2. MAPPING THE SPREAD OF *CAULERPA TAXIFOLIA* IN NSW

Macrophytes such as mangroves, seagrasses and saltmarshes are a conspicuous biological feature of many estuaries, harbours and sheltered coastal embayments. They are widely recognised as serving a number of important functions including sediment stabilisation and the provision of vital habitats for many marine invertebrates and coastal fishes. Quantifying the extent of these estuarine macrophytes is often undertaken to assess medium to long-term changes in their distribution and abundance, and measures such as the amount of seagrass often provide key performance indicators of estuarine health in 'State of the Environment' reports and other similar documents (Ward *et al*. 1998). Mapping of these macrophytes is typically done by remote sensing, and the technique most often used involves aerial photographs which are converted into images by scanning, ortho-rectifying and using image enhancement to optimise the features of interest (Walford & Williams 1998, Williams *et al*. 2003). Images are then mapped by onscreen digitising via a Geographical Information System (GIS).

Field mapping of *C. taxifolia* was undertaken to follow the change in size of known infestations and to locate any new infestations. Because recent aerial photographs of the estuaries under consideration were not available at the start of this project, a more direct approach was needed. Further, aerial photographic images do not give reliable resolution of underwater features deeper than approximately 1-2 m (G. West, pers. comm.), and *C. taxifolia* often occurs in water deeper than 2m. Even for *C. taxifolia* in shallow water, its spatial extent was likely to change much faster than for seagrasses, necessitating a system that could provide maps on a shorter time frame than would be possible using aerial photographs.

2.1. Field survey methods for *Caulerpa taxifolia*

The mapping protocol that we developed was designed as a rapid assessment technique and was not meant to be a comprehensive survey. It was restricted to NSW estuaries that were known to contain *C. taxifolia*. Further, because most of these estuaries were very large, it was not feasible to survey them in their entirety as it would have taken many months to do that, reducing the effectiveness of the rapid assessment approach. Only Narrawallee Inlet, the smallest estuary infested by *C. taxifolia*, was thoroughly searched each time a mapping survey was done there. For the other 7 estuaries, a field survey technique was developed which relied on the known or expected status of infestation. The technique was adaptive in that it was based on prior knowledge and risk assessment. Sampling effort could therefore be adjusted according to results from previous surveys. Prior to starting a particular survey, sections of the infested waterways to be mapped were classified according to three risk categories:

1. areas where *C. taxifolia* was known, had been reported, or had previously occurred
2. areas that were considered susceptible to invasion
3. areas not likely to be affected

For category 1, the assessment was based on reports from field researchers or members of the general public. All reports of new infestations were usually investigated within 2-4 weeks of the report being made. Spot investigations involved divers thoroughly searching in the vicinity of the report. If the presence of *C. taxifolia* was confirmed, that site was accorded a risk category of 1 and added to the schedule for the next mapping survey of that waterway.

For category 2, the assessment was based on knowledge acquired by field researchers (either NSW Fisheries or University of Wollongong) during other parts of the research program (see Chapters 3-5). Sites were considered susceptible if they were in shallow water (<6 m depth), and/or had sparse seagrass (especially if these bordered on dense seagrass), and/or were along sandy or mud shorelines with a gentle slope, and/or were in areas with boat moorings or common anchoring sites. The most susceptible areas were those in close proximity to existing *C. taxifolia* beds and that lay in the direction of the prevailing wind or current.

Category 3 included rocky foreshore that steeply dropped into water greater than 6 m depth, places with strong currents and anywhere deeper than 10 m. The areas identified as not likely to become affected were generally not included in surveys. However, if an area with these characteristics was adjacent to a known infestation (i.e. within approximately 500 m) it would be searched if time permitted.

Field surveys were done from a small boat equipped with a specially designed, habitat mapping system (Plate 2) that was based on a similar system designed to validate habitat maps of estuarine macrophytes and in-stream riverine features (G. West, pers. comm.). The system had two position-locating instruments: a Magellan Meridian handheld global positioning system (GPS) and a Trimble GPS Pathfinder Pro XR with differential global positioning system (DGPS) capability. The Trimble GPS has a positional accuracy of ±1 m when using a DGPS signal (provided free by the Australian Maritime Safety Authority). The Magellan system is accurate to ±5 m. Both GPS units output NMEA (National Marine Electronics Association) data that were logged to an on-board laptop computer that recorded latitude and longitude. The mapping system also included a Garmin Fishfinder 240 operating frequency 200kHz and temperature and speed sensors. The sounder also outputs NMEA data directly to the laptop.

Plate 2. The on board mapping system developed to document the spatial extent of *C. taxifolia* infestations in NSW waterways.

The system logged data at two-second intervals to a text file that had been set up with fields for all the measured variables along with a field for 'habitat category'. The operator on the boat could annotate this field with habitat information, one row at a time for every logged point, using predetermined key codes on the laptop. The way these habitat data were collected depended on water clarity and depth. In clear, shallow water, observations from the boat were adequate to estimate the extent of small infestations of *C. taxifolia* and its density. In deeper, more turbid water or for large infestations, SCUBA divers or underwater video was used. The software program 'ARCPAD' locates the boat's position and provides a current display of that position. When doing repeat surveys of an area, the previous map was loaded into the laptop to help locate previously affected areas. Survey methods for each of the three risk categories are detailed below.

2.1.1. Areas already affected by C. taxifolia

If *C. taxifolia* occurred as a small bed (< 10 m in all directions), a single GPS point was taken approximately corresponding to the centre of the bed, the size of the bed was estimated by eye and the density of *C. taxifolia* in the area noted. Density of the bed was scored as either dense (> 50% cover) or sparse (<50% cover) and the presence of other vegetation (seagrass or other algae) or other relevant features were noted. For medium sized beds (10-20 m in any direction), a diver swam around the margin of the bed and dropped weighted floats. GPS points were recorded by the mobile mapping unit while the boat followed the marker floats. If *C. taxifolia* was very extensive (> 20 m in any direction), an underwater video camera was towed through the area in a tight zig-zag pattern parallel to the shoreline. An observer in the boat noted the relevant data as seen on the video and relayed them to the operator of the mapping system. Divers were still often used in this latter situation to double-check video interpretations and to swim past the mapped boundaries to ensure that they truly represented the limit of the *C. taxifolia.*

2.1.2. Areas likely to be affected by C. taxifolia

An underwater camera was towed through the area, generally at depths of 2 m and then 4 m in a tight zig-zag pattern parallel to the shoreline. An observer watched from the boat and noted what was being seen on the video screen. Alternatively a diver was towed behind the boat instead of the camera and gave rope signals for presence and density of *C. taxifolia.* If the alga was found, the boat was stopped and a diver verified its presence. Relevant data were recorded as described above.

2.1.3. Areas considered unlikely to be affected by C. taxifolia

No surveys were undertaken unless adjacent to already affected areas. If time permitted, wide zig-zag searches were made with the towed video camera or by SCUBA divers.

2.2. Creating final maps

Once back in the office, the dataset saved on the laptop was downloaded to the NSW Fisheries server at the Port Stephens Fisheries Centre. The data set was then checked for extraneous data, cleaned if necessary and converted to a point coverage using ESRI ARCMAP Version 8.3. A polygon coverage of *C. taxifolia* boundaries was generated using the point data, and overlaid with depth contours (from a NSW Waterways data layer) and coverage of seagrasses or other relevant biological data (i.e. pre-existing NSW Fisheries layers).

2.3. Sites with *C. taxifolia*

Descriptions of the 8 NSW estuaries that were affected by *C. taxifolia* during this study are presented below (in order from north to south) and summarized in Table 2.1. The alga was found in April 2004 in a ninth estuary, St Georges Basin (see Figure 1.1), where it covered approximately 7.5 hectares.

2.3.1. Lake Macquarie

C. taxifolia was first discovered in Lake Macquarie at Crangon Bay in April 2001. It was removed from that site soon after by hand-picking (see Chapter 5) and has not been found there since. Subsequently, it was found on the northern and eastern shores of Pulbah Island, the southern shore of the Wangi Wangi peninsula, at Pearl Beach and at Mannering Park. At the time of the last mapping exercise, January 2004, it was recorded in living beds only at Mannering Park. However, there have been recent public reports and positive identification of fragments of *C. taxifolia* occurring on beaches along Wangi Wangi, which suggests that it may still be patchily distributed along the peninsula.

Mannering Park is located in the southwestern end of Lake Macquarie and has a northeasterly aspect, making it exposed to the predominant summer winds. All of the *C. taxifolia* occurs patchily in water less than 1 m deep and amongst dense *Z. capricornii*. The substratum consists of fine estuarine mud mixed with sand and is susceptible to suspension during episodes of strong winds and associated choppy conditions.

The Wangi Wangi peninsula is approximately 3km long and has a southwesterly aspect, making it exposed to the predominant southerly winds experienced during winter. Historically, *C. taxifolia* has occurred in several dense beds along this peninsula in depths up to 7 m. Most of these beds were well defined, occupying areas of previously bare sediment in deeper water than *Z. capricornii* usually occurs. There were occasionally small patches occurring amongst *Z. capricornii* in water less than 1 m deep, but only in summer.

2.3.2. Pittwater

C. taxifolia is confirmed in two locations in Pittwater (southern arm of Broken Bay). A small, sparse bed, first discovered in June 2001, is patchily distributed in mud in 1-4 m of water in Careel Bay, adjacent to the marina (Plate 3). A band of *Z. capricornii* occupies the shallows, with the majority of the *C. taxifolia* occurring immediately offshore of this band. There are small patches of *Posidonia australis* adjacent to the infestation, with significant beds of *P. australis* located approximately 200m to the north. The deep edge of the *C. taxifolia* is growing under permanent boat moorings. Careel bay has a northwest aspect making it a sheltered area for most of the year.

The second infestation was found and mapped in March 2004 in clean sand to the west of the Barrenjoey peninsula. A few small patches were also located along the eastern shore between Palm Beach and Careel Bay. In these 'new' areas, *C. taxifolia* typically occurs in the sandy patches between beds of *P. australis*, *Z. capricornii* and *Halophila ovalis*. Most *C. taxifolia* occurs in 1-4 m of water, although some attached plants were found as deep as 8 m. Due to its proximity to the heads of Broken Bay, the area is subject to tidal currents and is exposed to northerly weather.

2.3.3. Port Jackson

C. taxifolia was first discovered here in March 2003 and has been confirmed growing in three areas since then. Very small patches (<2 m diam.) or individual plants have been found in 1-3 m of water at Clontarf Marina, Clontarf Beach (500 m SE of marina) and along the beach immediately south of Parriwi Head (750 m SW of marina). In most of these areas, *C. taxifolia* is growing on clean sand, occasionally amongst sparse *Z. capricornii* and *H. ovalis*.

In the Manly area, the most significant infestation is at Little Manly Cove, where there is a large area of sparse, scattered *C. taxifolia* growing amongst sparse *Z. capricornii* and *H. ovalis*. The area has a southwesterly aspect exposing it to strong winter southerlies. Some individual plants have been discovered off Quarantine Beach (immediately inside Cannae Point). Small-scattered patches have also been found at Forty Baskets Beach (Western Manly Cove). The depth range of infestations is 2-7 m, mostly beneath permanent boat moorings and on clean sand.

In Chowder Bay (Clifton Gardens) sparse *C. taxifolia* grows on clean marine sand in 1-7 m of water amongst sparse *Z. capricornii*, *P. australis* and *H. ovalis*. There are small, dense patches growing adjacent to rocky reef in the northern corner of the bay. Chowder Bay faces southeast, making it exposed to most weather patterns.

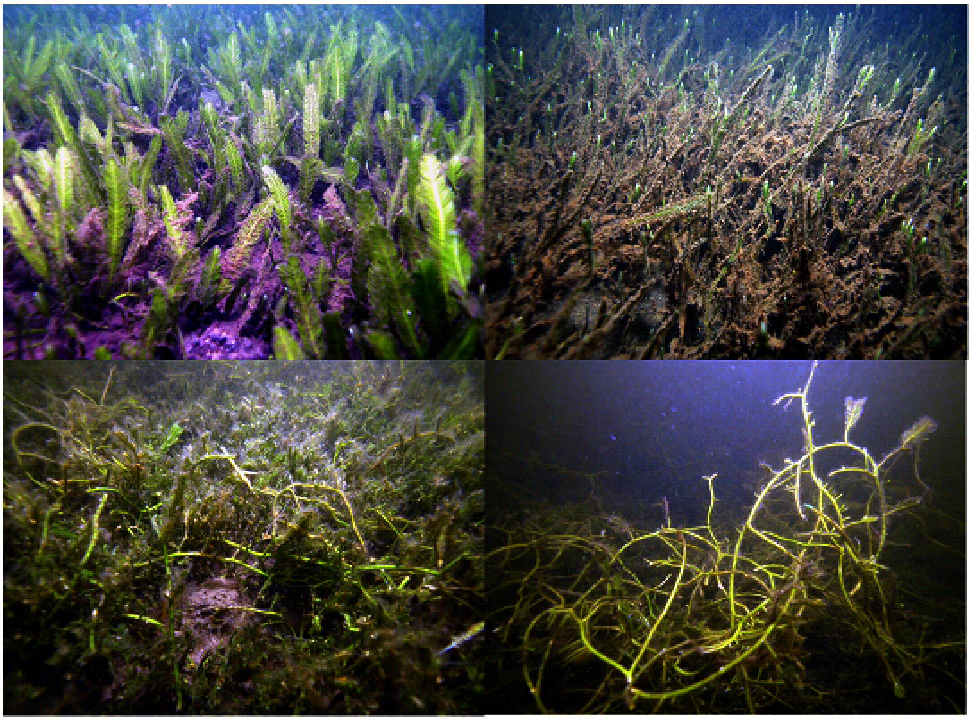

Plate 3. Examples of *C. taxifolia* growing in situ in NSW estuaries. Top left: Botany Bay, bottom left: Port Hacking, top right: Burrill Lake shallow, bottom right: Burrill Lake deep.

2.3.4. Botany Bay

The first (December 2001) and most significant infestation in Botany Bay occurs in Quibray Bay, where there is a large area of dense *C. taxifolia* (Plate 3) growing in fine mud in 0.5-3 m of water adjacent to substantial beds of *P. australis* and scattered *Z. capricornii* and *H. ovalis.*

A large area along the southern shores of Botany Bay is affected by sparse *C. taxifolia* growing in 1-2 m water depth amongst *Z. capricornii, P. australis* and *H. ovalis* on clean sand. Other areas in Botany Bay affected by sparse *C. taxifolia* with similar characteristics are Lady Robinson's Beach (easterly aspect, very exposed) and an area between the third runway and Port Botany (southerly aspect).

2.3.5. Port Hacking

C. taxifolia was first found at this locality in early 2000 at Fishermans Bay near Maianbar. However, the dense bed growing adjacent to extensive patches of the seagrass *Posidonia australis* disappeared following very heavy rainfall in the winter of 2003. It has not been encountered at this site since then. Currently, the worst affected area is Gunnamatta Bay, which has an extensive, dense bed of *C. taxifolia* in 1-4 m water depth along the northwestern shore in the end of the bay (Plate 3). An area of sparse *C. taxifolia, P. australis* and *Z. capricornii* surrounds the dense bed.

The bay is well protected and the substratum is mostly fine mud. The more exposed entrance to Gunnamatta bay can have an extensive area of sparse *C. taxifolia* growing on a clean marine sand bottom, but its occurrence here is very intermittent.

There are several other areas with beds of sparse *C. taxifolia* with similar characteristics to the entrance of Gunnamatta Bay: Simpson's Bay (directly opposite Gunnamatta Bay), which has mostly *Z. capricornii* as the associated seagrass; Burraneer Bay which has both *P. australis* and *Z. capricornii* and Jibbon Beach that has predominantly *P. australis*. Small, intermittent patches of *C. taxifolia* have been found in the western part of Port Hacking around Gogerleys Point. The most exposed location is Jibbon Beach, which is open to northerly winds, and swells which are common during the summer months. It is also adjacent to the open ocean making it more exposed to oceanic conditions than the other locations.

2.3.6. Lake Conjola

First discovered on the southern shores of Lake Conjola in April 2000, *C. taxifolia* has now spread to cover almost 28% of the shoreline of this lake and Berringer Lake (Table 2.1). At the time of initial discovery, there was estimated to be almost 100 hectares infested by *C. taxifolia* (Table 2.2). The alga grows on substrata ranging from fine mud to clean sand in 1-10 m water depth. With the exception of some scattered *Z. capricornii* and *H. ovalis*, there is little associated seagrass at present, although both seagrasses were formerly much more abundant (Meehan 2001). *C. taxifolia* is now the predominant aquatic plant in the system.

2.3.7. Narrawallee Inlet

The characteristics of Narrawallee Inlet make it unique compared to other estuaries affected by *C. taxifolia*. It is a small estuarine creek entering the ocean through a narrow mouth guarded by a shallow sand bar. The sandy channel is only approximately 150 m wide at its widest point and experiences strong tidal currents. The banks of the channel have dense beds of *Z. capricornii*, which decrease in density with water depth. *H. ovalis* co-occurs in these areas of lower density *Z. capricornii*. The central region of the channel is largely bare sand but often has large mats of entangled brown algae (*Ecklonia radiata* and *Sargassum* sp.), washed in from the ocean and from the rocky reef at the mouth.

C. taxifolia was first found here in April 2001. It is usually patchily distributed in 1-4 m of water amongst the *Z. capricornii* and *H. ovalis* along the banks of the channel. The middle of the channel can have scattered individual plants growing in the sand, but patches of *C. taxifolia* rarely occur here. Fragments of *C. taxifolia* are often found in the entangled mats of brown algae, which move along the bottom with the tide. The most well established beds have been found in a deep hole (4 m) on a bend in the channel, which appears to escape the effects of strong tidal flow and may act as a sink and/or source for fragments.

2.3.8. Burrill Lake

Patches of sparse and dense *C. taxifolia* affect most of the muddy, northern and western shorelines of the main body of Burrill Lake, having spread considerably since its initial discovery in March 2001. The dense patches are usually in deeper water (up to 7 m) where the stolons are often unattached to the substratum (see Plate 3). These patches are located offshore from areas of sparse *C. taxifolia* mixed with *Z. capricornii* and, to a lesser extent, *H. ovalis*. There is also a large area of sparse *C. taxifolia* in 1-5 m depth on the southwestern shore of the southwestern arm of the lake (Plate 3). *Z. capricornii* predominates here in the shallows, with *C. taxifolia* occupying vacant space in the seagrass bed.

Table 2.1. Characteristics of NSW sites affected by *C. taxifolia*. Further data on the locations can be found at http://www.dlwc.nsw.gov.au/care/water/estuaries/Inventory.html

Location	Waterway area (ha)	Depth range (m)	Associated seagrasses	Sediment type	Aspect of beds	% affected by *C. taxifolia*
Lake Macquarie	12000	0.5 – 7	*Z. capricornii* *H. ovalis*	Fine estuarine mud	NE, S	0.002
Pittwater	1730	0.5 – 12	*Z. capricornii* *P. australis* *H. ovalis*	Fine estuarine mud, Clean marine sand	NW, W	2.9
Port Jackson	4970	1 – 7	*Z. capricornii* *H. ovalis*	Clean marine sand	SW, E, S	0.07
Botany Bay	8000	0.5 – 3	*P. australis* *Z. capricornii* *H. ovalis*	Fine estuarine mud Clean marine sand	N, E, S	6.2
Port Hacking	1100	1 – 4	*P. australis* *Z. capricornii* *H. ovalis*	Fine estuarine mud Clean marine sand	N, S	5.0
Lake Conjola	590	1 – 10	*Z. capricornii* *H. ovalis*	Fine estuarine mud Clean marine sand	All aspects	28.0
Narrawallee Inlet	40	1 – 4	*Z. capricornii* *H. ovalis*	Clean marine sand	N	0.5
Burrill Lake	410	1 – 7	*Z. capricornii* *H. ovalis*	Fine estuarine mud	All aspects	6.5

2.4. Temporal changes in the extent of *C. taxifolia*

The mapping system was first trialed in the small Narrawallee Inlet in May 2001. Further refinement and trials were done in 2002 in Narrawallee, Lake Macquarie and Pittwater. Close to complete coverage of all estuaries (for areas with risk categories 1 or 2) was first done in summer 2003 (February and March). Complete surveys were then repeated in winter 2003 (August) and summer 2004 (Table 2.2; Appendix 1).

For large waterways with several large, but widely spread infestations (Botany Bay and Lake Conjola), the estimates obtained (especially the initial ones in summer 2003) are not likely to be very accurate. Several hundred hectares of *C. taxifolia* now grow in these two waterways. For the other mapped estuaries, the estimates presented in Table 2.2 are considered to be reasonably accurate. From summer 2003 to summer 2004, some estuaries experienced dramatic increases of over 200% (Botany Bay and Burrill Lake). The coverage increased by approximately 70% in Port Hacking and by lesser amounts in Port Jackson (30%) and Lake Conjola (6%). The summer coverage also increased in Pittwater, but this was due to the discovery of a large, but previously undocumented, bed at Palm Beach (Table 2.2). Coverage at Careel Bay remained virtually unchanged during this time. At the other two locations, Lake Macquarie and Narrawallee Inlet, the spatial extent of *C. taxifolia* decreased from high values in 2002 and 2003 respectively; for Lake Macquarie the decline was substantial (Table 2.2). These decreases were associated with large scale control operations in these two waterways (see Chapter 5).

Many southern locations showed a decrease in the area covered by *C. taxifolia* between summer and winter (Table 2.2). In Port Hacking this decrease was 50% in 2003 (from 32 to 16.6 ha), in Lake Conjola 30% in 2003 (155 to 111 ha), in Burrill Lake 65% in 2003 (6.3 to 2 ha) and in Narrawallee 48% in 2002 (3.9 to 2 ha). In addition, areas classified as having dense cover of *C. taxifolia* in summer often were classified as having sparse cover in winter. Observations during the surveys confirmed that *C. taxifolia* disappeared completely from many sites over winter, particularly in areas of shallow water.

2.5. Discussion

Regular mapping of infestations in NSW and extensive field observations have supported findings from the Mediterranean that beds of *C. taxifolia* reach their greatest extent at the end of summer and decrease in size during winter (Meinesz *et al*. 1995; Ceccherelli and Cinelli 1999). In most waterways, the shapes and sizes of beds of *C. taxifolia* are very dynamic and sometimes areas of *C. taxifolia* can disappear over relatively short periods of time (weeks – months). The exact causes for such changes are unclear, but they likely involve a variety of factors such as decreased temperature or salinity, increased turbidity or lack of nutrients (Vicente *et al*. 1993). *C. taxifolia* beds may also seemingly disappear because they are smothered by sediments, as happened in Fishermans Bay in Port Hacking and Narrawallee Inlet (Glasby *et al*. ms in review).

Other methods of mapping *C. taxifolia* in NSW could be explored. For example, researchers in the Mediterranean have recently used imagery obtained from a Compact Airborne Spectral Imager (CASI) mounted on board a small aircraft to obtain more precise estimates of the spatial coverage of the alga off the coast of France (Jaubert *et al*. 2003). Interestingly, they concluded that the actual extent of *C. taxifolia* in the areas they mapped was substantially less than had previously been claimed. This highlights the need, irrespective of what remote sensing technique is used (e.g.. aerial photographs or spectral imagery) for comprehensive ground truthing.

Mapping of the spatial extent of beds is only one tool for documenting and understanding the seasonal dynamics and spread of *C. taxifolia* in NSW waterways. Starting in 2004, additional field information will be routinely collected during mapping surveys. Quantitative data on the cover and amount of *C. taxifolia* will be recorded from two sites for each of two habitats in each affected waterway: *C. taxifolia* only and *C. taxifolia* mixed with seagrass. Data will be collected by divers sampling several replicate quadrats (50 x 50 cm) strung with 100 points to sample % cover of *C. taxifolia* and other habitats (e.g. bare, *Posidonia*, *Zostera* or *Halophila*). This will provide more accurate estimates of the density of *C. taxifolia* and seagrasses through time (i.e. rather than the two coarse categories used to date) and the average height of *C. taxifolia* beds. Samples of *C. taxifolia* will also be collected from each quadrat to provide additional information on plant morphology, which differs considerably between locations (Plate 3, see also Chapter 3). Finally, water quality measurements will be taken at each site.

Table 2.2. Mapped coverage (hectares) of dense (> 50% cover) and sparse (< 50% cover) *C. taxifolia* in 8 NSW estuaries, 2001-2004.

Estuary	Date	Dense	Sparse	Total	Comments
Lake Macquarie	Aug 2002	0.21	3.78	3.99	Earliest GPS estimate; prior to salt treatment
	Mar 2003	0.004		0.004	Isolated patches at Wangi & Mannering Park
	Aug 2003	0.01		0.01	Isolated patches only at Mannering Park
	Jan 2004		0.25	0.25	Isolated patches only at Mannering Park
Pittwater	Feb 2002	0.23		0.23	Earliest GPS estimate; C. tax. at Careel Bay
	Oct 2002	0.29		0.29	C. tax. at Careel Bay only
	Aug 2003		0.27	0.27	C. tax. at Careel Bay only
	Mar 2004		48.98	48.98	New infestation at Palm Beach (48.72 ha)
Port Jackson	Aug 2003		2.66	2.66	Earliest GPS estimate; C. tax. in 3 areas
	Mar 2004	0.03	3.46	3.49	
Botany Bay	Feb 2003	23.15	122.62	145.77	Earliest GPS estimate; not all sites surveyed
	Aug 2003	16.11	282.54	298.65	
	Mar 2004	16.93	482.15	499.08	First, complete summer survey
Port Hacking	Feb 2003	3.36	28.55	31.91	Earliest GPS survey of whole estuary
	Aug 2003	0.57	16.01	16.58	
	Mar 2004	6.37	48.73	55.1	
Lake Conjola	2000	63.27	32.87	96.14	Rough estimation from diver survey
	Feb 2003	57.52	98.19	155.71	Compilation of partial maps & diver surveys
	Aug 2003	51.21	60.49	111.70	Earliest GPS survey of whole estuary
	Feb 2004	148.12	17.32	165.44	
Narrawallee Inlet	May 2001		3.94	3.94	Earliest GPS survey
	Sept 2002		2.05	2.05	
	Feb 2003		6.21	6.21	Prior to salt treatment (see chapter 5)
	Aug 2003		0.19	0.19	
	Feb 2004	0.27	4.81	5.08	
Burrill Lake	Feb 2003	0.32	5.99	6.31	Earliest GPS survey
	Aug 2003		1.96	1.96	
	Feb 2004	3.11	23.38	26.49	