1. INTRODUCTION & BACKGROUND

1.1. Invasive *Caulerpa taxifolia*

Caulerpa taxifolia (Vahl) C. Agardh is a marine, green macroalga (Plate 1) that is endemic to tropical and sub-tropical regions around the world. It is primarily a subtidal species that has running stolons and feather-like fronds and can grow on hard and soft substrata. Species of *Caulerpa* are coenocytic, meaning that each plant consists of one, multinucleate cell. In Australia, native populations of *C. taxifolia* are found in the Northern Territory, Queensland, Western Australia and on Lord Howe Island (Phillips and Price 2002 and references therein).

Plate 1. A comparison of native *C. taxifolia* from northern Queensland (lower) and invasive *C. taxifolia* from NSW (upper). Photographs courtesy of Alan Millar, Royal Botanic Gardens, Sydney.

The alga came to international attention in 1984 when an invasive strain was discovered in the Mediterranean Sea in front of the Monaco Oceanographic Museum (Meinesz and Hesse 1991). This infestation rapidly colonised thousands of hectares of subtidal hard and soft substrata in the Mediterranean (Meinesz 2002). This invasive strain became known as the "aquarium strain", because it was presumed to have been introduced from marine aquaria in which it was (and still is) used as a decorative plant (Jousson *et al*. 1998, 2000; Fama *et al*. 2002). Molecular evidence supports this notion, demonstrating that the invasive strain in the Mediterranean is genetically

identical to a strain of *C. taxifolia* widely cultivated in aquaria for at least 15 years prior to its appearance in Monaco (Jousson *et al*. 1998). From Monaco, *C. taxifolia* spread to coastal localities in France, Spain, Italy, Croatia and Tunisia (Meinesz *et al*. 2001). By the end of 2000, the alga covered approximately 131 km^2 of seafloor in the Mediterranean (Meinesz *et al*. 2001).

Infestations of *C. taxifolia* were also reported from California at about the same time as they were recorded in NSW (Jousson *et al*. 2000; and see below). More recently it has been recorded from West Lakes and the Port River in South Australia (Cheshire *et al*. 2003). It is unclear whether the same invasive strain has colonised all these locations, and there is debate about the origin of the invasive aquarium strain first found in the Mediterranean. Numerous studies have indicated that the aquarium strain in the Mediterranean is genetically similar to populations of *C. taxifolia* that are native to Queensland (Benzie *et al*. 2000; Wiedenmann *et al*. 2001; Famà *et al*. 2002; Meusnier *et al*. 2002; but see Murphy and Schaffelke 2003). Thus, it is almost certain that the invasive strain of *C. taxifolia* that colonised the Mediterranean did not originate from southern NSW, as suggested by Meinesz *et al*. (2001), but rather from sub-tropical areas in Queensland (north-eastern Australia). The supposed cold-tolerance of the invasive *C. taxifolia* is also under question as native populations of the alga from Queensland can tolerate water around 10°C (Chisholm *et al*. 2000; Wright ms in review).

Vegetative fragmentation seems to be the primary mode of reproduction of *C. taxifolia* (Meinesz *et al*. 1993; Smith and Walters 1999), as it is for most other species of *Caulerpa* (Jacobs 1994). Sexual reproduction has been documented for native tropical *C. taxifolia* (Meusnier *et al*. 2002), but successful sexual reproduction has not been observed in invasive *C. taxifolia* in the Mediterranean (Zuljevic and Antolic 2000) or elsewhere (A. Millar pers. comm). *C. taxifolia* can grow extremely quickly and vegetative growth is the primary mode by which the alga has colonised large areas of seafloor in the Mediterranean and elsewhere. Species of *Caulerpa* are capable of regenerating from small pieces of stolon or frond (Jacobs 1994), so fragments are an effective means of dispersal (Belsher and Meinesz 1995; Ceccherelli and Cinelli 1999a).

C. taxifolia rapidly reaches high abundance in places it invades (Meinesz *et al*. 1995, Ceccherelli and Cinelli 1998; Williams and Grosholsz 2002). It has been listed as one of the world's top 100 worst invasive species because it can potentially invade seagrass beds (Ceccherelli and Cinelli 1999), modify organic and inorganic components of the sediment (Chisholm and Moulin 2003) and threaten biodiversity (Meinesz 2002). Experiments in the Mediterranean have shown that fragments of *C. taxifolia* can establish on the edges of beds of seagrass during the warmer months of the year (Ceccherelli and Cinelli 1999a). It is not yet clear how *C. taxifolia* may interact with seagrass, but it has been suggested that dense patches of seagrass might be resistant to invasion by *C. taxifolia*, whereas sparse seagrass might be susceptible to invasion (Villèle and Verlaque 1995; Ceccherelli and Cinelli 1999b; Jaubert *et al*. 1999).

1.2. *Caulerpa taxifolia* infestations in NSW

The first confirmed sighting of *C. taxifolia* in NSW was in Fisherman's Bay, Port Hacking, on the southern outskirts of Sydney (Figure 1.1), in April 2000. *C. taxifolia* was found growing in beds of the seagrass *Posidonia australis* in this bay and outbreaks were discovered subsequently in several other bays in the estuary. Also in April 2000, *C. taxifolia* was found 180 km south of Sydney in Lake Conjola (Figure 1.1). There is, however, anecdotal information that the alga may have invaded Lake Conjola between 1987 and 1995 and that the Port Hacking invasions may have occurred in 1998 or earlier (Grey 2001).

Subsequent to the initial introductions, infestations were confirmed in 6 further estuaries in NSW: Careel Bay in Pittwater, 25 km north of Sydney in December 2000, followed by Lake Macquarie (90 km north of Sydney) in February 2001, Burrill Lake (200 km south of Sydney) in March 2001, Narrawallee Inlet (230 km south of Sydney) and Botany Bay (20 km south of Sydney) in April

2001 and the northern part of Sydney Harbour in April 2002 (see Figure 1.1). Again, the dates that *C. taxifolia* was first recorded in these estuaries may be many years after it actually arrived in the waterway. As this report was being prepared, a ninth location, St Georges Basin (see Figure 1.1) was also confirmed as containing significant infestations of *C. taxifolia.*

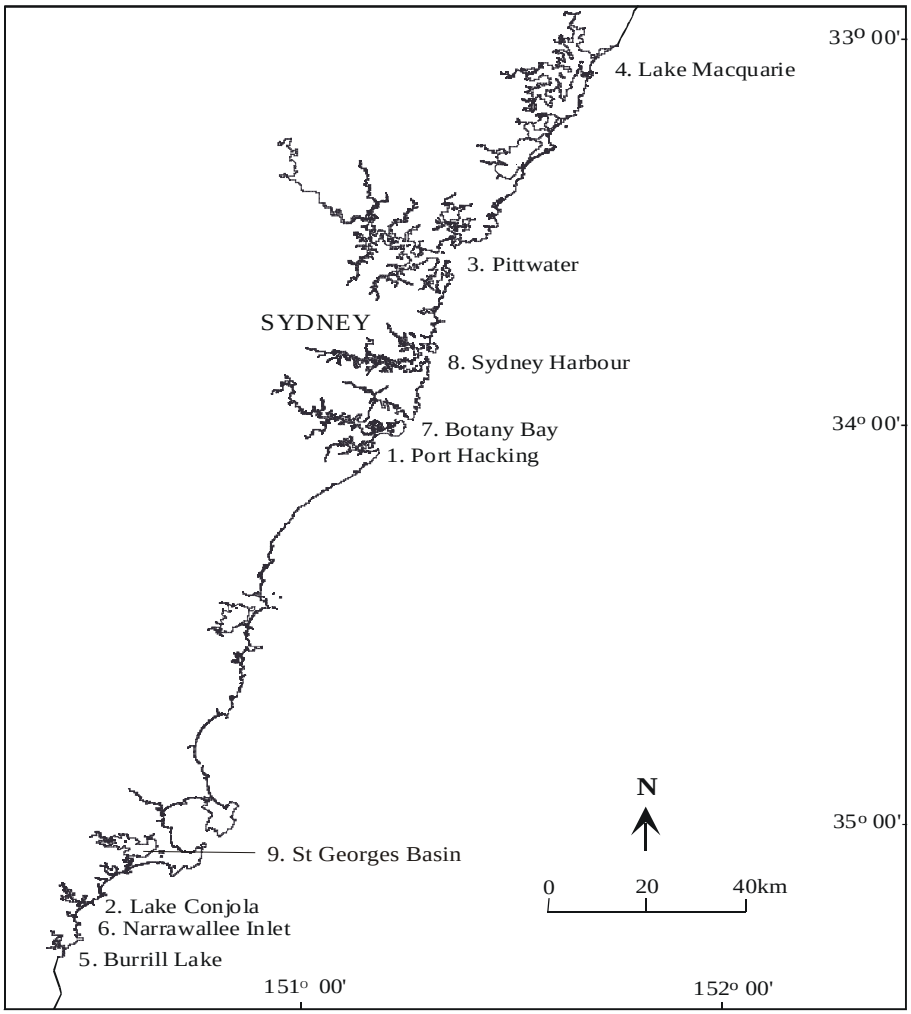

Figure 1.1. Sites where invasive *C. taxifolia* occurs in NSW (as at May 2004). Sites are numbered according to the order in which infestations were confirmed.

All outbreaks of the alga in NSW have been in bays and estuaries for which no previous record of the species exists. There is still uncertainty about the source of outbreaks of *C. taxifolia* in NSW (Phillips and Price 2002), but genetic evidence suggests that the various populations of *C. taxifolia* may have come from multiple sources, including native Queensland populations in Moreton Bay (Schaffelke *et al*. 2002; Murphy and Schaffelke 2003). Not only are there subtle genetic variations, but there is also considerable variability in the morphology of *C. taxifolia* from different waterways in NSW (Wright ms in review). It is highly unlikely that outbreaks in NSW represent a natural, southward range extension along the eastern Australian coastline (Millar 2002). This is because the 600 km break between the most northerly NSW population in Lake Macquarie and the southernmost populations in Queensland (Figure 1.1) is considered too great a distance for the natural transport of viable fragments.

The arrival of *C. taxifolia* in NSW has generally been attributed, as it was in the Mediterranean, to release from aquaria (Grey 2001). For example, at one heavily infested site in Port Hacking (Gunnamatta Bay) there was an aquarium shop that had stocked and sold *C. taxifolia*. Such an

introduction mechanism could readily account for the subtle genetic differences described by Schaffelke *et al*. 2002 if multiple releases had occurred from different aquarium stocks. However, it seems unlikely that the infestations in all 8 NSW estuaries were the result of separate releases from aquaria. Rather, there has probably been some translocation among NSW estuaries by other human vectors such as boating and fishing activities, as has also apparently been the case in the Mediterranean Sea (Relini *et al*. 2000). All waterways in NSW where *C. taxifolia* is now found are either frequently used anchorage sites or popular fishing spots, as has been reported for *C. taxifolia* infestations in other countries (e.g. Boudouresque *et al*. 1995). Several sites in Lake Macquarie, Lake Conjola and Narrawallee Inlet where *C. taxifolia* is found, for example, were commercial hauling grounds prior to the lakes being closed to commercial fish netting from May 2002. The alga is also found in areas previously used as hauling and trawling grounds in Botany Bay and Port Jackson. There is, however, no correlation between commercial fishing and the introduction of *C. taxifolia* in Port Hacking as this waterway has been closed to commercial fishing for many decades although it is a very popular recreational boating area. It is therefore likely that a combination of vectors has contributed to the arrival and spread of *C. taxifolia* in NSW.

As soon as *C. taxifolia* was discovered in NSW, controls were put in place by NSW Fisheries to limit the risk of translocation to other locations. Measures included the deployment of marker buoys to restrict access by boats and minimise anchoring in beds of *C. taxifolia*, fishing closures to prevent hauling or mesh netting, and restrictions on the aquarium industry necessitating permits to import or sell the species or to keep it in anything other than a fully-contained, private aquarium. An emergency declaration of *C. taxifolia* as noxious marine vegetation was followed in October 2001 by the alga being officially declared a noxious species under the NSW Fisheries Management Act 1994. A public education campaign also was initiated, involving public meetings, information brochures, website information, the erection of warning signs in popular boating areas, and a reporting hotline.

1.3. This report

There are four interrelated parts to this project, each of which is directly linked to more effective management of invasive *C. taxifolia* in NSW. As such, this project was done in conjunction with the development by NSW Fisheries of a statewide control plan for invasive *C. taxifolia* in NSW. This plan is available on the NSW Fisheries website at http://www.fisheries.nsw.gov.au/thr/species/fn-caulerpa.htm

Chapter 2 describes the distribution of *C. taxifolia* in NSW. It is important to accurately document the spatial extent of any translocation to new localities and the spread of the alga within already infested waterways. Techniques were developed, therefore, to obtain quantitative estimates of the location and coverage of all *C. taxifolia* in NSW waterways. Mapping has been done on several occasions since 2002 to provide a time series of the alga's increases and decreases in extent at all known sites. These data have aided the process of prioritising sites for control work and of evaluating the success of any eradication trials.

Control of *C. taxifolia* in NSW will ultimately depend on a sound scientific understanding of the ecology of invasive *C. taxifolia*, including its life history characteristics, growth potential, mechanisms of dispersal and susceptibility to marine herbivores. Preliminary investigations of these ecological parameters were done at the University of Wollongong and are described in Chapter 3 and Davis *et al*. (ms in review). Complementary research, funded by the Australian Research Council, is ongoing at the University of Wollongong and will be reported elsewhere (eg Wright, ms in review).

Chapter 4 describes an assessment, using field and laboratory experiments carried out by researchers at the University of Wollongong, of boating and other human vectors that may contribute significantly to the generation of fragments of *C. taxifolia* and the transportation of those

fragments to other localities. Results from much of this work have previously been reported in West 2003.

The main focus of the work done during this project was the development and trial of environmentally benign ways of removing *C. taxifolia* from NSW waterways. Such 'eradication' techniques, in combination with other management controls, might eventually lead to the elimination of this invasive alga from whole sites or regions. These 'eradication' trials are described and evaluated in Chapter 5.