barrens). While planktivores and species that consume macro-invertebrates were less likely to occur on reefs that supported Giant Kelp; the frequencies of occurrence of three other trophic groups (piscivores, herbivores and micro-carnivores) were unaffected by Giant Kelp.

Where the dynamics of Giant Kelp forests influence the local abundances of fish, density-dependent effects on *Macrocystis pyrifera* biomass and architecture (eg. plant height and structural complexity), common among both macrophytes and terrestrial plants, can greatly influence the relationship between plant density and recruitment of other species (Carr 1994). For instance, recruitment of the temperate reef fish, kelp bass (*Paralabrax clathratus*) is positively related to *Macrocystis* density, but is asymptotic at high plant densities indicating that recruitment saturates at intermediate densities of *Macrocystis* (100-130 stipes/30 m<sup>2</sup>) (Carr 1994). However, density-dependent constraints on blade biomass in *Macrocystis*, rather than larval supply, better explain the general asymptotic nature of the relationship between *Macrocystis* and kelp bass recruitment. Kelp bass recruitment is linearly related to the local abundance of kelp structure (ie. the number and biomass of overlapping *Macrocystis* blades) indicating that both, the quantity and quality of the recruitment habitat limited larval recruitment. Similarly, structural complexity per unit length of plant (eg. blade biomass per unit plant length) is inversely related to plant density and underlies an asymptotic relationship between structural complexity per unit reef area (the product of per-plant structural complexity and plant density) and kelp bass recruit density (Carr 1994).

#### 1.3.4 Drifting and Beach Wrack Kelp Plants

Forests of *Macrocystis pyrifera* are among the most productive communities on earth. However, much of the annual production of kelp forests is exported from the forest as large floating rafts (Harrold & Lisin 1989). Drift plants of *M. pyrifera* are large (0.2 to 20 m long) and abundant structures, which increase habitat complexity of coastal, pelagic ecosystems, especially in convergence zones (Kingsford 1995). Drift plants redistribute small fish and invertebrates, and their movement (by wind and oceanographic features) provide insights to the movements of meroplankton. The drift of whole *M.pyrifera* plants is also relevant to understanding the demography of kelp forests, whilst the droguelike qualities of plants can be used to study oceanographic features. For instance, radio-tracking studies of *M.pyrifera* rafts in Monterey Bay, California, has shown that, of 39 tagged kelp rafts (tracked by aircraft for 5-7 days), most were recovered ashore. However, the regional deposition pattern of locally produced kelp rafts suggests that rafts may be exported (as large parcels) to offshore benthic communities, where they may play an important role as food and/or habitat (Harrold & Lisin 1989).

The potential of drifting *M.pyrifera* holdfasts for dispersing and transporting associated faunal and floral species long geographic distances is probably unlikely. Edgar (1987) in a study conducted in Tasmania, reported that it is unlikely that *M.pyrifera* plants with intact holdfasts are drifting to New Zealand. While most of the common animal species and approximately half of the plant species associated with *M.pyrifera* holdfasts were still present on kelp holdfasts after 191 d at sea, very few of these species have been recorded from New Zealand. Edgar (1987) suggested that drifting kelps probably become negatively buoyant in the Tasman Sea because dissolved nitrate concentrations are insufficient for normal plant growth.

Once kelp plants are beach wracked ashore, they can form a major (and fluctuating) component of the shore drift (Marsden 1991) due to their large biomass. In a New Zealand beach, *Macrocystis pyrifera* drift was generally distributed evenly down to 20 m from the base of the dunes, and dominated the organic matter in summer periods, ranging from 0.07 to 2.2 kg/m strip of beach. Macrofauna play a major role in the colonisation and decomposition

of stranded *M.pyrifera* (Inglis 1989). The wrack is colonised by the supralittoral fauna in two distinct phases. The amphipod, *Talorchestia quoyana* was closely associated with drift material, especially fresh *M.pyrifera*. The macrofauna, including the talitrid amphipod *Talorchestia quoyana*, adult Diptera and Coleoptera, colonise the kelp within 1 day, with the highest numbers recorded after 3 days (Inglis 1989). Following this, their presence declines and the meiofauna, which consisted of nematodes, enchytraeids, dipteran larvae, and mites, become increasingly abundant. After 18 days in the field, meiofauna dominate the surface of the kelp plants.

As many wintering shorebirds feed (and nest) on algal wrack, kelp abundance can have direct effects of the abundance of shorebirds (Bradley & Bradley 1993). As such, kelp recovery and restoration can also enhance wintering shorebird numbers. Recent studies in southern California have reported significant increases in wintering shorebird species associated with rocky shorelines, following kelp recovery. Two species frequently seen feeding on algal windthrow (ie. Black and Ruddy Turnstones) showed the most dramatic increases after kelp had been restored. At a regional level, sandy beaches where *Macrocystis* has washed ashore, can provide small-scale, but important, habitat for migrant shorebirds in coastal areas, particularly where major wetlands are scarce or far apart (Lopez Uriarte *et al.* 1997).

## **1.4 Factors Affecting the Distribution of Giant Kelp**

### **1.4.1 Large-Scale Oceanographic Changes**

The distribution of *Macrocystis* is strongly influenced by natural oceanographic and physical influences, such as El Niño and La Niña episodes, storms, rainfall, and also, human-associated influences such as discharged wastewaters (Tegner & Dayton 1987, 1991, North *et al.* 1993 Tegner *et al.* 1997). Large-scale, low-frequency oceanographic phenomena are important to kelp forest successional processes, population dynamics, and competitive interactions among kelp guilds (Tegner *et al.* 1997). In particular, oceanographic conditions, strongly affect the population dynamics of *M.pyrifera* and its competitive interactions with the lower standing species. For instance, poor *M.pyrifera* growth, canopy formation, and survival during warm, nutrient-stressed El Niño periods (eg. 1982-1984) allow the persistence of understory populations, while extraordinary conditions for *M.pyrifera* growth during cold, nutrient-rich La Niña periods (eg. 1988-1989) can be associated with the near extinction of understory populations (Tegner *et al.* 1997).

At its geographical limits, the distribution of *Macrocystis* in Australia, southern California, Patagonia, Peru and South Africa is related to highest summer sea surface temperatures (Hay 1990b). Except for the special case of Baja California, *M.pyrifera* is intolerant of prolonged exposure to maximum summer sea surface temperatures warmer than 18-20°C, supporting Setchell's (1932) original proposal that the genus is limited to waters where the maximum monthly mean is less than 20°C. In New Zealand, *M.pyrifera* does not persist in areas where maximum temperatures exceed 18-19°C for several days, and where the warmest monthly isotherm does not exceed 16-17°C (Hay 1990b). Within Cook Strait, there has been an apparent easterly retraction of *Macrocystis* distribution since 1942. This may possibly reflect slight warming in ambient sea surface temperature over the last forty years (Hay 1990b).

At the lower limit, the distribution of *M.pyrifera* in the Kerguelen Islands, has been shown to be limited to waters with a temperature above 5.5°C (Belsher & Mouchot 1990). As such, the distribution of *Macrocystis* is a key ecological indicator of the effects of global warming, and changes in local and regional oceanographic conditions. The distribution of *Macrocystis* however is also affected by pollution. In southern California, declines in water quality related to turbidity from coastal development, ocean discharges, and non-point source runoff have caused significant reductions in the areal extent of Giant Kelp (*Macrocystis pyrifera*) beds (North *et al.* 1993).

## 1.4.2 Nutrient Availability

In *Macrocystis pyrifera*, growth and reproduction is closely linked with resource availability and environmental conditions (Reed *et al.* 1996). *Macrocystis pyrifera* has limited storage capacity for nitrates, with estimates of one month in Californian plants (Zimmerman & Kremer 1984) and two weeks in plants transplanted to a low nitrogen environment (Gerard 1982). In plants from the Falkland Island, internal nitrogen was exhausted approximately one month after a sharp decline in ambient nitrate concentration (and carbon reserves were formed) (Van Tussenbroek 1989b). As a result, growth rates of *Macrocystis pyrifera* are directly related to temporal patterns of nutrient input. For instance, inhibition of frond production during the summer months in kelp plants from the Falkland Islands, have been linked to extremely low concentrations of nutrients (Van Tussenbroek 1989b).

There is considerable debate about whether the periodic losses of *Macrocystis pyrifera* beds in southern California may be caused by very low concentrations of nutrients, particularly nitrate, rather than by warm water (Zimmerman & Kremer 1984, Zimmerman & Robertson 1985, Hay 1990b). As such, low kelp productivity, and low rates of frond initiation, during the 1982-84 El Nino in southern California thickened the depth of the nutrient-poor surface layer to about 50 m depth (well below the level of *M.pyrifera*, and more than twice as deep as in 1981, when there was no El Nino) (Zimmerman & Robertson 1985).

Studies on a kelp forest ecosystem in Southern California (Zimmerman & Kremer 1984) have identified 2 distinct components to the pattern of nutrient availability: (i) a long term, or seasonal, component that was consistent with large-scale, storm-induced mixing and horizontal advection during winter months, and (ii) vertical motions of the thermocline, bringing nutrients into the kelp forest, that occurred throughout the year with a frequency of ~2 per day, but were strongest during the summer months. Significantly, the major component of nutrient input in a kelp forest occurs during the winter. Further, nitrate limitation of *M. pyrifera* is a likely cause of reduced summer growth, as nutrient input from vertical thermocline motion is inadequate to sustain maximum growth of *M.pyrifera* at 10 m depth during summer months (Zimmerman & Kremer 1984).

Variation in nitrogen physiology and growth in Giant Kelp populations can also be related to natural patterns of nutrient availability (Kopczak *et al.* 1991). For instance, juvenile sporophytes from three geographically isolated populations of *M.pyrifera* had similar maximum rates of nitrate-saturated growth, but there were significant quantitative differences in their response to nitrate limitation. As such, plants from oligotrophic locations achieved maximum growth rates at lower ambient nitrate concentrations than in plants from eutrophic locations (Kopczak *et al.* 1991). Further, tissue nitrogen and amino acid concentrations were highest in plants cultured from an oligotrophic location at all external nitrate concentrations, suggesting that differences in nitrate requirements for growth may reflect the efficiency of nitrate uptake and assimilation at subsaturating nitrate concentrations.

Reproductive allocation and spore standing stock in *Macrocystis* are positively correlated with the nitrogen content of adult plants. Spore C/N ratios remain relatively constant over time in *Macrocystis*, despite large seasonal fluctuations in C/N ratios of vegetative tissue of adults plants (Reed *et al.* 1996). Nonetheless, spore C/N ratios were positively correlated with seawater temperature in *Macrocystis*.

Zoospores of the *Macrocystis pyrifera* also exhibit positive chemotactic responses to nutrients (Amsler 1988). Zoospores in artificial seawater are more likely to swim into seawater enriched with either nitrate, ammonia, or trace metals. Spores also settle more rapidly in seawater enriched with nutrients than in unenriched water (Amsler 1988). These results

indicate that the chemical properties of substrates are likely to be an important consideration in models of natural kelp recruitment and in kelp bed enhancement projects.

### **1.4.3 Storm Induced Mortality**

Episodes or seasons of storm waves, which cause structural failure of *Macrocystis pyrifera* plants, are probably the most important source of mortality for adult *Macrocystis* in California (Zobell 1971, Rosenthal *et al.* 1974, Gerard 1976, Foster 1982, Reed & Foster 1984, Dayton & Tegner 1984, Dayton *et al.* 1984, Tegner & Dayton 1987). This mortality is dominated by failures of the holdfast attachment, with the next most important cause being tensile failure of the stipes such that the fronds are separated from the holdfast usually following entanglement with a drifting plant (Dayton *et al.* 1984). Herbivory of kelp holdfasts by sea urchins increase the risk of detachment, particularly during storm events (Tegner *et al.* 1995).

Storm and temperature effects on kelp standing stocks and growth rates related to the 1982-84 El Niño in southern California have been reviewed extensively (Tegner & Dayton 1987, Dayton & Tegner 1990). Typically half or more of the biomass of a healthy giant kelp population is found in the upper 1 m of the water column (North *et al.* 1982). The storms of the winter of 1982-83 led to virtually complete canopy loss at Point Loma and considerable (13 to 66%) *Macrocystis* mortality which varied with depth and location in the forest (Tegner & Dayton 1991).

### **1.4.4 Herbivory, Predator-Prey Interactions and Overfishing**

#### **Herbivory**

Giant Kelp forests are also subject to dynamic changes induced by herbivory. Sea urchins are widely considered to be the major grazers in temperate subtidal ecosystems, with herbivorous fish being browsers of minor importance (Jones & Andrew 1990). Urchins can play a major role in the ecology of reefs, and in particular, the distribution and abundance of large macroalgae, such as *Macrocystis pyrifera*. In most of the temperate seas of the world, sea urchins can remove large brown algae from areas of reef and thereby fundamentally change the ecology of the reef (Andrew & Constable 1999). The rise and fall of sea urchin populations has enormous consequences for the types and numbers of algae, fish, and other organisms found on reefs, including commercially exploited species, such as abalone and lobster. The ecological role of sea urchins and their impact on kelp forests over large areas of reef has been the focus of research on the east and west coasts of North America, New Zealand, South Africa, Chile, Japan, and New South Wales. Not all species of sea urchin have this dramatic effect on the abundance of large brown algae.

In response to their high susceptibility to grazing, kelps on temperate rocky reefs have developed chemical plant defenses against grazers. As such, polyphenols are differentially distributed among tissues in the kelps, *Ecklonia maxima*, *Laminaria pallida* and *Macrocystis angustifolia*, as predicted by plant-defence theory (Tugwell & Branch 1989). Polyphenols are almost entirely restricted to the thin outer meristoderm of these plants, as predicted if they serve as a deterrents against grazing. The inner cortex and medullary tissue, forming most of the bulk of the plants, and infertile vegetative tissues, contain very low levels of polyphenols. In contrast, the holdfasts, stipes and meristems of plants (areas susceptible to grazers) contain high levels of polyphenols (ranging from 5 to 39% of dry mass). Again, these patterns are concordant with defence theory.

### **California - Sea Urchins, Otters and El Niño's**

In California, grazing by sea urchins is another major source of kelp mortality (Pearse & Hine 1979, Dayton 1985, Tegner & Dayton 1991, Tegner *et al.* 1995). When urchins reach high population numbers they are known to completely remove *Macrocystis* from an area, resulting in an 'urchin barren'. The Californian sea otter has been shown to have a significant influence in maintaining kelp forest communities, primarily by eating urchins (Estes & Palmisano 1974, Duggins 1980, Foster & Schiel 1988).

In California, storms and warm water associated with the massive El Niño of 1982-84 caused extensive reductions in standing stock and much mortality of *Macrocystis pyrifera* (Dayton & Tegner 1984, Tegner & Dayton 1987), the major component of the algal drift on which sea urchins feed (Leighton *et al.* 1966, Harrold & Reed 1985).

Several hypotheses concerning the interactions between kelps, sea urchins and El Niño events have been proposed to explain the extreme disruption of kelp forests communities observed in the late 1950s – early 1960s (Leighton *et al.* 1966, Tegner & Dayton 1987). These fall into 2 general categories. First, environmental conditions such as storms, warm water, or low light levels could reduce kelp standing stocks and/or productivity below the level needed to satisfy existing grazing demand. Second, grazing demand could increase due to increased sea urchin recruitment, movement, or decreased predation rates. Leighton *et al.* (1966) further suggest that sea urchin grazing rates rise faster than kelp growth rates in warm water. Some combination of these hypotheses is a likely explanation (Tegner & Dayton 1991).

## **New South Wales - Urchin Barrens and Abalone**

Sea urchins will eat almost anything but are mostly herbivorous and it is by feeding on large brown algae (ie. kelps) that they have their greatest impact on rocky reefs. In New South Wales, there have been several studies on the effects of urchins on reef ecology (see Jones & Andrew 1990, Andrew & Constable 1999). Two species, in particular, have been identified as playing a major role in the ecology of temperate reefs, the Black Sea Urchin (*Centrostephanus rodgersii*), and the Purple Sea Urchin (*Heliocidaris erythrogramma*). No other species of sea urchin in Australia plays such a dominant ecological role in the ecology of rocky reefs as the *Centrostephanus* in New South Wales. In all other states, urchins play only a minor role in the ecology of exposed rocky reefs (Andrew & Constable 1999). As a major grazer on rocky reefs in Tasmania (and southern Australia), the Blacklip Abalone, *Haliotis rubra*, plays a significant role in the ecology of temperate rocky reefs. As a competitor of sea urchins (particularly *Centrostephanus rodgersii*), it also has the potential to affect the distribution and abundance of large macroalgae, like *Macrocystis pyrifera*.

### **Black Sea Urchin (*Centrostephanus rodgersii*)**

*Centrostephanus rodgersii* is largely restricted to New South Wales, although they are found in eastern Victoria, around islands in Bass Strait and the along the east coast of Tasmania. *Centrostephanus* occupies a wide ecological range, occurring as far north as the Solitary Islands (among coral reefs), and as far south, as the Tasman Peninsula (among cold water kelps, ie. *Macrocystis* and *Durvillaea*) (Andrew & Constable 1999). *Centrostephanus* is most abundant in intermediate depths, between 2-20 m depth. On the margins of reefs in the shallowest water, they occur in crevices and depressions and do not move as far as those in deeper water. At depths greater than 20 m, *Centrostephanus* is less dense and occurs in crevices and depressions amongst the sessile fauna.

*Centrostephanus rodgersii* typically feed on detached macroalgae that drift into crevices and gutters where urchins are located. However, *Centrostephanus* consume almost all macroalgae (creating Barrens Habitat) and effectively maintain the naked substratum by removing all regrowth (including juvenile kelp plants), leaving only encrusting algae, limpets and sessile

animals. Larger kelp plants have greater survival, as *Centrostephanus* is not capable of climbing larger plants (Andrew & Constable 1999). As with many species of urchins, they may be locally very abundant and found in dense aggregations. On reefs in southern New South Wales, densities of 60/m<sup>2</sup> have been recorded. To-date, approximately 50% of nearshore reefs in central and southern New South Wales comprise Barrens Habitat. Areas of Barrens Habitat vary from small patches surrounding single urchins, to many hectares. In contrast to other species of urchins, such as *Heliocidaris erythrogramma*, *Centrostephanus* do not appear to form aggregations that remove all large algae in their path.

### **Purple Sea Urchin (*Heliocidaris erythrogramma*)**

*Heliocidaris erythrogramma* is more widely distributed around southern Australia: from southern Queensland to Shark Bay, Western Australia. *Heliocidaris* is found intertidally (in rock pools) and on subtidal rocky reefs, where they can be found in dense patches in crevices or burrows. Generally occur in densities less than 5/m<sup>2</sup>, but they can also be found in dense aggregations (20-80/m<sup>2</sup>) in protected waters, either on coarse sandy substrates, within seagrass beds, or in deeper waters on reefs. Like *Centrostephanus*, *Heliocidaris* feeds typically on detached plants, but it can also have dramatic effects on large brown algae (and seagrass beds) in sheltered waters. *Heliocidaris* is usually more sedentary than *Centrostephanus* but they can aggressively graze over kelp forests and seagrass beds under some circumstances (Andrew & Constable 1999). Very large densities (up to 180 m<sup>2</sup>) of *Heliocidaris* can form 'fronts' on the edge of seagrass beds.

### **Blacklip Abalone (*Haliotis rubra*)**

As a major grazer on rocky reefs and competitor of sea urchins (particularly *Centrostephanus rodgersii*), Blacklip Abalone also has the potential to affect the distribution and abundance of large macroalgae, like *Macrocystis pyrifera*.

Blacklip Abalone (*Haliotis rubra*) are some of the most abundant molluscs on rocky reefs in southern Australia. They occur as far north as Coffs Harbour in New South Wales, around Tasmania, and west to Perth, although they are most abundant in Victoria, Tasmania and southern New South Wales, where they form large aggregations under the dense canopy of the kelp, *Phyllospora comosa* (McShane 1999). Like most abalone, *Haliotis rubra* is a herbivore, feeding mainly on drift macroalgae. While they have clear preferences for different algae, their diet largely reflects the availability of drift macroalgae on reefs (McShane *et al.* 1994). In southern Australia, this would largely reflect the dominant macroalgae present on reefs, including large brown algae such as kelps. The larvae of abalone settle preferentially, but not exclusively, on crustose coralline algae. Factors that determine the distribution and composition of coralline algae therefore have the potential to influence the growth and survival of abalone. Such factors include the presence or absence of grazers such as other important molluscs and sea urchins. Grazers are important in maintaining coralline surfaces free of overgrowth by other algae.

In New South Wales, *Haliotis rubra* compete with *Centrostephanus rodgersii* (also a sedentary detritivore). In New South Wales, declines in catch and catch rates of Blacklip Abalone (*Haliotis rubra*) in the 1970s and 80s have been linked to increases in the distribution and abundance of sea urchins, particularly the dominant species, *Centrostephanus rodgersii* (Andrew 1993). By 1996, the commercial component of the TACC for abalone had dropped to 333 t (from a peak of 1200 t during 1971-72, and ~600 t during the early 1980s). During this time, the over-harvesting of abalone on many areas of reef, may have contributed to increases in the distribution and abundance of sea urchins, especially the dominant species, *Centrostephanus rodgersii* (Mike Heasman, NSW Fisheries).

By denuding reef areas of macroalgae (ie. 'urchin barrens'), *Centrostephanus* also effectively prevents recolonisation by abalone. As such, very few abalone are found in 'urchin barrens'. Manipulative experiments demonstrate that when *Centrostephanus* is removed, densities of small *Haliotis rubra* increase by an order of magnitude. Further, by reducing densities of *Centrostephanus*, 'urchin barrens' can be modified to alternative habitats that can enhance the recruitment, survival and growth of abalone (Andrew 1993).

Such a strong negative interaction between an established high-value fishery (ie. abalone), and an under-exploited resource (ie. sea urchins) with considerable potential for development, offers a rare opportunity to develop complimentary fishery management plans (Andrew 1993).

#### **1.4.5 Marine Pollution**

The distribution of *Macrocystis* however is also affected by pollution. In southern California, declines in water quality related to turbidity from coastal development, ocean discharges, and non-point source runoff have caused significant reductions in the areal extent of Giant Kelp (*Macrocystis pyrifera*) beds (North *et al.* 1993).

The microscopic, free-living gametophytes of *Macrocystis* are sensitive to the effects of pollution, particularly sedimentation (Devinsky & Volse 1978).

#### **1.4.6 Introduced Organisms**

Introduced organisms have the capacity to disrupt or displace (directly or indirectly) the ecological niche of native or indigenous species and populations. Further, the greater the degree of ecological overlap, the greater the potential for direct competitive interactions between introduced and native species.

In Tasmania, very little is documented on status and ecological impact of introduced marine species. Of the marine macroalgae, only the introduced Japanese Sea Kelp, *Undaria pinnatifida* (Harvey) Suringer, is thought to pose a potential threat to endemic macroalgae, and in particular, *Macrocystis pyrifera*. In a study on the distribution, biology and possible long term effects of the species in Tasmanian coastal waters, Sanderson & Barrett (1989) concluded that *U.pinnatifida* had the potential to affect the ecology of local seaweeds that occupy a similar ecological niche, and in particular, *Macrocystis pyrifera*.

##### **Japanese kelp (*Undaria pinnatifida*)**

The Japanese or brown kelp is native to the Japan Sea, particularly on the coasts of Japan, Korea and parts of China. It is also commonly known as Japanese kelp and 'wakame' and is cultured extensively in a number of countries as a fresh and dried food. As such, there may be potential for commercial harvesting in Australia ().

Japanese kelp it thought to pose a major threat to endemic algal communities, such as *Macrocystis pyrifera*, because of its rapid growth and capacity to exclude native species by overgrowing (Sanderson & Barrett 1989, Sanderson 1990). *Undaria pinnatifida* forms dense, monospecific forests, resulting in competition for light and space, and possible exclusion or displacement of native biota (and also, potential downstream effects on the food chain). Species that may be susceptible to displacement by *Undaria* include reef dwelling organisms such as abalone, rock lobster and oysters.

*Undaria pinnatifida* was first recorded in Tasmania (and Australia) in 1988, at Rheban (Orford) on the east coast (although evidence suggests that it may have been present in Tasmania since 1982). Since this time, it has expanded its range and is now found on Tasmania's east coast from Bicheno to Conningham. *Undaria* is thought to have been introduced to Tasmania in the ballast water and/or hulls of vessels transporting woodchips from the mill at Triabunna (Sanderson & Barrett 1989, Sanderson 1990). The only other state in Australia which has been invaded by *U.pinnatifida* is Victoria, where it has been recorded in Port Phillip Bay.

Like *Macrocystis pyrifera*, *Undaria pinnatifida* has a typical Laminarian or kelp life cycle with a macroscopic diploid sporophyte phase alternating with a microscopic haploid gametophyte phase. Microscopic haploid gametophytes may persist for several years, before releasing sperm and eggs into the water. The macroscopic sporophyte consists of a holdfast, stipe and blade, with distinctive thickened fluted sporophylls forming either side of the stipe. *Undaria* is a seasonal, 'annual' macroalga, senescing in late summer, leaving only the sporophyll and holdfast. Before dying completely, the sporophylls release millions of the microscopic zoospores. Between September and December, the alga is in full bloom with plants up to 3m in length. Differences between the Tasmanian and Victorian plants suggests that the size and shape of plants may vary with maturity and environmental conditions.

*Undaria pinnatifida* is an opportunistic and highly invasive macroalgae, with the ability to rapidly colonise disturbed or new surfaces, and cover large areas of inshore reefs. The alga occurs intertidally down to a depth of 15 metres, but it generally does not establish successfully in areas of high wave action, abundant vegetation, or in estuaries. Rather, it prefers sheltered reef areas, subject to oceanic influence (ie. salinities between 27 and 33‰). *Undaria* also fouls marine infrastructure such as mussel lines, vessel hulls and fish cages.

### **Spread of *Undaria***

Japanese kelp has spread gradually to more than 50 km of the Tasmanian coastline and is now found at Triabunna, Great Oyster Bay, Coles Bay, Blackman Bay and Maria Island (DPIWE 2002). This spread is attributed mainly to ocean currents and transfer via vessel hulls. Recent evidence suggests that it is also being spread by commercial fishing boats through plants being caught in nets (DPIWE 2002). In Coles Bay, the kelp has been found growing profusely on mussel culture lines. It also grows readily on ropes and cages causing fouling in marine farms (DPIWE 2002). where it has displaced native species such as rock lobster, abalone and oysters

*Undaria* is easily spread by boat owners not cleaning and washing boats, trailers, fishing equipment etc after leaving an infested area. A piece of the algae left on a net or anchor will survive for 1-2 days maybe more. Microscopic spores floating in water in the bottom of your boat will stay alive for a similar period of time.

A subsequent survey of the east coast of Tasmania estimated a standing crop of approximately 400 tonnes of kelp (DPIWE 2002), but the area of infestation was limited to the Triabunna-Rheban region (approximately 10 km of coast). A 1994 distribution survey indicated the infestation had spread to over 80 km of coast, from Coles Bay in the north and south to the Narrows (Marion Bay).

In July 1996 the kelp was identified in Port Phillip Bay. It has been predicted that the alga has the potential to establish on the southern Australian mainland from Cape Leeuwin (WA) to Wollongong (NSW) (Sanderson & Barrett 1989).

In January 1997, a small stand of *Undaria* growing in the Tinderbox Marine Reserve and raised the alarm. The algae was removed, however, the specimens indicated that at least one

'seeding' period had already occurred. Outbreaks have now been documented at Tinderbox Marine Reserve, Fortescue Bay, Canoe Bay, Norfolk Bay, Marion Bay and Great Oyster Bay/Schouten Passage. By reviewing the movement of *Undaria* outbreaks it is now evident that human intervention is spreading the algae.

### ***Undaria* Harvesting**

In eastern Tasmanian waters, the eradication of the *Undaria pinnatifida* is virtually impossible due to the elusive, microscopic gametophyte stage of the alga and the extent of colonization (Sanderson & Barrett 1989). By the early 1990s, *Undaria* in Tasmania had become sufficiently established to enable the development of a commercial scale harvest. As a control measure the Department of Primary Industry and Fisheries made provision for three licences to wild harvest, process and sell *Undaria* back to Japan. Because this product originated in Tasmania's unpolluted waters it has potential to command a high price as a Japanese delicacy with many healing powers.

Harvest operations are currently confined to the east coast of Tasmania, where significant concentration of *Undaria* occurs (DPIWE 2002). There are opportunities for further licences as the seaweed spreads further around the Tasmanian coast. It is currently found from the D'Entrecasteaux Channel to north of Bicheno. Since *Undaria* is an introduced marine pest, the harvesting of this species does not need to be constrained by concerns over resource sustainability. It was initially hoped that the harvest would help slow the spread of the pest, although levels of harvesting have not been sufficient to achieve this.

#### **1.4.7 Commercial Harvesting of Giant Kelp**

Giant Kelp (like other kelps) also have a capacity for some of the most remarkable growth rates in the plant kingdom - in southern California, *Macrocystis* plants can grow up to 50cm a day. These extraordinary growth rates, and their known industrial and pharmaceutical benefits, have resulted in the world-wide commercial harvesting and exploitation of Giant Kelp forests both, in Tasmania (eg. east coast) and overseas (eg. California). In the USA, *M.pyrifera* is harvested from large offshore beds off the coasts of California and Mexico. Some 120,000 tonnes wet weight are gathered each year using ships equipped with cutting machinery.

The first use of Giant Kelp on a large commercial basis was in California, for the purpose of producing potash (potassium carbonate) during the First World War. At the time, potash was a necessary ingredient in the production of gunpowder. The potash was derived from the kelp ashes after it had been burned. At that time, kelp was harvested by encircling a stand of kelp with a cable and then pulling on the cable. This generally had the effect of ripping out the entire kelp plant, including the holdfast. By comparison, today's harvest methods are limited to cropping the fronds, which are short-lived compared to the holdfast.

Giant Kelp that is currently harvested in California today is primarily used in chemical industrial applications. Algin, which is a product derived from kelp, is used as an emulsifier in processed foods and other products where a smooth texture is required (eg. paints, cosmetics, pharmaceuticals). Other uses of kelp are as food for cultured abalone, and as substrate for the herring-roe-on-kelp fishery (exported for Sushi).

Alginates are cell-wall constituents of brown algae (Phaeophyta). Alginates of one kind or another seem to be present in most species of brown algae but they occur in exploitable quantities (30-45% dry weight) only in the larger kelps and wracks (Laminariales and Fucales). Alginates are extracted chemically and used in bulking, gelling, and stabilizing processes. Products using alginates include charcoal briquettes, cosmetics, ceramics, cheese,

paint, asphalt, rubber tires, polishes, toothpaste, ice cream, and paper. About 25,000 tonnes of alginic acid per annum are extracted world-wide. The main producers are Scotland, Norway, China and the USA, with smaller amounts being produced in China, Japan, Chile, France and Spain.

#### **1.4.8 Seaweed Harvesting in Tasmania**

The direct harvesting of native seaweeds in Tasmania has largely been confined to the commercial harvest of Giant Kelp beds for alginate production in the 1960s and 70s. While there was considerable investment in this industry, the industry eventually proved unsustainable due to low levels of production and low market prices.

There is currently no direct harvesting of native seaweeds in Tasmania due to their ecological importance to marine ecosystems and fisheries resources. Harvesting of seaweed in Tasmania is presently confined to 3 activities:

1. the collection of beach cast Bull Kelp (*Durvilleae potatorum*) on King Island and the northern west coast;
2. harvesting of the introduced Japanese Sea Kelp (*Undaria pinnatifida*) on the east coast;
3. and the localised collection of beach cast seaweeds and seagrasses.

Bull Kelp harvesting is a major industry in Tasmania supplying about 5% of the world production of alginates and generating about \$2 million dollars of income for King Island. In contrast, small-scale licensed operations collect cast weed from several locations around Tasmania where large volumes of seaweed and seagrasses are washed ashore. The bulk of this cast weed is bagged and sold in garden shops as garden mulch.

Seaweed harvesting in Tasmania is currently managed as a 'fishery' by the Department of Primary Industries, Water and Environment.

### **1.5 Decline of Giant Kelp Forests – Overseas Studies**

Kelp forests in southern California began to decline in surface area about 1940, and all experienced major losses during the El Niño event of 1957-59. Many forests remained at low levels midway into the 1960s (North 1971, 1979, 1983, Harger 1983, Dayton *et al.* 1984). Systematic diving investigations of these communities began in 1956 and the proximal reason for the decline of the forests was determined to be intense sea urchin grazing (North 1964, Leighton *et al.* 1966, North & Pearse 1970). An 'apparent population explosion' of red urchins (*Strongylocentrotus franciscanus*) and purple urchins (*S.purpuratus*) was reported to have replaced many once luxuriant forests of *Macrocystis pyrifera*, and their continued grazing pressure prevented re-establishment of the vegetation (North & Pearse 1970). The eventual recovery of forests near the metropolitan areas of Los Angeles and San Diego followed urchin control programs, kelp restoration, and improved sewage disposal practices (Wilson *et al.* 1977, North 1983).

The 1982-84 El Niño provided an opportunity to re-examine how warm water events affect the relationship between kelps and sea urchins in southern California (Tegner & Dayton 1991). The Point Loma kelp forest, near San Diego, is one of the best known and studied kelp communities in the world, having been nearly continuously studied since 1956 (ie. North 1964, 1979, Tegner & Dayton 1981, 1987, Dayton & Tegner 1984, 1990, Dayton *et al.* 1984). After about 15 years of relative stability, the population of *Macrocystis pyrifera* was again devastated by the storms and warm water of the 1982-84 El Niño (Dayton & Tegner 1984, 1990, Tegner & Dayton 1987). Despite the larger physical disturbance of the 1982-84 El

Niño, many coastal kelp forests recovered much faster than after the 1957-59 El Niño event (Tegner & Dayton 1981). Comparison of the urchin density between the mid 1970s (Tegner & Dayton 1981) and the 1980s indicated that the commercial fishery for red sea urchins has greatly reduced their population. Tegner & Dayton (1991) suggested that the urchin fishery increased the long-term stability of this ecosystem by allowing faster kelp recovery after disturbance.

## 1.6 Current Status of Research/Knowledge

Despite the considerable ecological and economic significance of Giant Kelp forests in Tasmania and Australia, the basic fundamental knowledge required for their long-term conservation and management – ie. distribution, ecology, health, and potential threats or risks to their survival – is poorly known. While there is considerable literature on the subtidal ecology of kelp communities in southern temperate Australia, particularly the Common Kelp (*Ecklonia radiata*) (see Kennelly & Underwood 1992, Steinberg & Kendrick 1999), there is very little published research on the population biology or ecology of *Macrocystis*.

While specific kelp surveys have been conducted on the south-east and east coasts of Tasmania (eg. Cribb 1954, Olsen 1966, Sanderson 1987), almost nothing is known of the distribution of forests on the southern, northern and western coasts or the health or ecology of kelp forests generally. Unfortunately, the large-scale loss of Giant Kelp forests in Tasmania has also been exacerbated by the lack of any government policy or integrated research program to assess the status and management of these marine ecosystems in Tasmania.

The first studies conducted on Giant Kelp in Tasmania focussed primarily on the potential for its commercial exploitation for alginates (Cribb 1954). In the 1950s, CSIRO undertook detailed mapping, growth and harvesting trials to ascertain the potential biomass and cropping levels for commercial kelp harvesting.

Based on the CSIRO estimates of kelp production, Alginates Australia established a commercial kelp harvesting facility on the east coast of Tasmania in 1963, at Louisville (near Triabunna). Alginates Australia subsequently undertook regular (3-monthly) field surveys of the East Coast (aerial, boat-based) to ascertain the levels of standing crop available for harvest. In addition, the company investigated the impact of kelp harvesting on lobster recruitment (Olsen 1966). This latter study included detailed mapping of kelp beds in the Mercury Passage region.

In the early 1980s, NPWS undertook a series of SCUBA-based field surveys of Tasmania, to identify potential Marine Reserves (Edgar 1981, 1984b). These surveys provided detailed ecological descriptions of the marine habitats (and their conservation significance), including the presence of *Macrocystis* (*pyrifera* and *angustifolia*).

In the 1990s, further SCUBA-based field surveys (and mapping) were undertaken to identify potential Marine Reserve sites (Barrett & Wilcox 2001), including surveys of Bass Strait (Barrett & Edgar 1992) and southern and western Tasmania (Edgar & Barrett 1995). This was followed by broad-scale habitat mapping of the nearshore habitats of Tasmania, using aerial photography, at a scale of 1:100,000 (Edyvane *et al.* 2000). Most recently, finer-scale marine habitat mapping of the Bruny Bioregion (at a scale of 1:25,000) has identified locations of *Macrocystis*, but there was no attempt to systematically map this habitat (Barrett *et al.* 2001).

To-date there has been no recent field surveys of *Macrocystis pyrifera* (L.) C. Agardh forests in Tasmania, apart from aerial surveys conducted in 1986 (Sanderson 1987) and 1999 (Sanderson 1999). The aerial survey in June 1986 surveyed the east coast of Tasmania (ie.

Friendly Beaches to South East Cape) (Sanderson 1987), and estimated 10 km<sup>2</sup> of *M.pyrifera* beds (based on area of floating canopies).

## 1.7 Project Aims

The project will map and survey beds of *Macrocystis* around the coast of Tasmania, and undertake a detailed conservation, threat and recovery assessment, including (i) an analysis of the historical loss of *M.pyrifera*, since 1954 (using historical aerial photography, oceanographic data and data on the distribution of *Undaria pinnatifida*, and point and diffuse sources of pollution, to identify possible causes of the loss; (ii) identifying the potential for listing under Commonwealth and State/Territory endangered species legislation; (iii) an assessment of beds to determine potential sites for reservation as Marine Reserves; (v) identification of threats and management actions to reduce threats; and (vi) the design of an ongoing monitoring and recovery program (including proposed field trials, guidelines, opportunities for community-based involvement and participation), incorporating an international review of Giant Kelp monitoring, recovery and restoration techniques (particularly in California, where large scale losses have also occurred) and their potential applicability in Tasmania.

### PROJECT OUTCOMES (MILESTONES)

1. A review and collation of existing information on the ecology and distribution of *Macrocystis* in Tasmania, including collation, digitising and incorporation of existing inshore maps of *Macrocystis* distribution (Cribb 1954, Sanderson 1987) onto a spatial database.
2. Undertake a detailed mapping and biological survey of Giant Kelp habitats along the coast of Tasmania, using remote sensing technology and field ground-truthing.
3. Undertake a detailed temporal analysis of areas of significant historical loss of *Macrocystis* populations (ie. along the southeast coast of Tasmania), using historical aerial photographs, and correlation with possible causes, ie. oceanographic conditions (using historical surface sea temperature data) and distribution of *Undaria pinnatifida*, to assess the likely causes of the loss.
4. Production of an 'on-line' community and industry survey (ie. 'KelpWatch') to assess anecdotal records (and photographs) on the historical distribution and health of Giant Kelp habitat in Tasmania (including observations of pollution, introduced pests, urchin abundance, etc.).
5. Based on the results of the survey and temporal loss analysis, undertake a conservation and threat assessment of Giant Kelp habitats, identifying potential areas for reservation as Marine Reserves, and identifying threatening processes and management measures to assist with future conservation management and recovery.
6. Design of an ongoing monitoring and recovery program (ie. 'KelpWatch'), based on an international review of kelp monitoring, recovery and restoration techniques and their potential application in Tasmania, and opportunities for community-based involvement and participation.
7. Incorporation of all spatial datasets onto the PWS GIS platform (and the Australian Coastal Atlas).