Review

The biology of Australian weeds 56. *Hymenachne amplexicaulis* (Rudge) Nees

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Name

Botanical name

The genus *Hymenachne* P.Beauv. was established in 1812, based on *Agrostis monostachya* Poir. (a synonym of *H. amplexicaulis* (Rudge) Nees). Confusion regarding the typification of the genus was resolved by Panigrahi and Dubey (1986). The genus lies within the large, well supported, monophyletic subfamily Panicoideae of the family Poaceae (Grass Phylogeny Working Group 2001). Clayton and Renvoize (1986) placed *Hymenachne* in the subtribe Setarinae. However, recent phylogenetic analyses have shown that these subtribes are not monophyletic and therefore should not be recognized (Kellogg 2002).

The species name is derived from the Latin *amplexus*, meaning surrounding or embracing and *caulis* meaning stem. The species was first characterized by Rudge in 1805 as *Panicum amplexicaule* (Hill 1996). Synonyms include: *A. monostachya*, *Hymenachne myosurus* (Rich.) Nees, *Panicum amplexicaule* var. *deflexa* Doll, *Panicum amplexicaule* Rudge, *Panicum hymenachne* Desv, *Panicum perdensum* Steud., *Hymenachne pseudo-interrupta* (Li 1978) and *Hymenachne myurus* (Howard 1979).

Common names

The name 'Olive' was registered in 1988 for the cultivar of *H. amplexicaulis* released in Australia (Oram 1989). The plant has, however, been widely referred to as simply hymenachne in extension material distributed by Queensland and Federal Government Departments (Csurhes *et al.* 1999, Charleston 2006). This has caused confusion, particularly in the Northern Territory where the native species *H. acutigluma* is common and is also known as hymenachne. For this reason it is recommended that the introduced species should be consistently referred to in the vernacular as Olive hymenachne. In the USA, *H. amplexicaulis* is commonly referred to as West Indian marsh grass or trompetilla (Brambila and Santan 2004, Diaz *et al.* 2009). Common names used in other countries include: canutillo (Columbia); dal (dhal) grass, bamboo grass (India); carrizo chico, cañuela blanca (Bolivia); bamboegrass (Suriname); chingolo (Paraguay), water straw grass (Venezuela) (Tejos 1980) and azuche (South America) (Enriquez-Quiroz *et al*. 2006).

Taxonomy

Hymenachne looks similar to *Sacciolepis* but differs by the culms which are filled with aerenchyma while those of *Sacciolepis* are hollow (Pohl and Lersten 1975). There is some dispute as to the numbers of species within the genus. However, the most recent literature suggests approximately 10 species (Aliscioni *et al.* 2003). All species are aquatic perennial grasses that are found in tropical and subtropical regions. Species are distributed in the Asiatic tropics, the Pacific Islands, and Central and South America (Pohl and Lersten 1975). One species, *Hymenachne acutigluma* auct. non (Steud.) Gilliland, is native to Australia (Bogdan 1977, Calder 1981). There has been some confusion between the invasive *H. amplexicaulis* and native *H. acutigluma* within Australia (White 1932, Blake 1954). Prior to the publication of Webster's (1987) book describing Australian Paniceae, the Australian native *H. acutigluma* was referred to in Australian herbaria as *H. amplexicaulis*. Within the Northern Territory, where *H. acutigluma* is a fairly common grass on the floodplains, there was some confusion between *H. acutigluma* and the introduced *H. amplexicaulis* (J. Clarkson personal observation). That there has been recent confirmation of hybridization between *H. amplexicaulis* and *H. acutigluma* will likely add to this confusion between the two species (Department of Environment and Resource Management unpublished data).

Description

The following description of Olive hymenachne was drawn from Csurhes *et al.* (1999).

Hymenachne amplexicaulis is a robust, stoloniferous, perennial grass commonly 1–2.5 m tall. It grows rooted in the substratum and its stems float out into deep water. The glabrous stems are erect or ascending from a prostrate base and are filled with white pith (aerenchyma). Roots are produced from the lower nodes. Leaf blades are 10–45 cm long and up to 3 cm wide, mostly lanceolate and cordate at the base. They are markedly narrower in the upper half. Ligules are membranous. The panicles are narrow, spike-like, cylindrical, 20–40 cm long, sometimes with two or more long upright branches. Spikelets are lanceolate, upright and 3–5 mm long (Cabrera 1970, Bogdan 1977). Flowering culms are 80–95 cm tall, sparingly branched, with up to four nodes. Primary branches of the panicles have spreading secondary branches, 0.5–2 cm long, and are scabrous on the margins. Pedicels are 0.2–1 mm long with disarticulation at the base of the spikelet. Spikelets are dorsiventrally compressed, linear-lanceolate, 3–4 mm by 0.6–0.8 mm. Lower glumes are 1.5–1.8 mm long, triangular, 3-nerved, hyaline, smooth, glabrous, acute. Upper glumes are 3–4 mm long, linear-lanceolate, 5-nerved, hyaline, glabrous, long acuminate. The lower floret is neuter; lower lemma 3–4 mm by *c.* 1 mm, linear-lanceolate hyaline. Upper floret is hermaphrodite; upper lemma 2.5–3.5 mm long, white, hyaline, smooth, lanceolate, glabrous, acute; upper palea hyaline, smooth, not enclosed at the apex by the lemma (Wildin 1989). The plant employs the C3 photosynthetic pathway and has a chromosome number: $2n = 24$ (Watson and Dallwitz 1992).

Distinguishing characters

Hymenachne amplexicaulis is readily distinguished from the native species, *H. acutigluma*, and also from the other commonly encountered aquatic grasses, para grass (*Urochloa mutica* (Forrrsk.) T.Q.Nguyen) and aleman grass (*Echinochloa polystachya*) (HBK) Hitchcock) by its broad, stem clasping leaf bases (Figure 1). The length of the spikelet further serves to separate *H. amplexicaulis* from *H. acutigluma*. Spikelets in the former are 3–4 mm long compared with 4.5–5 mm long in the latter. The leaf blades of *H. amplexicaulis* are also shorter and broader than those of the native species (Cameron 2003b) (Figure 2).

Figure 1. Inflorescence and distinctive stem clasping leaf base (insert) of *Hymenachne amplexicaulis* (Photo: C. Gardener).

Figure 2. Leaf blades and stem of *Hymenachne acutigluma* (left) and *H. amplexicaulis* (right). Notice the differences in the size of leaf blades and leaf clasping between the two species (Photo: B. Salau).

History

Commonwealth Plant Introduction records show three introductions of *H. amplexicaulis.* The first was acquired from Guyana in 1934 through CSIRO Division of Plant Industry, Canberra as CPI 5820. The fate of this introduction is not known. As no herbarium records of *H. amplexicaulis* have been found prior to 1987, it is possible that the plant was either incorrectly identified as *H. amplexicaulis*, never released from quarantine or died out before it could escape field trial sites. The second introduction (CPI 61149) was received by CSIRO Tropical Crops and Pastures in 1973 (Broué 1973). Wrongly named *Eriochloa imbricata*, the seed was imported from the International Research Institute, Tucupita, Venezuela. There is some doubt as to the source of the original material. It is thought to have been either Haiti or the Dominican Republic (Oram 1989). In 1983 R. Reid of CSIRO Tropical Crops and Pastures, Townsville received vegetative cuttings as CPI 99889 from A. Kretschmer of the Agricultural Research Centre at the University of Florida, Fort Pierce, Florida USA. Once again the fate of this material is unknown.

Initial experimental planting (from the 1983 introduction) occurred on grazing properties in Central Queensland. One of these properties was 'Granite Vale' near St Lawrence, the property of J. and P. Olive (hence the cultivar name 'Olive'). There were numerous other areas where *H. amplexicaulis* was trialled, including properties around the lower Burdekin River catchment (coastal north Queensland). In August 1988, *Hymenachne amplexicaulis* cv. 'Olive' was approved for release by the Queensland Herbage Plants Liaison Committee, which recommended registration on the submission of the Queensland Department of Primary Industries (Wildin 1989).

Figure 3. *Hymenachne amplexicaulis* grown in a ponded pasture situation (Photo: K. Charleston).

The introduction and approval of Olive hymenachne was for use within ponded pastures (Figure 3), which have arisen through the construction of artificial ponds, or the construction of banks for the purpose of capturing or holding water and developing pasture. The construction of ponded pastures prevented seawater incursion (along the coast), collected water runoff during storms, increased the catchment area, and if built on floodplains, could retain flood flows. While ponded pastures existed since the 1930s, in the early 1970s there was a boom in beef prices and crop areas were being converted to pasture. To improve production, ponded pastures became more prevalent. The species used for ponded pastures include both native and introduced plants. Para grass was the most common species used in ponded pastures. The introduction and approval for release of Olive hymenachne allowed deeper water areas of the ponded pasture to be utilized. The release of

Olive hymenachne was actively promoted with the ponded pasture concept via the extension publication 'Ponded pasture systems – capitalizing on available water' by Wildin and Chapman (1987). Graziers throughout northern Australia were made aware of the concept and the species suitable for planting (Wildin 1991).

The Queensland Environmental Protection Agency raised concerns regarding the plant's propensity to invade natural wetlands during the late 1980s when *H. amplexicaulis* showed evidence of establishing outside of planted areas (Csurhes *et al.* 1999). The problem was further highlighted in 1989 in the lower Burdekin area of coastal, north Queensland. Graziers had been planting *H. amplexicaulis* in natural and artificial ponds in the Giru, Clare and lower Burdekin areas, and there was evidence of the plant naturalizing outside of these areas.

In the Northern Territory, *H. amplexicaulis* was also being promoted for more productive pastures in floodplain areas (Cameron 1999). It was planted as a pasture grass in the Northern Territory along the Adelaide, Daly, Finniss and Mary River floodplains, and at Arafura Swamp in northern central Arnhem Land. The species was also used to suppress seedling growth of *Mimosa pigra* (Paynter 2004). At the same time as *H. amplexicaulis* was being promoted as a pasture species, there was literature indicating that it had potential as a major weed in Northern Territory catchments (Rea and Storrs 1999). It has now spread through parts of these catchments, including important conservation areas such as Kakadu National Park. It was first reported in Kakadu in August 2001 at two separate locations, one at Four Mile Hole (Wildman River catchment) and the other at The Rap region (South Alligator Creek) (Kakadu GUN-WOK 2001).

Hymenachne amplexicaulis was listed as a potential weed by Humphries *et al.* (1991). The threat was further highlighted in the 'Probing Ponded Pastures Workshop' in 1991, where the potential for *H. amplexicaulis* to spread to surrounding wetlands was discussed and highlighted in a number of papers (Hopkinson 1991, Clarkson 1991). Hopkinson (1991) noted the need to investigate some management restrictions on ponded pasture species through localized restrictions on sensitive catchments, monitoring escape, and developing management systems that minimize the impact of invasion of native communities. Despite these initial reports and concerns, *H. amplexicaulis* continued to be planted (Clarkson 1995). In 1997, its invasiveness was realized when dozens of infestations were reported in and around sugar cane areas. An extensive aerial survey commissioned by the Invicta Cane Protection and Productivity Board at that time revealed extensive infestations in coastal wetlands in the Giru area and in the Burdekin River Irrigation Area (BRIA). Additional infestations were found at the Burdekin Agricultural College, two farms in the Mulgrave area of the BRIA, the Mulgrave balancing storage dam, irrigation supply channels downstream of the Haughton balancing storage dam, the Selkirk riparian zone and in a lagoon behind Dalbeg in the lower Burdekin area (Schultz 1997). By 2000, the total area of infestation was estimated to be at least 1000 ha (Department of Natural Resources, Mines and Water (DNRMW) 2006).

Distribution

Native

Hymenachne amplexicaulis grows naturally in seasonally flooded lowlands and along river banks throughout tropical and subtropical areas of South and Central America (Bogdan 1977). The Missouri Botanical Garden's 'TROPICOS' data base gives the plant's general distribution as: Argentina, Belize, Bolivia, Brazil, Columbia, Costa Rica, Ecuador, El Salvador, French Guiana, Guatemala, Guyana, Hondoruras, Mexico, Nicaragua, Panama, Peru, Paraguay, Suriname, Uruguay, Venezuela, and the West Indies. This area lies between the northernmost herbarium record of the plant at Tabasco, Mexico (latitude 19°N) and the southernmost record in southern Paraguay (28°S) (approximate latitudes) (Figure 4). Within Venezuela, *H. amplexicaulis* forms extensive stands and dominates at least 20% of the 5 000 000 ha of flooded lowlands (Gonzalez-Jimenez and Escobar 1977).

Introduced – worldwide

The species is a significant weed in Florida, where current records confirm its presence in wetlands and rivers in 14 counties (Diaz *et al.* 2008a). *H. amplexicaulis* is also considered a principal agricultural weed in Suriname, a common weed in Indonesia, and is present as a weed in Trinidad (Holm *et al.* 1979).

Introduced – Australia

Hymenachne amplexicaulis has spread considerably in the last two decades and is now widely distributed within waterways and wetlands across coastal and subcoastal Queensland and the Northern Territory. Small populations extend to northern New South Wales (Figure 5).

Accurate mapping of *H. amplexicaulis* is difficult due to its many small populations (<1 ha) and distribution on private land where it is used for pasture (see section on Legislation). Many landholders are unwilling to have *H. amplexicaulis* populations recorded, given the legislative requirements. Hence the distribution of

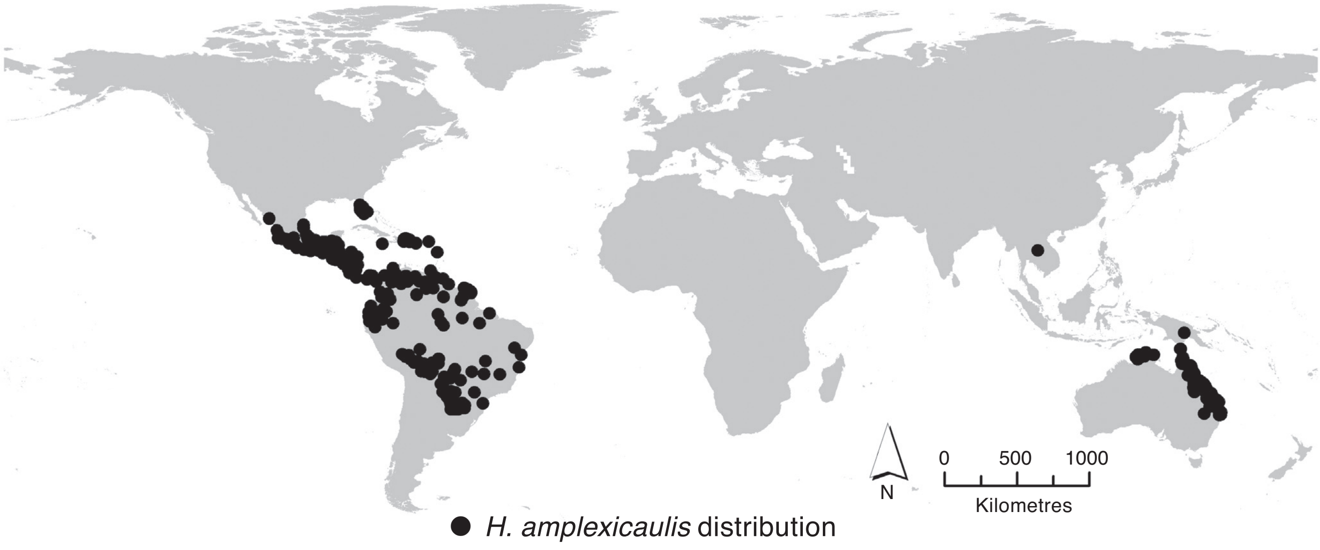

Figure 4. Worldwide distribution of *Hymenachne amplexicaulis* (Missouri Botanical Gardens 2009).

Figure 5. Current distribution of *Hymenachne amplexicaulis* and its abundance mapped in Australia (17 × 17 km grid). Data from state department records and expert opinion. Source: Queensland Department of Primary Industries and Fisheries unpublished data.

H. amplexicaulis is likely to be underestimated. Current estimates indicate approximately 8000 ha infested within Queensland, 3000 ha within the Northern Territory (C. Collins unpublished data) and 55 ha within northern New South Wales. The main infestations of *H. amplexicaulis* are currently located in central (Rockhampton, Fitzroy River) and northern (Ayr-Burdekin catchment, Ingham-Herbert River catchment, Tully-Murray catchment, Barron River catchment) Queensland. Isolated infestations occur in Cape York and southern Queensland. Recent mapping in the Northern Territory has shown *H. amplexicaulis* infestations around the Daly River Catchment (5.9 ha), Finniss River Catchment (1 ha), Darwin/Blackmore River Catchment (1 ha), Adelaide River Catchment (2216 ha), Mary River Catchment (550 ha), Wildman River Catchment (61 ha), South and East Alligator River Catchment (101 ha) and Goyder River Catchment (Arafura Swamp) (151 ha).

Potential distribution within Australia

The predictions made previously by Csurhes *et al.* (1999) appear to support the current distribution of *H. amplexicaulis*. These predictions were based on its distribution in North, Central and South America. Climate analysis, using the CLIMEX computer modelling package (Skarratt *et al.* 1995), suggests that climates experienced in coastal areas of northern Australia are similar to those experienced in the plant's native range.

Thus far, species distribution modelling only incorporates climatic suitability. The distribution of *H. amplexicaulis* is also a function of available habitat (e.g. wetlands/floodplains). Therefore the species has the potential to colonize suitable habitats over much of coastal, northern Australia, including the Kimberley Ranges and the central coastal region of Western Australia, the Top End of the Northern Territory, most of Queensland's coastal and eastern region, and northern New South Wales (Charleston 2006). Within inland regions, suitable conditions for *H. amplexicaulis* could be created on clay soils by irrigation or by artificial or natural banks that trap overland water flow. The plant is not expected to persist on well-drained soils. Potential distribution modelling using non-climatic variables such as soil and wetness index suggest the potential distribution may extend beyond coastal northern Australia (L. Wearne unpublished data).

Given that the species can invade into deeper water habitats than comparable species such as para grass, and that para grass is estimated to cover about 140 000 ha in Queensland and the Northern Territory (Walker and Weston 1990, Low 1997), the potential distribution of *H. amplexicaulis* may be far greater than the latter species.

Habitat

Vegetation communities – native and introduced range

Hymenachne amplexicaulis is a transforming species, forming large homogenous stands in tropical floodplain areas in both its native and introduced ranges (Gonzalez-Jimenez and Escobar 1977, Costa 2005, Enriquez-Quiroz *et al.* 2006). In its native range *H. amplexicaulis* is associated with water-logged basins, tall grasslands, forest edges and marsh ponds. However, is less common and often absent in grassland and forest edges. *H. amplexicaulis* can also be a co-dominant with *Leersia hexandra* (Swartz) (Tamayo 1981). In Australia, *H. amplexicaulis* can now be found growing in water storage facilities, irrigation channels, roadside ditches, natural lagoons and cane paddocks (Csurhes *et al.* 1999). The species has been able to establish and spread in floodplains/wetlands outside of tropical areas (e.g. northern NSW and southern Queensland. Growth of *H. amplexicaulis* has been found to be less prolific in situations where tall, natural vegetation provides shade over the banks of lowland streams (L. Wearne unpublished data). The species is associated with other pasture species, such as para grass, where vegetation is often disturbed through seasonal flooding and/or cattle grazing (L. Wearne unpublished data). In these circumstances, it tends to form the largest stands on open floodplain areas, where there is little competition from other species. It will also establish along streams and rivers, although populations will often be more dispersed, forming smaller isolated populations. Where both *H. amplexicaulis* and para grass grow together, *H. amplexicaulis* will dominate in wetter, deeper areas of a floodplain, or stream system and para grass will dominate in drier areas. Both species will co-dominate in areas between these two zones (L. Wearne unpublished data). *H. amplexicaulis* can also be found growing alongside native hymenachne stands.

Depth and duration of inundation are important determinants for *H. amplexicaulis* establishment and spread. Currently there is conflicting information regarding the length and time *H. amplexicaulis* can survive exposure to flooding. Available literature indicates *H. amplexicaulis* is able to tolerate prolonged inundation periods. In Australia, it has persisted in seasonally flooded areas (1–1.2 m deep) for over 20 years with no reported decline. Where flooding is greater than 1.2 m, *H. amplexicaulis* was found to grow poorly (Gonzalez-Jimenez and Escobar 1977, Lyons 1991). In Venezuela, similar water depths were documented. There, *H. amplexicaulis* was able to tolerate inundation for 297 consecutive days in water 1.2 m deep (Tejos 1980). In other areas where *H. amplexicaulis* is found, water depth and duration varies. In Florida, *H. amplexicaulis* can be found in freshwater ponds characterized by standing water (up to 3 m) for at least nine months (Kalmbacher *et al.* 1998) and can grow in protected areas up to 4 m deep, which become shallower during the dry season (Costa 2005).

In Australia, *H. amplexicaulis* has been observed growing in deeper water (>4 m). However, this occurs through floating rafts (common after floods) or growth on dense floating mats of water hyacinth (DNRMW 2006). *H. amplexicaulis* does appear limited by well-drained sites that dry out completely during the dry season. In fact, Medina and Motta (1990) considered *H. amplexicaulis* to be the least drought tolerant of several grass species from seasonally flooded savannas in south-west Venezuela. As such, *H. amplexicaulis* prefers seasonally flooded land in areas where its roots have access to wet or damp soil during the dry season (Chacón-Moreno *et al.* 2004).

There is very little information available on the influence of soil type or nutrients on *H. amplexicaulis* survival and abundance. However, the most vigorous stands of *H. amplexicaulis* in Australia exist in lowland areas where nutrients and sediments have been deposited from upstream agriculture (Csurhes *et al.* 1999). Nutrient studies indicate the species responds positively to increased soil nutrients, increasing both stem number and biomass (L. Wearne unpublished data). Habitat suitability studies indicate alluvial soil, which is high in clay, is correlated with the presence of *H. amplexicaulis* in the Herbert River Catchment (L. Wearne unpublished data). In other studies it was determined by visual observation that *H. amplexicaulis* occurs predominantly on Chobee muck soils (very deep, very poorly drained soils) (Hill 1996). Failure of *H. amplexicaulis* to establish in research trials in Florida has been attributed to soil type (Kalmbacher *et al.* 1998); however, the influence of soil type was not investigated and it is possible that failure was due to an unfavourable soil moisture regime rather than soil type *per se*. Observations also indicate that the plant does not persist in estuarine or brackish wetlands and its abundance declines sharply as the frequency of saltwater intrusion increases. In vegetation surveys *H. amplexicaulis* was never found in lagoons or areas with significant salt concentrations during part or all of the year (Meerman *et al.* 2006).

Growth and development

Growth

In Kibbler's (1997) flooding experiments on *H. amplexicaulis*, detailed descriptions were made on the species' growth response to flooding. The following description was drawn from Kibbler (1997): 'Following flooding *H. amplexicaulis* commenced rapid stem elongation within three days. Within one week, stems reorientated from a prostrate to an erect position and developed adventitious roots from submerged nodes close to the soil surface. At the same time, leaf sheaths in the upper part of the stem expanded. After three days *H. amplexicaulis* began developing adventitious roots from the expanded submerged nodes of the elongating stem'. Additional findings included the cessation of internodal growth and the production of adventitious roots. The stem rapidly elongates, thus maintaining the leaves above the water, allowing emergent leaves to function at full photosynthetic capacity (Kibbler and Bahnisch 1999b, Diaz *et al.* 2008b, Sellers *et al.* 2008).

Once leaves are submerged, they begin to senesce and decompose within a few days. At the end of the wet season when the water level drops, the plants fall to the ground. A thick layer of material, composed of the remains of dead and green leaves and stems, covers the area. In a few days, young buds arise from the nodes and begin to grow. At the beginning of the next wet season, the old stems and some of the young plants die and form the bulk of the litter material to be decomposed during the following year. The surviving plants form the new pasture (Bulla *et al.* 1990).

The overall growth of *H. amplexicaulis* decreases as light intensity decreases. However, the species is able to maintain leaf area even under low light conditions (Kibbler 1997). Growth also responds positively to flood period, with biomass production ranging from 5911 to 18 162 t $ha^{-1} y^{-1}$ during the flood period and from 5553 to 7836 t $ha^{-1} y^{-1}$ during the dry season (Tejos 1978b)

Morphology

Hymenachne amplexicaulis plants have short leaves and the youngest leaves are situated at the top of the canopy where light availability is high (Niels *et al.* 1998). When flooded, the morphology of the plant adapts to the conditions: the stem elongates rapidly and becomes erect and the number of tillers decrease. The stem becomes less dense, and flooded plants collapse when removed from water, in comparison to non-flooded plants. Leaf growth is increased within flooded plants at the expense of the roots, presumably maintaining effective photosynthetic leaf area (Kibbler and Bahnisch 1999a).

Physiology

Hymenachne amplexicaulis shows a number of physiological adaptations to cope with extensive periods of flooding. Anatomical adaptations include aerenchyma in all organs (flooded and non-flooded plants), which would provide buoyancy as well as aiding the circulation of gases. In addition, there are large cavities in the stem, the presence of large bulliform cells to enable leaves to roll and unroll, and a well developed epidermis with supersized and lignified cells in the roots, which prevent collapse and exclude toxins that may accumulate under anaerobic soil conditions. Flooded stems require less support than non-flooded stems, hence the plant reallocates resources away from the stem through production of a narrower cuticle and thinner parenchyma cell walls in the elongated nodes of the new growth. These resources can then be used for new leaf growth and stem elongation. Moreover, when flooded, the previously exposed, but submerged nodes produce adventitious roots. It is thought that resources from submerged senescing leaves are reallocated to the new leaves higher up. That nitrate concentrations are strongly non-uniform in the leaves supports this theory (Niels *et al.* 1998).

Reproduction

Flowering and seeding

Hymenachne amplexicaulis reproduces from seed and stolons. It can grow vegetatively from a stem containing a single node (Sellers *et al.* 2008). Growth of plants can occur throughout the year, provided there is adequate soil moisture. However, a major flush of biomass occurs during the wet season (January – April) in the tropics, presumably as a result of increased humidity and flooding (L. Wearne unpublished data).

Flowering is primarily triggered by short days (Diaz *et al.* 2009). However, other factors such as soil moisture and temperature are thought to play a role. In Australia, peak flowering of *H. amplexicaulis* populations occurs for 1–2 weeks during April and May (late autumn) (Wearne *et al.* 2008). Populations can continue to produce flowers beyond this period, although at a much reduced rate. *H. amplexicaulis* has been observed flowering multiple times during a single year in northern Queensland, with plant stems often able to produce two flowering spikes in the same flowering period (L. Wearne personal observation 2007). Flowering is delayed by at least a month in southern Queensland and northern New South Wales (L. Wearne unpublished data). In the Tully-Murray catchment, land managers have observed two distinct flowering periods, mid-April to May (peak period) and December (not as prolific) (D. Sydes personal communication). Plants will continue to produce flowers throughout the year, although at a much reduced rate, if soil moisture is available (L. Wearne unpublished data). In Florida, flowering and seed set also occur in autumn, which coincides with the end of the wet season (Hill 1996). An extended flowering period, from September to March, has been observed in the West Indies (Adams 1972) and Bolivia where flowering occurs from October – April (Killeen 1990).

Recent pot experiments in Australia document a flowering period from April to August, with a single flower head producing in excess of 4000 seeds. On average 26 ± 21 flower heads m^{-2} y^{-1} are produced. The time from germination to plant maturity was 88 ± 5 days (Vitelli *et al.* unpublished data). Seeding of *H. amplexicaulis* populations followed a similar trend to flowering events. Peak seeding of northern Australian populations in Ingham, Ayr and Darwin occurred during late May into early June. Populations continued to seed beyond June, although at a much reduced rate. Grazing had substantial impacts on some populations at Julatten, Ayr and Darwin, limiting both flowering and seeding of *H. amplexicaulis* (Wearne *et al.* 2008).

Germination

Fresh seed collected from *H. amplexicaulis* and seed stored for two months had 11–50% empty seeds. Viability of filled seeds (caryopses that contained an embryo) stored for two months was over 96%. Seed viability of four month old seeds decreased to 78% (Campbell *et al.* 2009).

In an experiment involving a range of constant temperatures, non-dormant, freshly collected *H. amplexicaulis* seeds germinated between 21 and 35.5°C. Optimal conditions for germination were between 34–35.5°C, with approximately 50% and 90% of seeds germinating respectively. No seeds germinated above 35.5°C (Figure 6).

Germination is generally restricted to the dry season when flood water recedes from the flood plains (L. Wearne unpublished data). Mass germination occurs on the exposed soil of flood plains. Germination can also occur in areas where there is substantial inundation. However, this is on top of decomposing *H. amplexicaulis* biomass, rather than the exposed soil surface (L. Wearne unpublished data).

Dormancy

Germination trials of *H. amplexicaulis* indicate that seed dormancy is complex, being influenced by combinations of light, temperature and nitrate. Maximum germination occurs under a combination of alternating temperature (12 hour cycles of 30/20°C) and the presence of light (either constant or intermittent) and the addition of KNO_3 (Campbell *et al.* 2009). Germination trials in Venezuela documented a similar positive response to KNO_3. In this study, seeds also responded to gibberellic acid (600 ppm), although the response of KNO_3 was significantly greater (Rene and Oropeza 1985).

The requirement for diurnal temperature fluctuations increases the opportunity for enforced dormancy, therefore increasing the opportunity for freshly fallen seed to be incorporated into the soil seed bank rather than germinating straight away (Williams 1983). Enforced dormancy could occur where there is water on top of the soil which may cause anaerobic conditions and/or prevent high or fluctuating temperatures necessary for germination. That peak seed drop of *H. amplexicaulis* occurs when the plant is still inundated suggests that this may be a likely mechanism to enable a proportion of seeds to be incorporated into the soil seed bank. A failure to germinate in the absence of light is common to species of disturbed habitats (Grime *et al.* 1981), such as riparian and floodplain habitats where *H. amplexicaulis* establishes.

Fresh seeds also responded to nitrate, which is indicative of floodplain habitats, where there is substantial nutrient run-off. That fresh and two month old seeds needed a combination of three environmental factors for maximum germination suggests that germination occurs when conditions are most favourable. In older (four month) seeds which have lower viability, KNO_3 is not required, hence germination can occur under suboptimal conditions (Campbell *et al.* 2009).

From a management perspective, the dormancy mechanisms of *H. amplexicaulis* suggest that removal of above ground plant material through burning or other means may expose the soil to greater temperature fluctuations and higher light intensities and therefore stimulate emergence from the seed bank (Campbell *et al.* 2009).

Seed bank longevity

A seed burial trial conducted over eight years (1999–2007) compared the effects of time and depth of burial on *H. amplexicaulis* seed bank longevity. Seeds were also stored in the laboratory for comparison. Results indicate that *H. amplexicaulis* seed is persistent, with up to 21% of seed on the surface (0–2 cm) still viable after six years, and 8–24% viable after eight years (Figure 7). Where seeds were laboratory-stored, viability was found to be only 10% after 16 months storage at room temperature (20–30°C) and decreased to 0% after three years (Figure 7).

Dispersal

Hymenachne amplexicaulis is spread through both stolons and seed. Human-mediated dispersal of runners provided most of the early point sources of spread (J. Clarkson personal observation). Following promotion by the Queensland Department of Primary Industries in the late 1980s, runners of *H. amplexicaulis* were transported and planted widely in ponded pasture systems on grazing land throughout coastal and sub-coastal north and

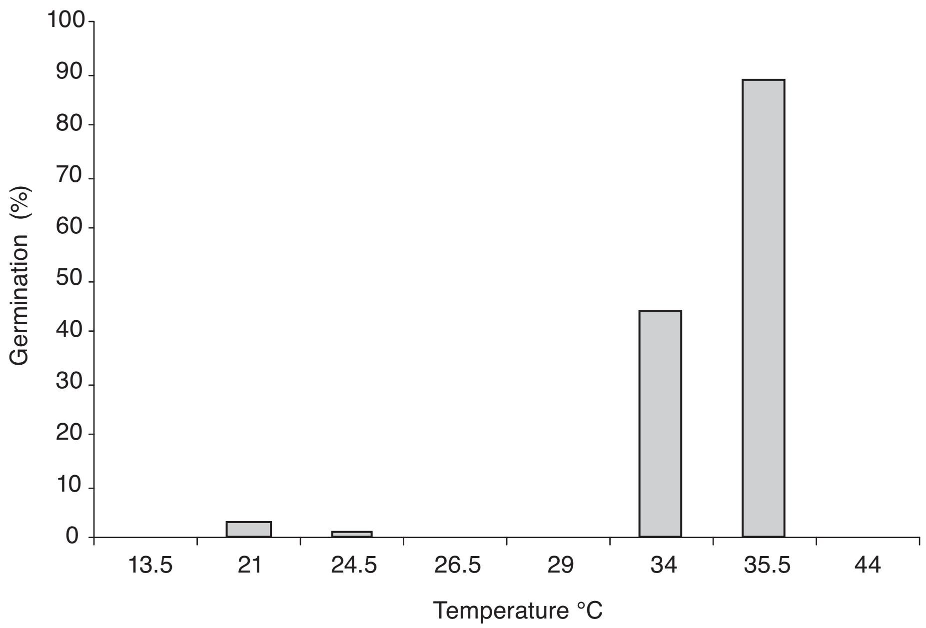

Figure 6. Germination of *Hymenachne amplexicaulis* seeds in relation to temperature (S. Setter unpublished data).

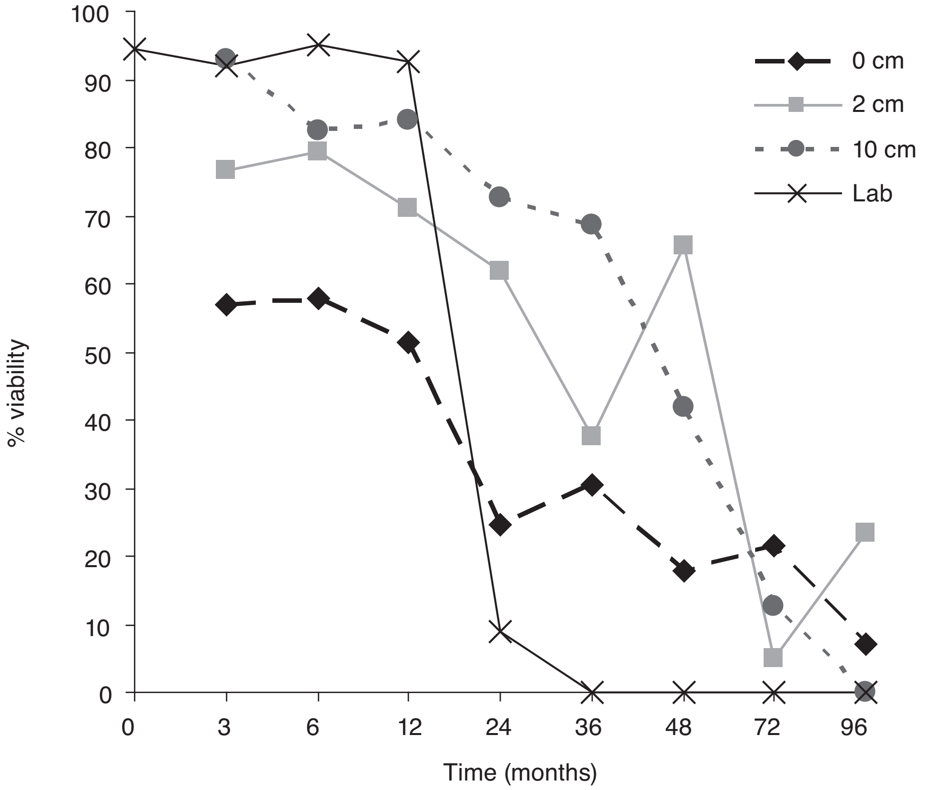

Figure 7. Viability of *Hymenachne amplexicaulis* seeds buried at three different depths across time (S. Setter unpublished data).

central Queensland. Seed was produced in North Queensland (Mareeba-Dimbulah area) but this was rarely used for pasture establishment. However, in the Northern Territory, establishment via seed was the only mechanism used for *H. amplexicaulis* establishment (J. Clarkson personal observation). Once plants are established, seed provides the mechanism for rapid spread within and between wetland areas, and is probably much more important than vegetative spread of *H. amplexicaulis* over long distances. Stolons can also spread over some distance, usually following physical damage from floodwaters or when pondage banks fail.

Bird-mediated spread is also suspected, although there is no hard evidence that this happens or to what extent it might happen. In Kakadu National Park, Northern Territory, new occurrences are thought to be the result of waterbirds moving in from nearby catchments such as the Mary River, where *H. amplexicaulis* is prolific (Low 1997, Walden and Nou 2008). Cattle- and human-mediated dispersal (via machinery) are also mechanisms likely to be involved in the movement of *H. amplexicaulis* stolons and seed. Currently there are limited data on *H. amplexicaulis* dispersal mechanisms.

Importance

Hymenachne amplexicaulis is a controversial plant species as it is considered both beneficial and weedy. The available Australian and overseas evidence suggests that it has the potential to transform large areas of floodplain, wetlands, water storage facilities and irrigation channels into monocultures, with major economic and environmental consequences (Clarkson 1991, Humphries *et al.* 1991, Csurhes and Edwards 1998).

Detrimental

Environmental impacts. In Australia, *H. amplexicaulis* tends to invade and dominate (with 93% cover and 100% biomass) waters where emergent and floating-attached/submergent native vegetation occurs. By comparison, in uninvaded native plant communities, cover and biomass is shared by multiple species. As a result of the dominance of *H. amplexicaulis*, floating-attached/submergent native aquatic plants are displaced. The resulting emergent *H. amplexicaulis* grass beds harbour fewer plant species and have a 30-fold increase in plant biomass. In deeper river channels *H. amplexicaulis* is capable of forming a floating mat over the water surface, resulting in shading of the submerged vegetation (Houston and Duivemvoorden 2002). In Florida (USA), *H. amplexicaulis* colonized the deeper part of the marshes and formed floating mats. Native plant species were absent from areas dominated by *H. amplexicaulis*. During flooding events, the only plant emerging from the water was *H. amplexicaulis*, hence demonstrating its potential for outcompeting native species (Overholt *et al.* 2006).

Changes in vegetation structure as a result of *H. amplexicaulis* invasion, as discussed above, have been implicated as an important factor influencing macroinvertebrate and fish faunal composition (Houston and Duivemvoorden 2002). Compared with areas dominated by native vegetation, areas dominated by *H. amplexicaulis* support a higher relative abundance of introduced fish (3% vs. 79% respectively). This increased abundance of introduced fish was reflected in other studies, where para grass had established in comparable wetland areas (Arthington *et al.* 1983). In both *H. amplexicaulis* and para grass stands, the increased stem density is thought to provide a greater lateral concealment for exotic fish, and an abundance of plant food. The composition of macroinvertebrate assemblages has also been shown to differ in *H. amplexicaulis* compared to native stands (Houston and Duivemvoorden 2002, Kinnear *et al.* 2008). Coleoptera were favoured in *H. amplexicaulis* stands while other faunal groups, Ephemeroptera, Hemiptera, and Odonata were disadvantaged (Houston and Duivemvoorden 2002). Similar results were documented in Florida, although in this study, sites were sampled across seasons (Overholt *et al.* 2006). Macroinvertebrate taxa were also simplified in *H. amplexicaulis* stands, although this was amplified during summer. *H. amplexicaulis* sites had lower abundances of individuals, especially in the orders Diptera, Coleoptera and Hemiptera, compared to native sites. The only insect species that was collected in large numbers in *H. amplexicaulis* stands was the exotic true bug, *Ischnodemus variegatus* Signoret (Hemiptera: Blissidae), which is a *H. amplexicaulis* specialist native to South America. The native blissid *Ischnodemus brunnipennis* (Germar) was found in large numbers in sites dominated by the native *Panicum hemitomon* Schult., and Ishneumonidiae, Braconidae and other parasitic Hymenoptera were only found in these sites. The presence of a diverse group of macroinvertebrate orders in *P. hemitomon* sites suggests more complex food webs functioning in native compared to *H. amplexicaulis* stands (Overholt *et al.* 2006).

There has not been substantial research done on vertebrate impacts as a result of *H. amplexicaulis* invasion. Turtle and waterbird richness were found to increase following removal of *H. amplexicaulis* in the Fitzroy Catchment. However, other factors, including breeding responses, 'sightability' early in the study, and the delayed effects of flooding on the ecosystem may have influenced this result (Kinnear *et al.* 2008). Research done on the impacts on avifauna of a similar invasive macrophyte, para grass (Ferdinands *et al.* 2005) can provide useful information on the likely impacts of *H. amplexicaulis*. In this study most birds did not use para grass habitat; in fact most birds were associated with native vegetation or habitats with little or no para grass. In particular, sedgelands dominated by *Eleocharis* spp. and *Cyperus* spp., bare ground, open water, and areas of mixed grassland/ herbland/ sedgeland appeared to be the habitats supporting large numbers of wetland birds. Although there were not enough data to make conclusions about most bird species, Ferdinands *et al.* (2005) noted that 'it seems reasonable to propose that a monoculture of dense, matted grass that produces little edible seed offers limited food resources for birds and impedes access to other resources in the water or soil'. It is clear from the documented studies that habitat modification as a result of high-biomass invasive macrophytes, such as para grass and *H. amplexicaulis*, will have negative effects on wetland biodiversity.

There have been limited studies on the impact of *H. amplexicaulis* on water quality. However, in comparable wetland systems where invasive weeds have been removed from waterways, there have been rapid and substantial increases in dissolved oxygen saturation and improved suitability of the habitat for fish (Perna and Burrows 2005). Houston and Duivenvoorden (2002) found no physicochemical differences (pH, dissolved oxygen, conductivity, turbidity) between wetlands invaded by *H. amplexicaulis* and uninvaded areas. However, measurements were taken only once at each site, which is below the recommended limits for an accurate value of dissolved oxygen (Perna and Burrows 2005). In a recent study in the Mungulla Wetlands, where dissolved oxygen was monitored across time and water depths, the water within *H. amplexicaulis* stands had much lower dissolved oxygen availability than the uninvaded open water. For example, at 0940 h the near-surface water adjacent to *H. amplexicaulis* invaded areas was 87% saturated with oxygen while the water within the *H. amplexicaulis* stands was only 17% saturated, which is well below the 30% minimum concentration required to prevent acute stresses from developing in sensitive species of local fish (Nicholas and Burrows 2009). In a similar study from the Fitzroy River (Rockhampton), no significant decline in water quality was detected following herbicide spraying of *H. amplexicaulis*, nor was there an improvement (Kinnear *et al.* 2008). This is a potentially important finding and suggests that any improvement in water quality accompanying *H. amplexicaulis* removal must be either minor or take longer than the duration of the project. The initial condition of the wetland itself may play an important role in the response of the system following *H. amplexicaulis* invasion or removal. Where a system is already degraded, improvements in water quality may be minimal even if *H. amplexicaulis* has been removed (Kinnear *et al.* 2008).

Additional impacts of *H. amplexicaulis* include impediment of fish passage due to physical barriers (dense *H. amplexicaulis* infestations) and/or low dissolved oxygen (physiological barrier) (Challen and Long 2004). Such impacts have ecological, economic and social consequences. While this has been highlighted as a significant issue in the literature (Challen and Long 2004), it has yet to be quantified. In a recent study in Horseshoe Lagoon (North Queensland), where most of the aquatic weeds (*H. amplexicaulis* being a significant weed in this system) were sprayed or mechanically removed, rapid water quality improvements resulted. However, monitoring revealed that many native fish species seemed unable to recolonize the lagoon. Subsequent water quality monitoring found low levels of dissolved oxygen (DO) in areas downstream from Horseshoe Lagoon that both reduce fish passage potential (through avoidance of low DO conditions) and mean that many migrating fish get caught in the creek system downstream of Horseshoe Lagoon where they may not survive the dry season. This has raised concerns that while removal of *H. amplexicaulis* from one area may improve water quality, the complete system may have to be addressed before ecological processes such as fish migration are restored (Veitch and Burrows 2007).

There are significant conservation areas in Australia to which the further invasion of *H. amplexicaulis* poses particular threats. Concerns have been raised in Northern Territory, where *H. amplexicaulis* is considered a key threat to wetlands within the World Heritage listed Kakadu National Park (Walden and Nou 2008). Within Queensland, *H. amplexicaulis* has established within tributaries connected to Lakefield National Park (Clarkson 1991), hence raising concerns for the extensive wetland systems which harbour rare flora and fauna species. Sainty and Jacobs (1994) suggest that *H. amplexicaulis* might occupy a niche sometimes filled by water lilies (*Nymphaea* spp.) and pink lily or native lotus (*Nelumbo nucifera* Gaertn.). In addition, *H. amplexicaulis* may have competitive advantage over certain native marsh species such as *Pseudoraphis spinescens* Vick., *Paspalum distic*hum L. and *Leersia hexandra* Sw., which are naturally dominant in seasonal freshwater marshes of northern and central Queensland (Sainty and Jacobs 1994). Water birds, such as magpie geese, *Anseranas semipalmata* (Latham), depend upon a range of wetland plant species, including native sedges (*Eleocharis* spp.), *Oryza* spp., *Ischaemum* spp. and native hymenachne for food and secure roost sites (Bayliss and Yeomans 1990, Wilson 1997). Thus, although it is not known what impact the development of extensive, pure stands of *H. amplexicaulis* will have on bird populations, it is likely to be negative.

Human health. Recent health concerns resulting from *H. amplexicaulis* invasion have been expressed by the Rockhampton City Council in regard to the association between *H. amplexicaulis* populations and the increased populations of two species of mosquito, *Mansonia uniformis* (Theobald) and *Coquillettida xanthogaster* (Skuse), in the area. *C. xanthogaster* is of particular concern due to its potential to transfer Ross River infection to humans (Queensland Government 2002). The thick mats of *H. amplexicaulis* prevent fish from feeding on mosquito larvae, thus allowing mosquito populations to increase. Research is currently examining best management practices to solve this issue (Livingstone Shire Council 2005).

The establishment of *H. amplexicaulis* within water storage facilities could cause considerable public concern, given the application of herbicides needed to control the species (Csurhes *et al*. 1999).

Economic losses. The economic cost of *H. amplexicaulis* is difficult to estimate. Although the north Queensland sugar industry suggests that productivity can be decreased through direct competition from *H. amplexicaulis*, there are limited data to support this view. The true economic cost to the sugar cane industry appears to arise from the cost of control. *H. amplexicaulis* has been shown to block drainage/irrigation channels and water storages that supply irrigation water to cane farms. The species needs repeated spraying, hence control costs are relatively high. Additionally, if the propagule source (from neighbouring properties or upstream) is not controlled, control costs would be continual, hence having a significant impact on final returns. Although there has been no overall cost placed on losses as a result of *H. amplexicaulis*, some cane farmers reportedly suffer losses of \$A80 000–\$A100 000 y^{-1} due to poor drainage (Csurhes *et al.* 1999).

For local councils and landholders the continued cost of control of *H. amplexicaulis* is also a significant issue. Although this has not been calculated, the continued management of *H. amplexicaulis* represents an ongoing problem for local councils. Costs include herbicide, labour and resources to access waterways (T. Sydes personal communication). As the majority of infestations occur on private land, there is an additional cost of trying to enforce compliance with current legislation. Since the longevity of *H. amplexicaulis* soil seed bank is greater than eight years, these costs are ongoing. Economic losses due to management need to be further quantified.

Other potential problems and costs relate to damage of infrastructure. This is a particular problem during floods when large rafts of *H. amplexicaulis* are deposited against bridges and barrages. The species also has caused havoc with boats, when in 2007 fast moving floodwaters resulted in large masses of *H. amplexicaulis* catching on moored boats, snapping their anchoring and sweeping the vessels downstream (The Morning Bulletin, Rockhampton 2007).

Beneficial

The introduction of *H. amplexicaulis* was for use as a ponded pasture species. The requirement for a ponded pasture system was due to the decline in live weight gain of beef cattle during the dry season when protein becomes scarce due to low quality pastures (the so-called 'protein drought'). This was a particular issue in Queensland's tropical and sub-tropical native pastures (Wildin 1991, Pittaway *et al.* 1996). The development of ponded pastures and the introduction of species that could be used in this system resulted in the continued production of grass (and protein) throughout the dry season. *H. amplexicaulis* has particular advantages as a ponded pasture species. The principal benefit is its ability to grow in water up to 1.2 m deep, which effectively extends the use of ponded pastures to inland areas of Queensland with poor dry season rainfall and high evapotranspiration. *H. amplexicaulis* has appealing agronomic characteristics, including high nitrogen values (Howard-Williams and Junk 1977), high protein content (13.9% DM) (Dirven 1965), an ability to remain palatable well into the dry season (Bogdan 1977, Tejos 1978a) and high forage production (up to 18 t DM ha^{-1} y^{-1}) (Rony Teys 1978, Tejos 1978b). In Suriname, crude protein content was found to be high: 15.8% in the whole plant, 22.6% in the leaves and 9% in the stem, with crude digestibility of 66–80%. Total Digestive Nutrients (TDN) values range from 54–76% (Bogdan 1977).

The true economic benefits of *H. amplexicaulis* are difficult to estimate. There have been a number of economic studies of the value of ponded pastures, which are indirectly related to *H. amplexicaulis*. Jamieson and Bourne (1996) assessed the profitability of ponded pastures in Queensland's grazing lands. The analysis concluded that ponded pastures could yield satisfactory returns and increase whole property profits under the right circumstances. Wildin and Chapman (1987) estimated that a 100 ha ponded pasture grazed at a stocking rate of one beast ha^{-1}, with each beast gaining 180 kg live weight y^{-1}, can potentially provide an income of approximately $A15 000 above the return expected from undeveloped land. The economic benefit directly related to ponded pasture systems and indirectly to *H. amplexicaulis* is likely to be different across geographic areas. In central Queensland, the development of ponded pasture systems and the use of *H. amplexicaulis* within these systems is generally believed by the grazing industry to be positive. In the 'wet tropics' region, where alternative dry season fodder is often in good supply, the plant is considered far less valuable. Recent landholder feedback in central Queensland, suggests that cattle will avoid *H. amplexicaulis* in the dry season if other grasses (native or exotic) are available (Kinnear *et al.* 2008). Currently there is no statistically valid experimental work clearly demonstrating the improved benefits of *H. amplexicaulis* in comparison with other ponded pasture species such as para grass.

Legislation

In 1999, *Hymenachne amplexicaulis* was identified as one of the 20 Weeds of National Significance (WoNS). This was based on four major criteria: the invasiveness of the weed, the weed's impact, the potential for spread and the socio-economic and environmental values likely to be impacted. While there was no legislative power as a result of inclusion in the WoNS list, listing did provide a mechanism for prioritizing weed management at the state, regional and local levels. Individual landowners and managers are ultimately responsible for managing WoNS and state and territory governments are responsible for overall legislation and administration (Thorp and Lynch 2000).

Commonwealth

Since 1998 *Hymenachne amplexicaulis* plant or seed material has been prohibited for import to Australia under the Commonwealth plant quarantine legislation (Quarantine Act 1908) (Anon. 2006). The plant was also recently included (September 2009) as a threatening process in the list of key threatening process under section 183 of the *Environment Protection and Biodiversity Conservation Act (1999)*.

Tasmania

Across Australia, Tasmania was the first state or territory to declare *H amplexicaulis*. The species was declared in October 2001 (Tasmanian Government Gazette 2001).

Queensland

Hymenachne amplexicaulis was declared as a Class 2 noxious pest under the *Land Protection Pest and Stock Route Management Act (2002)* in July 2003 (Queensland Subordinate Legislation 2003). The definition of Class 2 is that the species has already spread over substantial areas in Queensland and potentially has serious economic, environmental and social impacts. Under this legislation, landholders must take reasonable steps to keep their land free of *H. amplexicaulis* by controlling and, if possible, eradicating any outbreaks on their property, and preventing spread into areas free of *H. amplexicaulis*. It is an offence to keep or sell this species without a permit (*Land Protection Act 2006*).

South Australia

Hymenachne amplexicaulis was declared in June 2005 under the *Natural Resources and Management Act (2004)*, preventing the selling of *H. amplexicaulis* or its seeds throughout the state (South Australian Government Gazette 2005).

Western Australia

Although there are reports of plantings of *H. amplexicaulis* in Western Australia, the species has not been found to date. It was declared a P1 and P2 weed under the *Agricultural and Related Resources Protection Act (1976)* in August 2005. P1 prohibits the introduction and movement of plants, seed, contaminated machinery and produce across Western Australia. P2 means that any *H. amplexicaulis* found must be treated to prevent propagation, and infested areas must be managed to prevent any further spread (Western Australia Government Gazette 2005).

Victoria

Hymenachne amplexicaulis was declared as a 'Restricted' weed in October 2005 under the *Catchment and Land Protection Act 1994*. This category includes plants that pose an unacceptable risk of spreading in the state or to other parts of Australia if they were to be sold or traded in Victoria, and are a serious threat to another state or territory of Australia. Trade in these weeds and their propagules, either as plants, seeds or contaminants in other materials is prohibited (Victorian Government Gazette 2005).

Northern Territory

Hymenachne amplexicaulis was declared as a Class B and Class C weed in November 2005 under the *Weeds Management Act (2001)*. Class B means that its growth and spread must be controlled and Class C prohibits its introduction into the Northern Territory (Northern Territory Government Gazette 2006).

Australian Capital Territory

Within the Australian Capital Territory *H. amplexicaulis* was classified as a prohibited pest plant in 2005 under the *Pest Plants and Animals Act (2005)*. Under this legislation the propagation and commercial supply of *H. amplexicaulis* is prohibited. The reckless supply, use or disposal of contaminated material, machinery and vehicles is prohibited (Australian Capital Territory Pest Plants and Animals Declaration 2005).

New South Wales

On 1 March 2006, *H. amplexicaulis* was listed as a Class 1 weed in New South Wales under the *Noxious Weeds Act (1993)* (New South Wales Department of Primary Industry 2009). This means that it poses a serious threat to primary production or the environment and it is not present in the state or is present only to a limited extent. The Act also states that 'the plant must be eradicated from the land and the land must be kept free of the plant'. There are a number of small infestations in northern New South Wales which are all undergoing eradication (R. Ensby personal communication).

Management

National approach

The National Hymenachne Committee (WoNS committee) has established national management objectives for *H. amplexicaulis* (Figure 8). In areas where the main *H. amplexicaulis* infestation is present (Cairns to central Queensland, Darwin), containment is the objective, i.e. the current populations will not extend outside of specified zones. Where satellite populations are present (Cape York, Northern NSW, Goondiwindi), these are considered eradicable. Areas considered as particularly susceptible to *H. amplexicaulis* invasion are highlighted for surveillance. Isolated populations that have a high probability of spreading are classified for eradication. This includes populations in Townsville, Cape York, northern New South Wales and southern Queensland. This approach is currently under review, with the further aim of classifying water catchments throughout Australia into zones with differing *H. amplexicaulis* management objectives (National Hymenachne Committee unpublished data 2009).

Although the eradication of *H. amplexicaulis* from Australia is unlikely, control regimes and careful management can contribute towards weed containment and minimizing the adverse impacts of infestations. The chances of successful control are greatly improved when *H. amplexicaulis* is in the early stages of invasion; thus, early detection and rapid response is important for early containment and eradication (DNRMW 2006). Effective control strategies for *H. amplexicaulis* are limited due to restrictions on the use of some herbicides in aquatic environments, human alterations of hydrology resulting in increased nutrient availability, and site inaccessibility. Current best practice methods for *H. amplexicaulis* include the use of herbicides, mechanical removal and grazing. Riparian restoration following active removal of *H. amplexicaulis* also needs to be considered. The nature of the infestation (isolated patches vs. large monostands), wetland typology, climatic factors, site accessibility and landholder cooperation are all factors that will influence the cost, time, and likely success of the control and management of *H. amplexicaulis*. Management objectives and the total costs required to achieve the objective should be determined before implementing any control strategy.

Chemical control

There are no herbicides registered (on label) for the control of *H. amplexicaulis*, which therefore makes chemical control extremely difficult. Herbicides can only be used legally for *H. amplexicaulis* following the approval and issue of a minor use permit by the Australian Pesticides and Veterinary Medicines Authority (APVMA). Glyphosate (present as the isopropylamine or momoammonium salt) has a minor use permit for the control of *Hymenachne* spp. in Queensland. Glyphosate can be used at above label rates (Table 1) and applied via boom, handgun, knapsack or aerially (helicopter) a maximum of four times per year in Queensland. It can be used in non-agricultural areas, native vegetation, pasture and aquatic areas (all bodies of fresh and brackish water which may be flowing, non-flowing or transient,

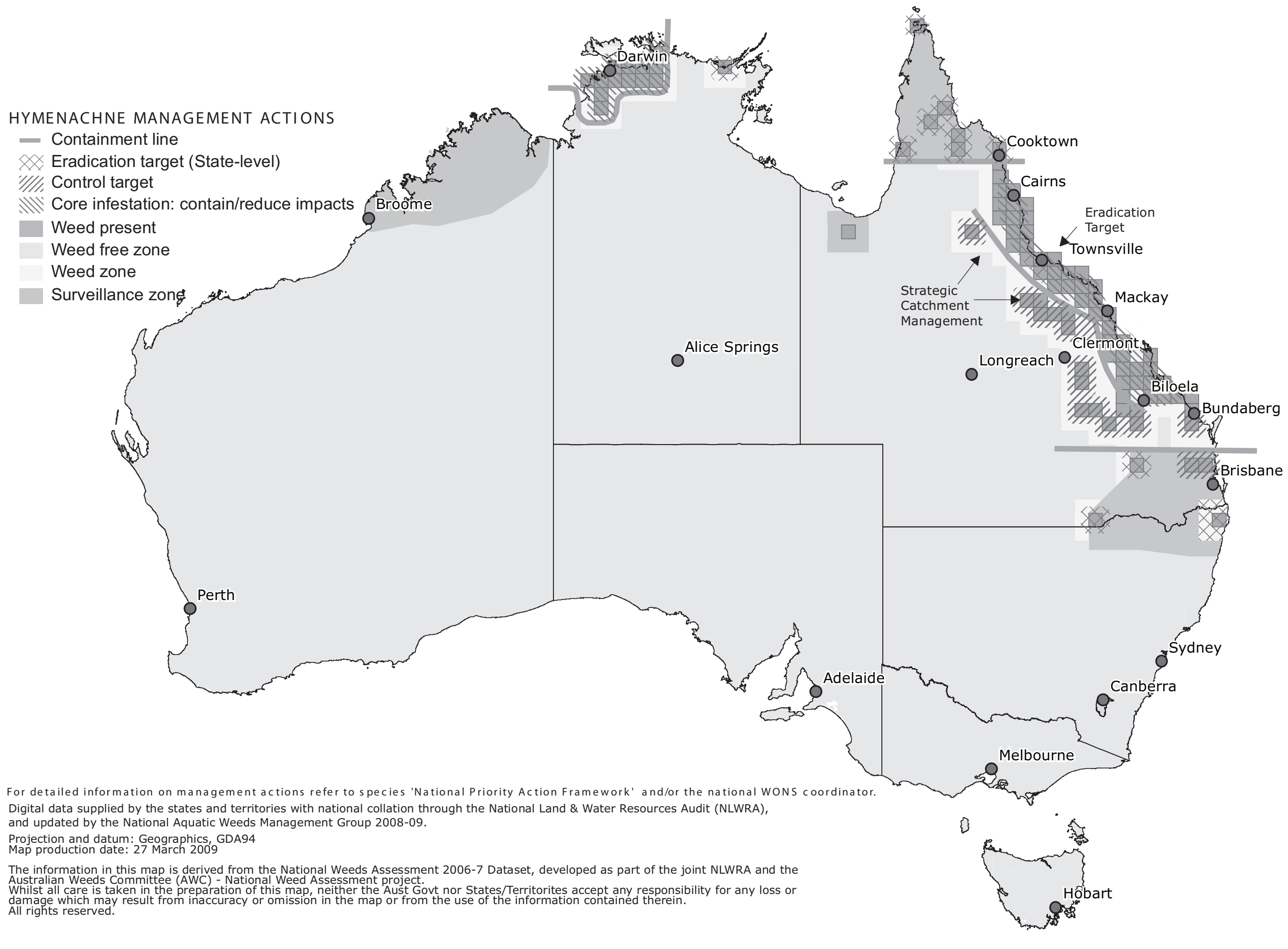

Figure 8. National weed management actions for *Hymenachne amplexicaulis*.

Table 1. Herbicides approved for use on *Hymenachne amplexicaulis* in Queensland (APVMA 2009).

Active chemical constituents	Application method	Rate
Glyphosate (360 g L^{-1}) present as the isopropylamine salt	boom/aerial, spot spray	14 L ha^{-1}
Glyphosate (360 g L^{-1}) present as isopropylamine and monoammonium salts	boom/aerial, spot spray	14 L ha^{-1}
Glyphosate (540 g L^{-1}) present as the isopropylamine and monoammonium salts	boom/aerial	9.3 L ha^{-1}
Glyphosate (700 g kg^{-1}) present as the mono-ammonium salt	boom/aerial	7.2 L ha^{-1}
Nufarm Bonus Adjuvant – ammonium sulphate (250 g L^{-1}), alkylethoxyphosphate monoammonium salt (188.5 g L^{-1}), ammonium propionate (19 g L^{-1}) and soyal phospholipids (15 g L^{-1})	boom/aerial	1–2 L may be used with any of the above if required

also on the margins of streams, lakes, dams and channels). Glyphosate cannot be applied within 0.5 km upstream of potable water intake in flowing water or within 0.5 km of a potable water intake in a standing body of water such as a lake, pond or reservoir (Table 1) (APVMA 2010).

Recent chemical trials indicate that fluazifop (2014 g a.i ha^{-1}), imazapyr (2000 g a.i ha^{-1}), glyphosate (5040 g a.i ha^{-1}), haloxyfop (400 g a.i ha^{-1}) and hexazinone (5000 g a.i ha^{-1}) are the most effective herbicides against *H. amplexicaulis* (Vitelli *et al.* 2005). However both hexazinone and imazapyr are broad-spectrum herbicides and pose off-target problems. Therefore, application in natural wetlands may cause substantial impacts to native vegetation. Hexazinone, in particular, has also been noted for its mobility in soil after application and, following rainfall, can move into surrounding non-target areas. Chemical trials based on optimum application rates for fluazifop, imazapyr, glyphosate and haloxyfop found that glyphosate was the least effective in causing stem mortality (Vitelli *et al.* 2005). Both season and life stage were found to influence the effectiveness of particular herbicides. Glyphosate was the least effective herbicide during flowering periods and imazapyr was 20–30% less effective when applied in autumn/winter (J. Vitelli unpublished data).

Studies in Florida similarly found glyphosate to be the least effective herbicide (Sellers *et al.* 2008). Their trial consisted of glyphosate at 4.2 kg a.i ha^{-1}, imazapyr at 1.1 and 1.7 kg a.i ha^{-1}, and glyphosate + imazapyr at 4.2 kg a.i ha^{-1}. While all three combinations provided at least 90% control three months after treatment, *H. amplexicaulis* regrowth six months after glyphosate application had resulted in only 70% control, which was significantly lower than all the other treatments. In contrast to the above studies, timing was not found to have an impact on the control of *H. amplexicaulis*. However, it appeared to impact on the re-establishment of native species. Water depth also did not appear to influence control of *H. amplexicaulis* with these herbicides. Regardless of water depth, glyphosate + imazapyr reduced *H. amplexicaulis* biomass by as much as 97% compared to untreated controls. The Florida study suggests that excellent control of *H. amplexicaulis* can be obtained using glyphosate, imazapyr, or a tank-mix of these herbicides at any time during the growing season (Sellers *et al.* 2008).

Rate screening trials of the most widely used chemical for control of *H. amplexicaulis*, glyphosate, demonstrated that high rates are required for control. The lowest effective rate for glyphosate is 5.0 kg ha^{-1} (Vitelli *et al.* 2005). Glyphosate (360 g L^{-1}) needs to be applied at a minimum of 14 L of product ha^{-1} for the control of *H. amplexicaulis*. As with most control of weeds, a single spray application will not provide full control. *H. amplexicaulis* populations need to re-sprayed every three to six months as necessary (Vitelli *et al.* 2005).

Given the effectiveness of haloxyfop in the control of *H. amplexicaulis* (particularly in deeper water situations) and its selectivity, there is strong support to have this chemical approved for use in aquatic situations. The application (minor use permit) for the use of haloxyfop across Queensland is currently in the process of assessment by the APVMA. Trials to evaluate the rate of breakdown of haloxyfop (haloxyfop R-methyl ester) and its first order metabolite haloxyfop acid in water, and the bioaccumulation of these compounds in non-target organisms, were recently completed (J. Vitelli unpublished data). Results indicated that the half-life of haloxyfop R-methyl ester within open (creek water) and closed (tank) water systems was 3 h and 24.5 h respectively. Haloxyfop acid had a half-life of 727 h in creek water and 13 061 h in distilled water (J. Vitelli unpublished data). Thus, the potential residual effects to off-target organisms have been shown to be minimal.

A major concern with spraying large infestations of *H. amplexicaulis* has been the impact on water quality. Previous management recommendations have suggested mosaic spraying, with the argument being that large amounts of dead or dying plants may create oxygenation problems in the waterways as the rotting matter decays. Studies from the Fitzroy Basin, Rockhampton showed that the application of either half/half or full spray treatments would be appropriate for management in systems with very high *H. amplexicaulis* cover (Kinnear *et al.* 2008). No significant differences in the water quality parameters were recorded from 'natural' and 'recovered' sections of the study site. Hence the use of spray control (and the short term ecological effects) is far more desirable compared with the 'do-nothing' approach (Kinnear *et al.* 2008).

The economic costs of herbicide spraying, however, far exceed costs of other management methods. Aerial spraying by helicopter is around \$A115 ha^{-1} and is appropriate for large or inaccessible infestations. Edge spraying by boat, four-wheel drive or four-wheel bikes costs approximately \$A500 d^{-1} (M. Pyott personal communication 2009).

Mechanical damage/physical control

Mechanical or physical control of *H. amplexicaulis* results in aboveground biomass being removed. The most common and effective way is by use of a mechanical harvester. This type of control has been undertaken in some areas with limited success. While it reduces the problems associated with the use of herbicides, mechanical/physical removal will not completely control *H. amplexicaulis*, and success is dependent upon the complete removal of both the infestation and any loose plant fragments. In addition, *H. amplexicaulis* has a long-lived seed bank, so ongoing management will be required. The advantages of mechanical harvesters are the removal of large mats of *H. amplexicaulis* in a relatively short time, and prevention of large volumes of decomposing matter, which can affect water quality. A number of shire councils in Queensland, including Burdekin and Rockhampton, have successfully used weed harvesters and/or excavators for the control of *H. amplexicaulis* in some areas (Csurhes *et al.* 1999). Costing is difficult to determine, and is based on the density of *H. amplexicaulis* and access to the system. At the Cairns Botanic Gardens, a mechanical harvester was used to clear approximately 1 ha of *H. amplexicaulis*. Management time was three days, assisted by a backhoe mounted weed rake. The costs were approximately \$A1200 to transport the harvester and \$A3500 for the operation. On larger local waterways, costs may be as high as \$A4000–\$A6000 ha^{-1}. Whether the weed can be stored on site or has to be removed by truck also changes the costs significantly (M. Pyott personal communication 2009). The sole use of a mechanical weed harvester for *H. amplexicaulis* control does not appear to be cost effective. Rather, this method can be employed in order to increase access through otherwise impenetrable floating weed mats, which in turn will allow bankside infestations to be sprayed effectively by boat.

While limited work has been done on the effect of continued damage or cutting on *H. amplexicaulis*, experiments from Australia (L. Wearne unpublished data) and Florida (Hill 1996) indicate that sustained cutting may reduce plant vigour. Recent research indicates that the effect of damage interval and frequency on *H. amplexicaulis* is influenced by inundation depth and duration. Growth rates and plant survival were reduced significantly where *H. amplexicaulis* was exposed to sustained damage and continued inundation (L. Wearne unpublished data).

Land management practices

Grazing. Controlled grazing represents a viable means of broadacre control of *H. amplexicaulis* in wetland and riparian zones which are seasonally inundated, but dry out sufficiently to allow cattle access. However, in the wet tropics where wetland/riparian areas do not dry out, grazing may not be an option. There are also significant negative impacts associated with grazing, including reduced water quality and increased bank erosion, which need to be considered. There have been a number of *in situ* trials examining the impacts of grazing on invasive macrophytes, including *H. amplexicaulis*. These trials suggest that intensive grazing pressure at the end of the dry season may be successful in removing *H. amplexicaulis* populations from stream channels. However, there is little information on the stocking rates used within the trials, or what species replace *H. amplexicaulis* once it is removed (Wetland Care, Australia 2008).

Flooding and drying. Flooding of *H. amplexicaulis* can offer some control, particularly where plants are kept short (e.g. burning, grazing, slashing) and then inundated. This may result in substantial death of large stands, with the remaining growth weakened and more susceptible to spray control. Spraying *H. amplexicaulis* stands prior to flooding may result in death of some stands, particularly in deeper areas of a floodplain. Further work is required to fully understand how such techniques can be utilized (DNRMW 2006). The successful use of flooding as a management tool is dependent on the onset of the wet season, or alternatively being able to control timing of flooding.

Revegetation. Experiments using both artificial (shade cloth) and natural (vegetation) shade suggest decreases in the biomass of *H. amplexicaulis* over time (Figure 9). Shade cloth and yearly spraying caused a decrease in biomass after the first year, and *H. amplexicaulis* continued to decrease during the six years of the experiment. Where shade cloth only, shade cloth and initial spray, or revegetation and yearly spray were used, *H. amplexicaulis* initially increased and did not decrease until year two. As there was no control treatment it is difficult to make any formal conclusions from this experiment. However, the results do suggest a decrease in *H. amplexicaulis* associated with shading and that restoration of riparian native vegetation may be an effective long-term method of controlling invasive macrophytes, such as *H. amplexicaulis*, especially in disturbed cane-land stream channels (see Bunn *et al.* 1998). Extensive revegetation of riparian systems in the Tully/Murray catchment is proving to be successful for longer term control options for *H. amplexicaulis* (D. Sydes personal communication). Although the initial management costs are high (approximately \$A20 000 ha^{-1}; S. Januchowski and P. Visconti unpublished data), costs are dramatically reduced after the initial outlay, and the environmental benefits are likely to be greater. Further information is required on the effects of shade, and/or competing vegetation for the longer term control of *H. amplexicaulis*.

Fire. *Hymenachne amplexicaulis* is susceptible to burning so long as plants have dried off sufficiently, particularly at the end of the dry season (Cameron 2003b). Fire has been used successfully at Lambell's lagoon and Kalinga (Queensland Parks and Wildlife Service) (John Clarkson personal observation) as part of an integrated control program. Studies on similar species further show that fire may be a useful tool in some circumstances. Within Kakadu National Park, indigenous people seek to limit the abundance of the native hymenachne (Whitehead *et al.* 2003). If undisturbed, this species forms dense monocultures similar to those of *H. amplexicaulis*. Aboriginal fire managers developed techniques to reduce the grass biomass progressively, by scheduling fires earlier while shallow water was still present on the floodplain (Whitehead *et al.* 2003). This has resulted in the opening of floodplain wetlands, allowing other native species to re-establish. Such results suggest that fire may present a viable and effective management tool in wetland areas infested with *H. amplexicaulis* which are prone to drying down in the dry season. The timing of fire can be critical, and needs to coincide with the start of the wet season for best results. The role of fire and the integration with other control techniques needs to be further considered, especially given the limited herbicide options.

Social and economic barriers to the management of H. amplexicaulis

Developing broad-scale control activities for *H. amplexicaulis* will be difficult because of varying attitudes and opinions towards the plant. In addition,

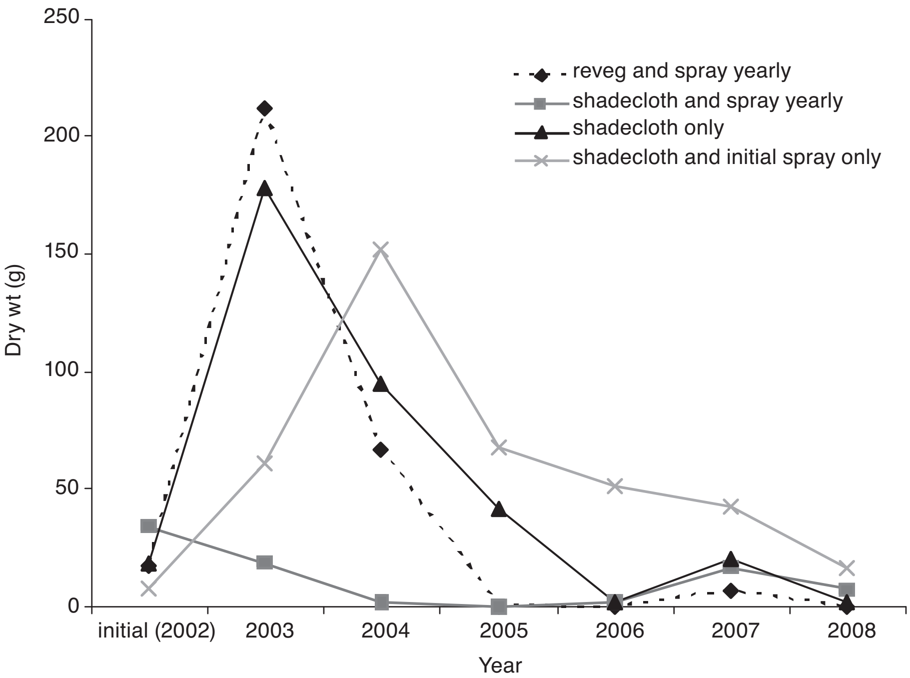

Figure 9. Effects of shade, revegetation and spray on the biomass of *Hymenachne amplexicaulis* (S. Setter unpublished data).

attempting to introduce and enforce a blanket approach across all regions, infestations and landholder types is unlikely to be successful, given (a) the variability in values and opinions surrounding *H. amplexicaulis*; and (b) the differences between infestations regarding accessibility and the efficacy of different control measures. On the other hand, the need to integrate activities aimed at the control and management of *H. amplexicaulis* is clear. The engagement of all stakeholders, working in an appropriately prioritized, consistent and persistent way, and considering other activities being undertaken in the region, is critical in progressing successful management (Miles *et al.* 2009).

Recent landholder surveys on *H. amplexicaulis* in the Fitzroy Basin identified a number of insights into some of the barriers preventing its control (Kinnear *et al.* 2008). This includes significant disagreement about the impacts of *H. amplexicaulis* on production; some viewed the species important for production, while others considered it a weed. Management efforts varied amongst landholders, some persisting in control, some giving up control, and others viewing control as a waste of effort. Many landholders considered other terrestrial weeds a higher priority for management. There was also a considerable lack of knowledge about the species by landholders and a lack of interest by landholders in non-infested areas. Furthermore, there was a general antipathy towards potential regulatory controls, and the legislation itself (through its classification of *H. amplexicaulis* as a Class 2 weed) is not enforced. This encourages landholders who are controlling *H. amplexicaulis* to give up, because surrounding landholders are not controlling infestations and are not forced to. Landholders also substantially underestimated costs of *H. amplexicaulis* management (42%), and once true costs are realized many give up and become disillusioned with the prospect of long term management (Kinnear *et al.* 2008).

The results from the Kinnear *et al.* (2008) study as well as other current management programs identify positive opportunities for improvement of *H. amplexicaulis* management. In areas where there is substantial information about *H. amplexicaulis* and the areas to be managed, combined with successful landholder engagement and incentives, successful long term management can be achieved. Control by the Burdekin Shire Council (Charleston 2006) and Cassowary Coast (D. Sydes personal communication) are examples where *H. amplexicaulis* management is undertaken in a way that includes evaluation of priority sites, landholder engagement and information, landholder incentives for ongoing management, and a commitment by both the landholders and council managers for a long term financial and time commitment. This approach has led to heavily infested wetlands and waterways being clear of *H. amplexicaulis* for many years. Such a strategic approach to management could be used for the control of *H. amplexicaulis* infested areas across Australia.

Natural enemies

In a recent study on natural enemies of *H. amplexicaulis* in Australia, 16 phytophagous insect species were found (K. Bell unpublished data). The most common insects were a rice leaf-folder, *Cnaphalocrocis medinalis* (Guenée) (Lepidoptera: Crambidae), which is a polyphagous pest on many grass species, including rice, sugar cane, maize, wheat and sorghum. An undescribed Lepidoptera species in the genus *Proselotis* (Gelechiidae) was occasionally collected on *H. amplexicaulis*, as was the seed-feeding aphid, *Hysteroneura setariae* (Thomas). All species were also found on the native hymenachne. The survey found minimal damage by insects to either *H. amplexicaulis* or the native hymenachne. Although some damage to leaves by the rice leaf-folder and a few other occasional leaf-folding Lepidoptera was observed, the overall impact to the plants is likely to be inconsequential. The only other insect noted to occur on *H. amplexicaulis* in Australia is the small leaf-rolling caterpillar *Marasmia* spp., which causes dead and dying leaf tips. This insect was found on both *H. amplexicaulis* and the native hymenachne (Cameron 2003a). Other insects mentioned to occur on the native hymenachne include tar spot (*Phyllachora* spp.) which causes small, black, shiny raised spots (Cameron 2003a) and an unidentified Delphacidae species (K. Bell unpublished data). Four insect species have been recorded on para grass, and it is thought they may have some impact on *H. amplexicaulis*, although none of these was found in the most recent study (K. Bell unpublished data). These insects include the lawn armyworm, *Spodoptera maurita* (Boisduval), common armyworm, *Mythimna convecta* (Walker), pasture leafhopper, Toya sp. and caddis-flies (Elder and O'Brien 1996).

Severe insect damage to *H. amplexicaulis* has been documented in Florida populations. The insect identified as the blissid bug, or chinch bug (*Ischnodemus variegatus*) naturally occurs in South America, and is a recent occurrence within Florida (Brambila and Santan 2004). *H. amplexicaulis* is the only host mentioned for *I. variegatus* in South America (Slater 1987), although Baranowski (1979) cites a record on *Thalia geniculata* L. (Marantaceae) from Suriname. *I. variegatus* has been reported as a potential biocontrol agent for *H. amplexicaulis*. The symptoms include a reddish coloration on the stem and foliage of this weed (Slater 1987). Current studies in Florida indicate *I. variegatus* nymphs are highly specific to *H. amplexicaulis*. Temperature studies on the development of *I. variegatus* suggest that if it arrives in Australia, the tropical climate of the northern regions would likely provide ideal conditions for its development and population growth (Diaz *et al.* 2008b). Tests performed on the native hymenanche found this species to be an inferior host in comparison to *H. amplexicaulis* (Diaz *et al.* 2008b).

Little is know about the fungal pathogens of *H. amplexicaulis* worldwide (Soares and Barreto 2006). The world literature contained only 11 fungal records of this species. These include *Balansia strangulans* (Mont.) (Stevenson 1975), *Anthostomella tomicum* (Lév) Sacc., *Cercospora* sp., *Leptosphaeria grisea* Pass., *Balansia paspali* Henn., *Balansia vorax* var. *paspal* (Henn.) Tesdoro, *Coniothyrium* sp., *Phyllachora acutispora* Speg. and *Phyllachora hymenachnei* (Chardón) Arx & E. Mull. Recent surveys which have been undertaken in the native range in Brazil have also identified *Curvularis lunata* (Wakker), *Phyllachora minutissima* Welw. and Curr.), *P. acustispora* Speg. and *Passalora fusimaculans* (GF Atk.) (Monteiro *et al.* 2003, Soares and Barreto 2006). Although *C. lunata* is known to occur in Australia and is regarded as common and widespread (Sivanesan 1987), it has not been recorded on *H. amplexicaulis* here (Monteiro *et al.* 2003). It was noted that perhaps local isolates are not pathogenic to *H. amplexicaulis* and the introduction of the Brazilian isolate might have an impact. As *C. lunata* was found capable of colonizing several grass species, there is limited potential for it to be used as a biological control agent, since a high degree of host specificity is normally required by quarantine authorities before such an agent can be introduced. Another fungal species, *Ohyllochora* sp., was also found growing on *H. amplexicaulis*. However, only plants growing on dry river banks were affected; partly submerged plants did not show any sign of the disease (Monteiro *et al.* 2003).

A biocontrol program in Australia would require *H. amplexicaulis* to be nominated and approved as a target for biological control. Given the species' rapid spread into northern Australian waterways and the problems with control, such a program deserves serious consideration (Monteiro *et al.* 2003). However, it would require approval from the production sectors, which is likely to be difficult given the value still placed on this species by parts of the grazing industry. Its success would also be contingent on the availability of damaging natural enemies that would not significantly impact on the native hymenanche. The availability of sufficiently host-specific natural enemies is yet to be confirmed, although results on *Ischnodermus* are encouraging (Diaz *et al.* 2008b).

Acknowledgments

The authors acknowledge substantial input from Shane Campbell. Thanks also to Shane Campbell and Stephen Setter for their unpublished data and constructive discussions, and input from Merv Pyott, Rob Cobon, Travis Sydes and Damon Sydes. This work was funded through the Australian Federal Government, Department of Agricultural, Forestry and Fisheries (Defeating the Weed Menace).

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