

The spread of the introduced *Euphorbia paralias* (Euphorbiaceae) along the mainland coast of south-eastern Australia.

Petrus C. Heyligers

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Euphorbia paralias, Sea Spurge (Euphorbiaceae), indigenous to the sandy shores of southern Europe and northern Africa, was first collected in Australia near harbours: at Albany, Western Australia in 1927 and at Port Victoria, South Australia in 1934. *E. paralias* seeds are buoyant and dispersed by ocean currents. By 1974 *E. paralias* had reached Wilsons Promontory, but was not recorded from southern New South Wales until 1987, while in East Gippsland it was first recorded in 1993. Since then it has spread to other beaches in this region and has also turned up on Lord Howe Island.

Surveys have been carried out to ascertain the status of *Euphorbia paralias* in East Gippsland and southern New South Wales during the last decade. The results together with other observations have been correlated with the published results of drifter experiments. The latter relied on reporting back of stranded bottles, cards or envelopes released at certain distances offshore. The establishment of *E. paralias* in southern New South Wales, before doing so in East Gippsland, is in agreement with the stranding pattern of bottles released west of Wilsons Promontory. Another bottle and two cards released in eastern Bass Strait washed up on Lord Howe Island, thus underpinning the assumption that the colonising *E. paralias* seed was carried there on ocean currents. *E. paralias* is still expanding its range in New South Wales. Modelling based on climatic parameters has shown that extension to the lower North Coast of New South Wales can be expected. However, the spread of the introduced sea-rocket *Cakile edentula* beyond its known climatic range into the Great Barrier Reef area could provide a precedent for what may also happen in the case of *E. paralias*.

Introduction

Euphorbia paralias L., Sea Spurge (family Euphorbiaceae), is a coastal dune plant native to sandy shores of the Atlantic Ocean from Mauritania to southern Ireland and England, the Mediterranean Sea and the Black Sea (Heyligers 1993). In Australia the first herbarium collections of this species were made at Albany in 1927 and at Port Victoria in 1934. This strongly suggests that seeds were accidentally introduced through shipping, possibly in ballast carried by grain ketches. As *E. paralias* seeds are buoyant in sea water and spread by ocean currents, the species progressed west as well as eastward, along the coasts of southern Australia (Heyligers 1989a, 1989b, 1993, Wilcock 1997). By 1974 it had reached Norman Bay on the west coast of Wilsons

Promontory and in 1982 I spotted plants on the east side at Five Mile Beach. The earliest collection in Tasmania was made in 1980 along Waterhouse Beach in the north-east. In 1982 *E. paralias* was also collected on Flinders Island and in 1984 on King Island.

During his coastal survey of New South Wales in 1987 Clarke (1989) found *Euphorbia paralias* plants on Loader Beach, about 10 km south of Narooma (Fig. 1). In the 1980s I regularly visited several beaches along the South Coast of New South Wales and in East Gippsland to research the influence of plant species on dune development. After intensifying reconnaissance of beaches in the Narooma area, I found a large population of *E. paralias* on the small alcove beach of Scuff Bay, not far north from where the first plants were seen. This beach was likely to be the spot first colonised by *E. paralias* on the east coast, thus forming a focus for further spread. New occurrences were documented through my observations as well as by members of the Eurobodalla Natural History Society with the result that by 1995 Sea Spurge was found to be widespread along beaches stretching about 20 km north and south from Narooma, while scattered occurrences were reported between Broulee and Pambula (Heyligers 1989b, 1991, 1995).

In 1993 the Eastern Victorian Coastal Trek (Heislors 1994) provided an opportunity to investigate the distribution of *Euphorbia paralias* in Gippsland. The participants walked along all beaches from the entrance of Port Phillip Bay to Cape Howe. They came across only one occurrence of *E. paralias* west of Wilsons Promontory, at Cape Conran (Fig. 1). Some years later, Parks Victoria (G. McLeod, pers. comm.) reported several new occurrences in East Gippsland, while in New South Wales *E. paralias* had been found on beaches a few kilometres south of Jervis Bay (Mills & Associates 1998). The present paper reviews the dispersal and establishment of *E. paralias* in recent years and investigates to what degree dispersal by ocean currents has influenced the colonisation process in coastal south-eastern mainland Australia.

Morphology and ecology

Euphorbia paralias is a perennial with a long taproot. The 30–55 cm long stems die after flowering and are replaced by new shoots from the root crown (Fig. 2). Stem number is influenced by growing conditions; a vigorous three or four year old plant can produce up to 100 stems in a season, but under unfavourable conditions this figure can be less than ten. Side-branches may develop anywhere along the stems, giving *E. paralias* the capacity to grow through accumulating sand. A plant on a lower lee slope which received sand blown over the dune crest, had at least twice coped with a 30 cm deep sand deposit by producing new shoots at the latest surface level. I did not succeed in digging out the root crown, but there had been at least one earlier deposition event. Elsewhere I have seen shoots breaking through the surface of a dune crest on which *E. paralias* plants had been buried by recent heavy sand accumulation. On the other hand, the taproot anchors the plant during erosion. Immediately below the crown the root has a diameter of 2.5–3 cm and tapers over a length of 30–40 cm to a mere millimetre. Blown-out plants show that this thin root penetrates for a metre or more into the sand. From the tapered section of the root a few lateral roots, about 1 cm thick, grow out horizontally.

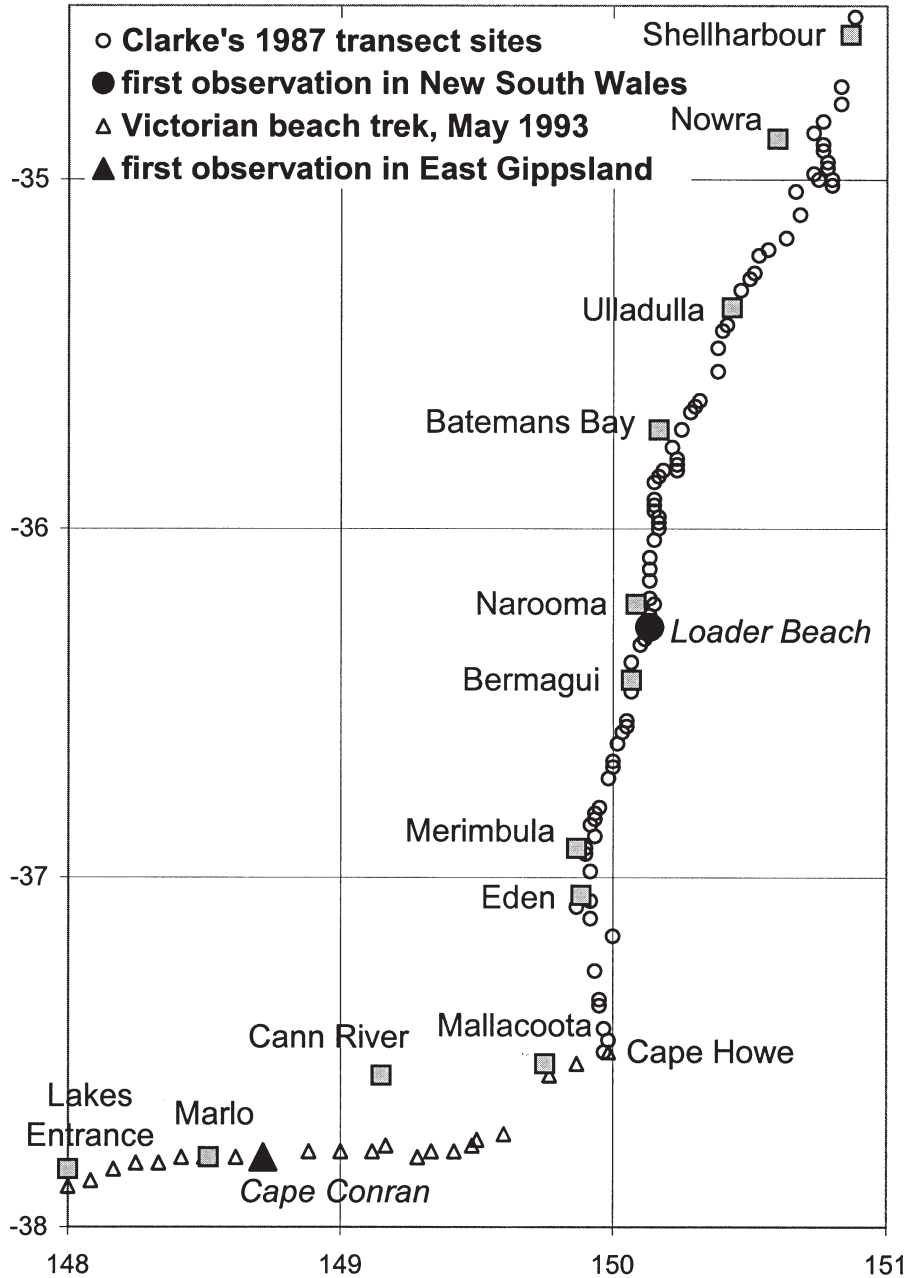


Fig. 1. Systematic coastal surveys during which the first observations of *Euphorbia paralias* in New South Wales and East Gippsland were made. Open circles indicate the position of the transects surveyed in 1987 (Clarke 1989), open triangles the route followed by the participants of the 1993 beach trek (Heislars 1994). The first observation sites for *E. paralias* are indicated with black symbols.



Figure 2. A single *Euphorbia paralias* plant on the sandspit at Potato Point, c. 20 km north of Narooma, photographed in March 1992, showing three generations of stems: old, browned-off flowering stems, stems presently flowering, and a few younger shoots.

Flowering appears to be more dependent on growing conditions than on time of year. Each shoot has the potential to develop a terminal, branched, leafy inflorescence. Vigorous plants can produce 25 to 80 fruits per stem. With three seeds per fruit, this means the annual production may be over 20 000 seeds per plant. However, seed production is variable with severely stressed plants producing virtually no seeds. *E. paralias* has two modes of dispersal: the three-valved fruits open explosively and the globular seeds, about 3 mm in diameter, are buoyant. Seedlings around single plants show that the effective 'firing range' does not extend much beyond 2 m. If a seed lands in open vegetation or on the beach, slope and wind may increase this distance. By keeping seeds in jars with seawater I found that most seeds float for at least one and a half years and that some stay afloat for more than eight years. No data are available on effective buoyancy periods at sea. After two years about half the floating seeds had lost their viability, while none germinated after six years. Seeds that sank were not viable. Dry-stored seeds remain viable for at least seven years (Heyligers 1993).

Methods

Distribution surveys

A survey of *Euphorbia paralias* occurrences along the New South Wales South Coast between Batemans Bay and Merimbula was organised in cooperation with the Eurobodalla Natural History Society and the Far South Coast Birdwatchers for November 2000. I followed up this survey in February 2001 and inspected 32 beaches between Batemans Bay and Shellharbour (Heyligers 2002). In East Gippsland Westhead (1996) and Gormley (1997) had surveyed beaches from Marlo to Mallacoota for Parks Victoria. In addition, P.J. Wilcock provided data obtained through an Australia-wide questionnaire (Wilcock 1997), K. Mills from a weed survey of Cudmirrah and Conjola National Parks (Mills & Associates 1998) and L. Evans, New South Wales National Parks and Wildlife Service Far South Coast Region, from counts at Nadgee Nature Reserve. The most recent extension of the range of *E. paralias* to Lord Howe Island was reported by K. Mills (pers. comm.).

Drifter experiments

To assess the role of sea currents in dispersal of *Euphorbia paralias* seeds, results obtained with drift bottles (Anon. 1968), drift cards (Marshallsay & Radok 1972) and drift envelopes (Wood 1996) were used. The earlier experiments were carried out before satellite tracking of drogued buoys dramatically changed oceanographic research. However, for the study of plant dispersal, data obtained by the drifter method provide more relevant information, as drifters are subject to the same wind and current forces as propagules afloat on the ocean surface. However, in contrast to drifters dropped from ships or offshore oil and gas platforms, propagules need to reach the sea by other means, for instance through beach erosion or offshore winds.

Anon. (1968) lists the results from experiments carried out by the CSIRO Division of Oceanography between September 1958 and May 1962. Each month 50 weighted bottles were released at four different positions at the western entrance to Bass Strait. Two release positions were close to the mainland, namely about 15 km south of Cape Northumberland and 55 km southwest of Cape Otway. Bottles were ballasted with blue-metal chips to float with only 2 cm of the neck exposed. Retrieval information was received for nearly one third of the 8050 bottles released. In addition, at the Cape Otway site, between January 1960 and January 1961, 600 bottles without ballast were used to compare with the performance of weighted bottles. Of these 55% were recovered. For the purposes of this paper only data from recoveries along the mainland coast east of Wilsons Promontory have been used.

On 19 December 1969 Marshallsay and Radok (1972) released driftcards in five batches of 500 from oil and gas platforms in eastern Bass Strait. These cards were made from high-density PVC. About one-quarter of the cards released from Barracouta, the platform closest to the shore, were later found, whereas the proportion of retrieved cards from other platforms was not as high.

Wood (1996) used floats made from clear plastic envelopes. On 25 occasions, from June 1985 to October 1987, batches of five floats were released at 9 km, 35–45 km and 50–90 km east of Wollongong. Recovery rates were close to 30% for the near-shore and mid-distance batches and 10% for the batches dropped further out to sea.

Nomenclature

Nomenclature follows Harden (1990–1993). The spelling of *Tetragonia tetragonioides* is adopted from Gray (1997).

Results

The distribution of *Euphorbia paralias*

Since its appearance in southern New South Wales in the mid-1980s and in East Gippsland in the early 1990s, *Euphorbia paralias* has spread to many other beaches. Early in 2001 its range stretched from Jervis Bay in the north to Marlo in the south, a total distance of about 550 km, with an outpost on Lord Howe Island, about 850 km to the east-north-east of Jervis Bay.

To show the history of this spread, observations along the Australian mainland coast have been summarized over four periods (Fig. 3a–d). The first period (1987–1992) spans the time from the first record of *Euphorbia paralias* at Loader Beach up to the first find in East Gippsland. The second (1993–1995) covers this event and ends with the first survey of the New South Wales South Coast. The third period (1996–1999) incorporates detailed surveys in East Gippsland, while the fourth (2000–February 2001) includes results of the second South Coast survey. Maps also show the location of beaches where *E. paralias* was not seen, to give some measure of reliability. Fig. 4 summarises the data presented in Fig. 3.

At many sites *Euphorbia paralias* occurs in small numbers. This is demonstrated by the detailed surveys between Marlo and Mallacoota (Westhead 1996, Gormley 1997; Fig. 5). Considerations of scale made it necessary to base the mapped number of plants on the number of individuals, including seedlings and immature plants, present per one minute longitude (or c. 1.5 km). Hence, in quite a few cases where the map shows a modest number of plants, these do not necessarily grow together, but usually comprise several single plants, some groups of a few mature plants and surrounding seedlings. It is evident from comparison with Fig. 3 that the greatest concentrations of plants occur at and near the sites where *E. paralias* was found in 1993 and 1994.

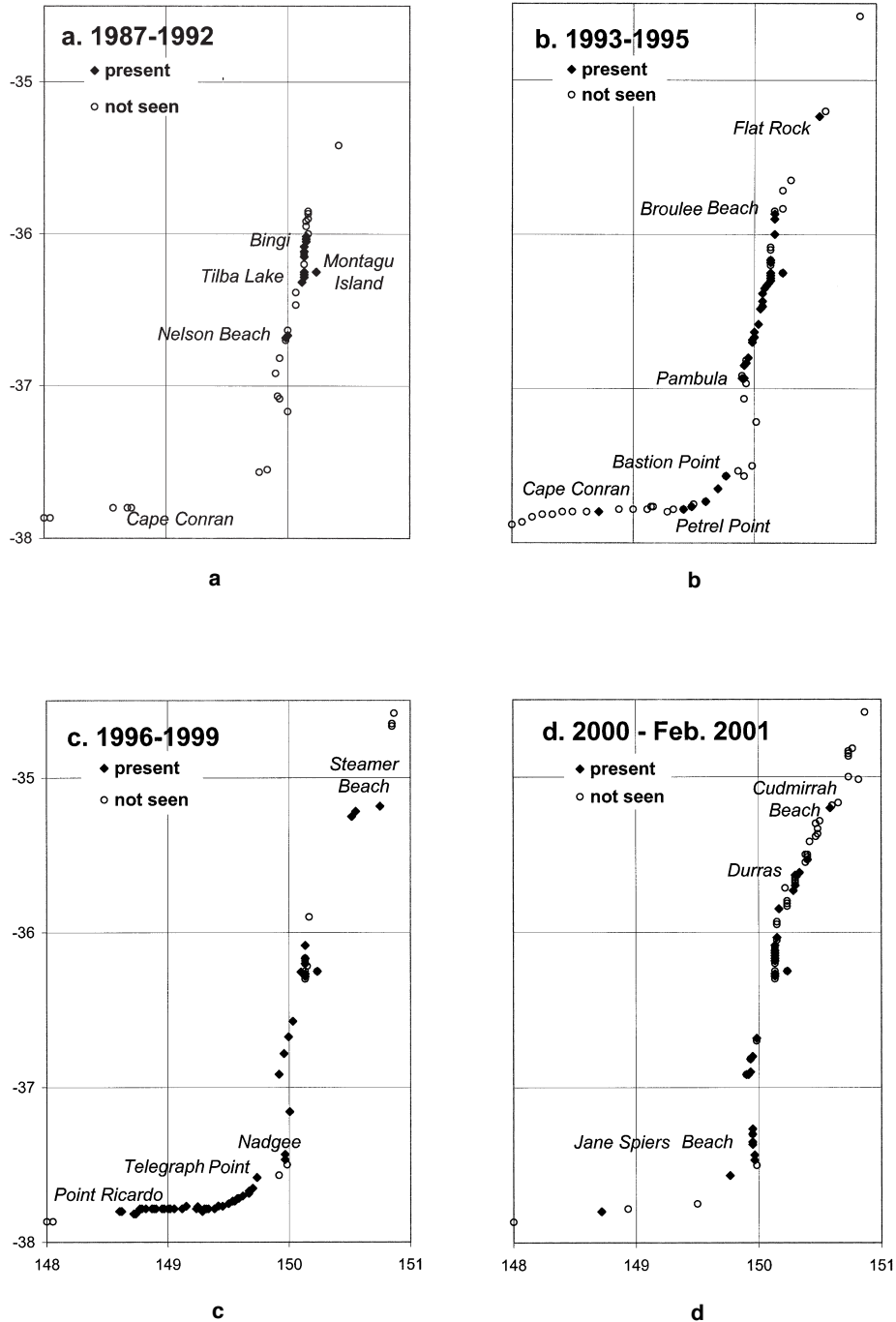


Fig. 3. Observations of *Euphorbia paralias* between 1987 and 2001. Map a summarises the years between the discovery in New South Wales and the Victorian beach trek; b, the time from the trek up to and including the 1995 South Coast survey, c, the period in which the East Gippsland surveys were done, and d, the results of the second South Coast survey. The coastline has been not been indicated to make the observations stand out more clearly.

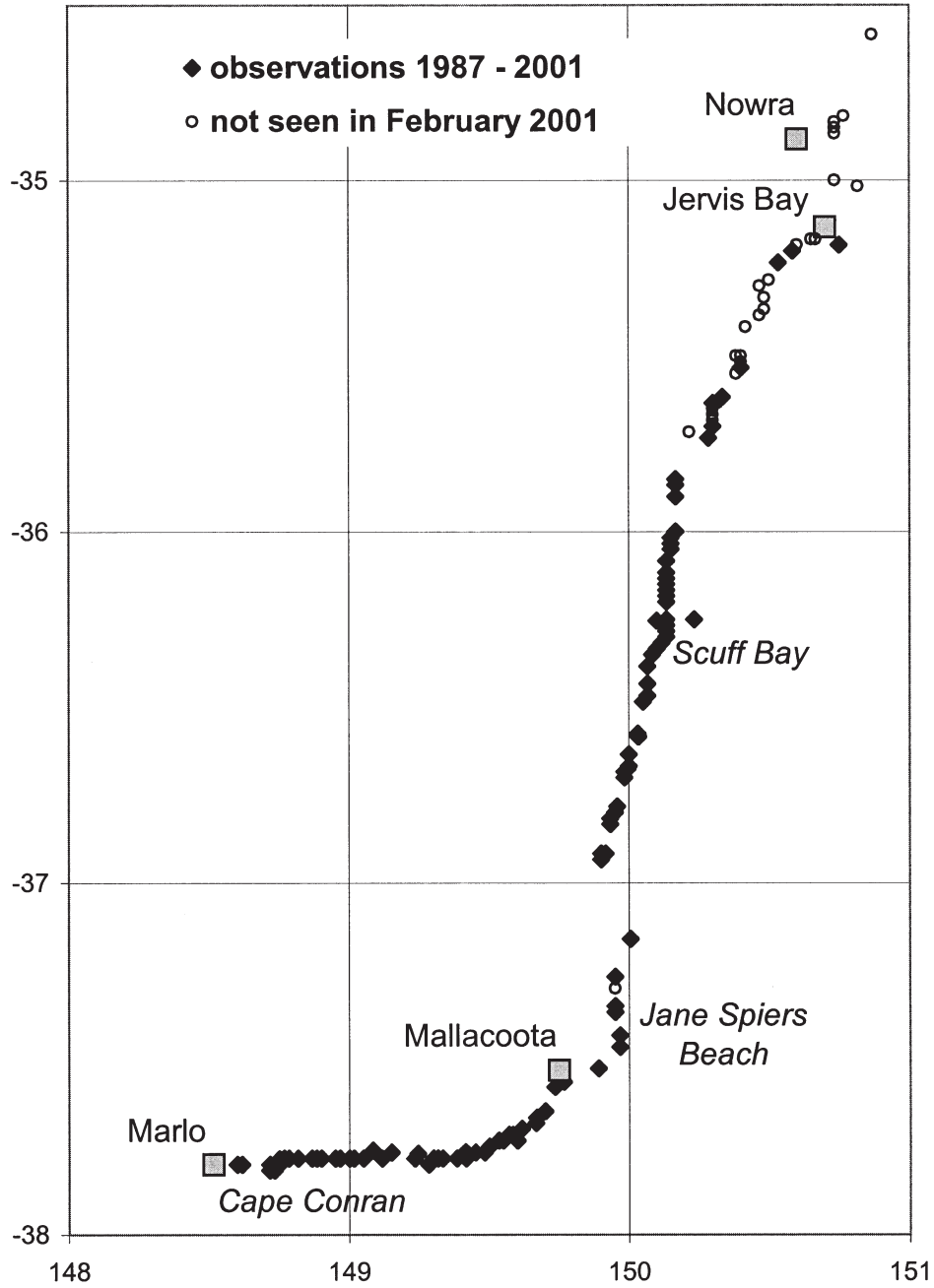


Fig. 4. An overview of *Euphorbia paralias* occurrences in south-eastern coastal mainland Australia.

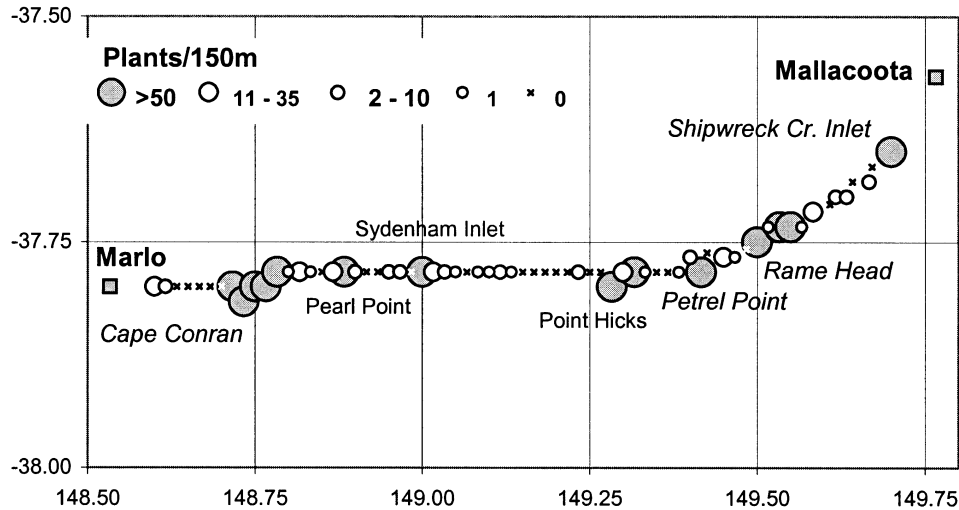


Fig. 5. Distribution of *Euphorbia paralias* along the coast between Marlo and Mallacoota, based on data from Gormley (1997) and Westhead (1996). Geographic names in italics refer to sites where *E. paralias* was originally seen in 1993 or 1994; those in regular case to additional sites with > 50 plants/150 m found during the 1996 and 1997 surveys.

Sea currents

Many weighted drift bottles released off Cape Northumberland and Cape Otway drifted around Wilsons Promontory and washed up along the Gippsland coast (Fig. 6). The first recoveries were 23 and 24 days after release, when four bottles were picked up on the southwestern end of Ninety Mile Beach. Subsequent retrievals along this beach were made 48, 67 and 100 days after release. Only a few bottles drifted past Cape Howe and stranded on the New South Wales coast. The first of these was found near Green Cape after 67 days at sea, the next one, near Sydney, after 118 days. The fate of unweighted bottles was very different. No bottles were reported from Gippsland, but strandings were widespread along the east coast of New South Wales and Queensland. Their journeys took more time than the weighted bottles, with the first recoveries coming from southern New South Wales after 116, 145 and 148 days. One bottle was found on Lord Howe Island 564 days after release.

From the 500 cards released from Barracouta, 130 were recovered from East Gippsland beaches (Fig. 7). The retrievals were concentrated along the eastern section, where 110 cards were found within nine months after release (Marshallsay & Radok 1972). Of these, 23 were picked up in the first week at Point Hicks and most of the remainder were found within three weeks. No cards of this batch were found along the east coast.

In contrast, the 2000 cards released from the other platforms, located further out in Bass Strait, bypassed this stretch of coast (Fig. 6). Over the next year and a half 22 of them washed up along the east coast as far north as Cape Tribulation in northern Queensland. The first two recoveries came from the Port Kembla area after 80 days. In addition, two cards were found on Lord Howe Island 198 days after release.

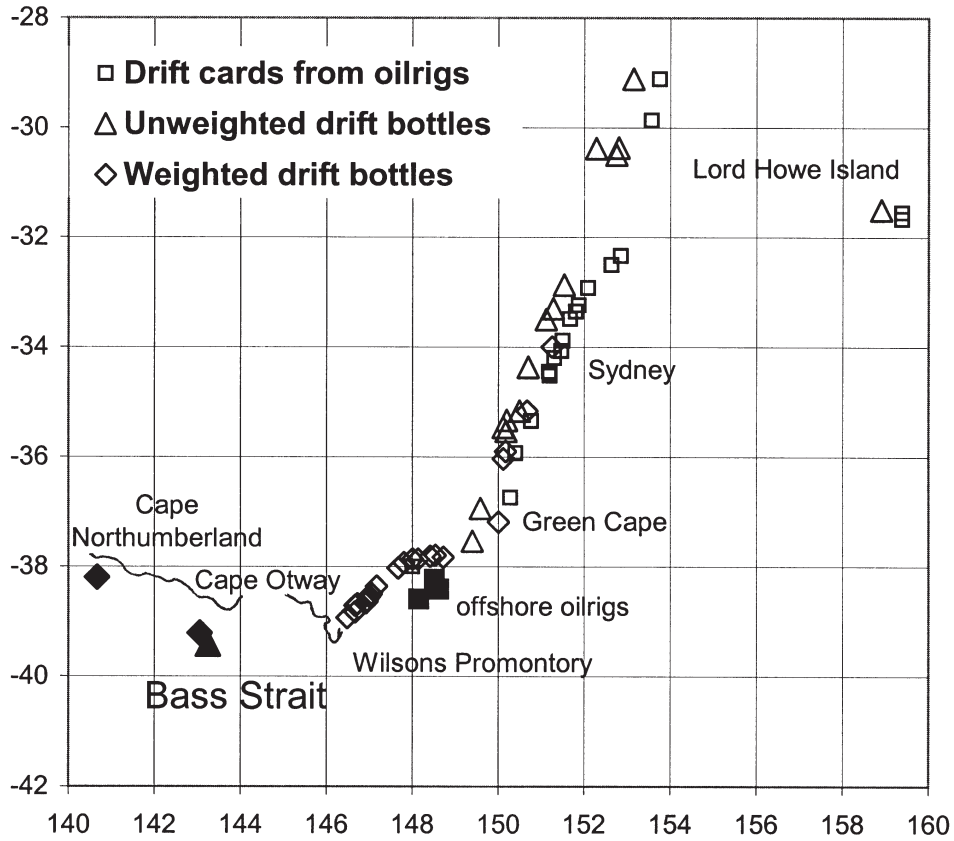


Fig. 6. Schematic map of Bass Strait release locations of drift cards and drift bottles (solid symbols) and recovery sites east of Wilsons Promontory and along the coast of New South Wales (open symbols). Data extracted from Anon. (1968) and Marshallsay and Radok (1972).

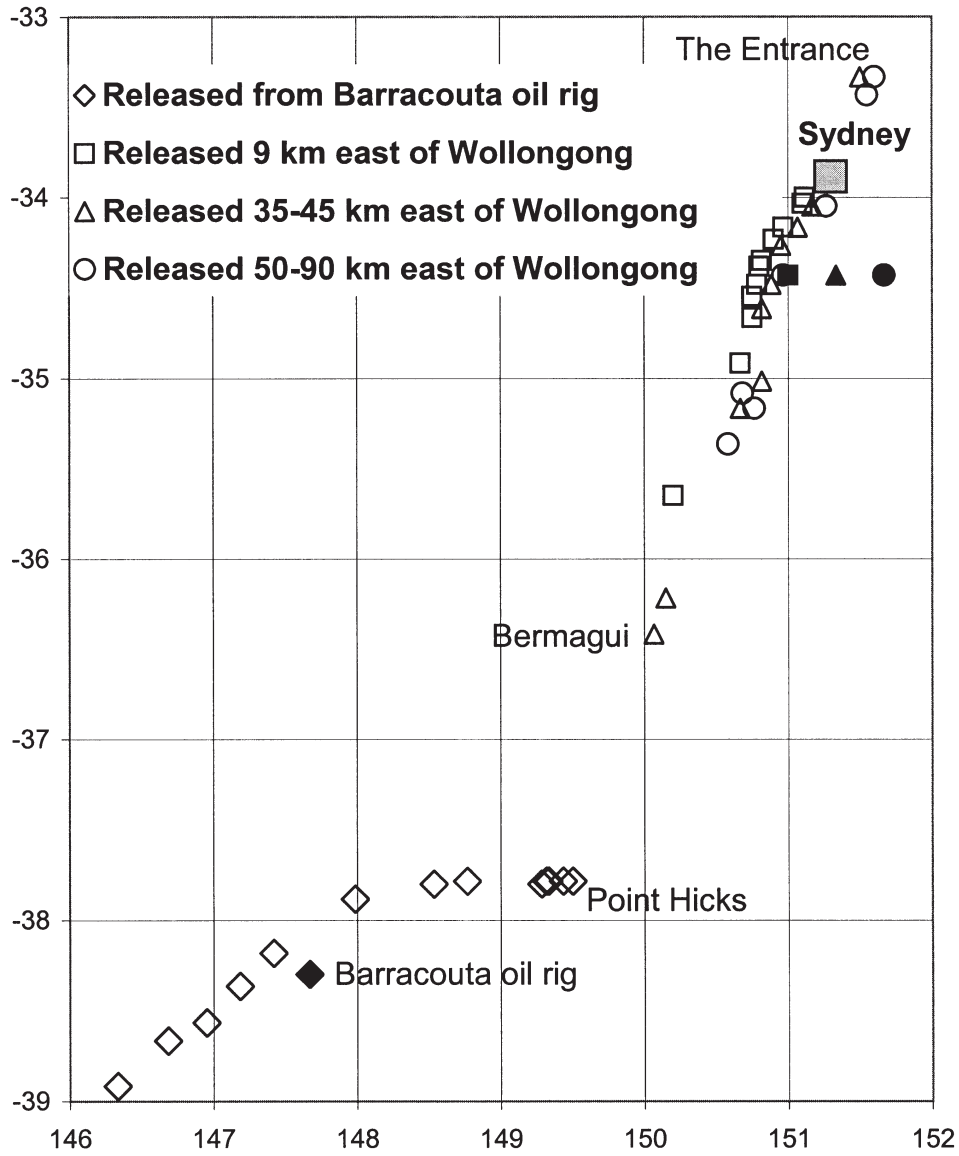


Fig. 7. Schematic map of retrieval locations (open symbols) for floats released at short distances offshore (solid symbols): cards from the Barracouta oil rig and envelopes thrown overboard at incremental distances from Wollongong. Data extracted from Marshallsay and Radok (1972) and Wood (1996).

Recoveries of floats released at various distances out from Wollongong were limited to the 310 km stretch of coast between Entrance Point and Bermagui (Fig. 7; Wood 1996). Recovery times for floats released 9 km offshore could be as short as one day; those for floats released about 40 km offshore two days and for the ones released further out three days. The float that was picked up at Bermagui was released at the 40 km site 28 days earlier. From six groups of floats, released in late autumn or winter months, no recoveries were reported at all.

Discussion

Evidence of dispersal by sea

Effectiveness of propagule dispersal by sea is demonstrated by plant assemblages that germinate and subsequently flourish in flotsam lines on the upper beach. A good example was seen at Myrtle Beach, south of Durras, where vigorous young plants of *Euphorbia paralias*, *Atriplex cinerea* Poir. (Chenopodiaceae), *Cakile maritima* Scop. (Brassicaceae) and *Tetragonia tetragonioides* (Pallas) Kuntze (Aizoaceae) were found growing together in flotsam along the margin of the low dune terrace with *Zoysia macrantha* Desv. (Poaceae) vegetation. Like the seeds of *E. paralias*, fruits of the other three species are buoyant in seawater (Heyligers 1989b, 2001). Also, it is not unusual to find flotsam remnants around older *E. paralias* plants in swales on the inland side of foredunes. Such flotsam was deposited there during storm high tides, either directly through wave overwash or via low areas in the foredune.

Where do drifting seeds come from?

Retrievals of drift cards and drift envelopes show that recovery rates for releases close to the coast can be quite high. From this one may assume that local dispersal of *Euphorbia paralias* seeds by inshore currents generated by wind or tides is a relatively efficient way of establishing pioneer plants in the vicinity of existing populations. In contrast, retrieval rates for releases further out at sea are much lower. The corollary of this is that, if seeds were pushed further out to sea, for instance by persistent offshore winds, and became entrained in major current systems, the chances of stranding are greatly diminished. To counteract this effect a large and enduring seed source is needed. Which poses the question: where is this source to be found?

Because *Euphorbia paralias* plants are very uniform, variation in habit cannot be used to make an informed guess about the origin of a seed that initiated a particular population. *E. paralias* is widespread and, in places, very common along the southern coastline west of Wilsons Promontory (Wilcock 1997). This large section of continental coastline must function as a steady seed supplier. Given the easterly direction of the prevailing current systems, the majority of the seeds, like the unweighted drift bottles released near Cape Otway, would bypass East Gippsland due to the barrier formed by Wilsons Promontory. Eventually, some of them would have stranded at Scuff Bay, Jane Spiers Beach, Flat Rock or Lord Howe Island.

Where did *Euphorbia paralias* arrive in southern New South Wales?

Until recently, I had assumed that Scuff Bay was the spot first colonized by *E. paralias* on the east coast of mainland Australia. However, in 1997 National Parks and Wildlife Service personnel discovered a population of *Euphorbia paralias* numbering more than 10 000 mature plants on the rather inaccessible Jane Spiers Beach in Nadgee Nature Reserve (L. Evans, pers. comm.). In view of that large number, colonization could have been more than a decade ago and contemporaneous with the appearance of *E. paralias* at Scuff Bay, if not earlier. An unweighted drift bottle released off Cape Otway was reported from Mallacoota Inlet 138 days after release and another one from Merimbula seven days later. This demonstrates that stranding of a seed from a source west of Wilsons Promontory in the Cape Howe area is a feasible proposition and that such a journey to the New South Wales South Coast could be achieved in less than half a year. In any case, it appears that we are dealing with two independent colonisation events.

Favourable habitat conditions

Although *Euphorbia paralias* is now widespread in southeastern coastal mainland Australia, it is not necessarily common over this area. There are still a number of beaches where it is absent, and at many others plant number are low. Only under favourable growing conditions do pioneer plants give rise to large populations: 100 or more individuals are not uncommon in such situations, with a population of well over 10 000 plants at Jane Spiers Beach the largest that has been reported. From my observations it would seem that favourable conditions occur where a fresh supply of sand or flotsam enriches the nutrient status of the foredunes, while a reliable source of fresh water appears to be a contributing factor.

Pioneering plants growing further inland from the beach, for instance in a dry swale behind the foredune, may develop into sizable individuals, but many of the surrounding plants of the new generation often remain small. In such circumstances colonisation of the local beach progresses only at a slow pace or, alternatively, plants may die and disappear. Even large populations such as the one at Scuff Bay may seriously decline after a number of years (Van der Heul, pers. comm.). This could be due to a decrease in nutrient status of the site. There is some evidence that plants grow better in association with *Acacia sophorae* (Labill.) R.Br. However, as shrubs increase in height, the *E. paralias* stems become elongated and eventually plants die from lack of light. Dune erosion can be another cause of disappearance, but at the same time this process provides an opportunity for seed dispersal.

The likelihood of future spread

Euphorbia paralias has established a firm foothold in East Gippsland and southern New South Wales. Various agencies, such as National Parks services and Dune Care groups, have attempted to eradicate *Euphorbia paralias* from some beaches (Gormley & Britton 1997, Heyligers 2002, L. Evans pers. comm.). Given the fecundity of this species, such effort will need to be sustained to have a long-lasting effect (Wilcock 1997). Moreover, nearby areas will remain a seed source for local dispersal and range extension. As drifter experiments have shown, many of the cards and envelopes released at

relatively short distances from the shore wash up on beaches in the general vicinity of release points. In East Gippsland drift cards were found over a distance of 220 km; along the southern coast of New South Wales drift envelopes were found over 310 km. Weather conditions influence local wave and current regimes and are the predominant agency in determining the fate of drifting objects including seeds. As is evident from Fig. 7, the resulting movement can be in either direction along the coast. In the case of *E. paralias* seeds, these may strand along beaches with an existing or recently eradicated population, or wash up at new locations. It is the latter process that leads to a gradual range extension.

In addition to local populations, many occurrences of *Euphorbia paralias* west of Wilsons Promontory will provide an ongoing seed supply. As discussed earlier, these seeds could strand at locations well beyond the present range of the species. This raises the question: how far beyond? Wilcock (1997) used the computer software program 'Climate' to predict the potential range of *E. paralias* in Australia based on its native distribution. His map shows that, climate-wise, most of the East Gippsland coast and the New South Wales coast south of Port Macquarie has a 50–60% suitability rating for growth of *E. paralias*. Predictions using the 'Bioclim' program and based on the mid 1990s Australian distribution gave similar results. However, climate factors are not necessarily the overriding determinants of distribution limits. In the case of seashore plants a striking example is provided by the sea-rocket *Cakile edentula* (Bigelow) Hook., a strandline species from the Atlantic and Great Lakes shores of temperate North America. It was introduced to Australia around 1850 and became established along the shores of Bass Strait. From there it spread west to South Australia and north to New South Wales and southern Queensland (Rodman 1986). In 1958 it had reached Heron Island and since then has been collected on several other Great Barrier Reef islands as far north as Bushy Island, at c. 21°S well inside the tropics (Heyligers 1996). On the mainland it has also been collected near Mackay at a similar latitude. The southernmost occurrences in its native range are on the Outer Banks of North Carolina at c. 36°N, roughly at the transition between the cool-temperate climate zone to the north and the warm-temperate, subtropical zone to the south (Rodman 1974, Müller 1982). If *E. paralias* were equally 'insensitive' to climatic conditions, it would be impossible to predict how far north this species could spread. Unweighted drift bottles released in western Bass Strait and drift cards from outlying oilrigs have been reported back from as far north as Cape Tribulation at c. 16°S. Their time at sea varied from one year to 21 months, short enough for many floating *E. paralias* seeds to remain viable.

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