Review

The Biology of Australian weeds 60. *Sagittaria platyphylla* (Engelmann) J.G. Smith and *Sagittaria calycina* Engelmann

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Name

Sagittaria (Alismataceae) are aquatic herbs with 40 described species and eight infraspecific taxa. The genus has a natural distribution throughout North and South America, Europe, Africa and Asia, but species diversity is highest in the neotropics, temperate North America and eastern Asia. The name *Sagittaria* is derived from the Latin word *sagitta*, meaning 'arrow', which refers to the arrowhead shape of the emergent leaf blades produced by many species.

Description

Species of *Sagittaria* are primarily emergent but a few species are submersed and produce floating leaves. All species are herbaceous with basal leaves and scapose inflorescences. Leaves of *Sagittaria* are petiolate with a distinct blade or phyllodial without an expanded blade. The inflorescences are racemose or paniculate, producing nodes with whorled flowers. The proximal node or nodes usually produce carpellate flowers or less often functionally carpellate flowers with abortive stamens, or rarely perfect flowers. The distal nodes of the inflorescence bear staminate flowers. Flowers of *Sagittaria* are comprised of 3 sepals and 3 petals which are white, rarely with a purplish spot. The carpellate flowers bear numerous carpels spirally attached to a conical receptacle. Staminate flowers produce up to 30 stamens. The fruits of *Sagittaria* are achenes with the style forming a distinct beak.

In Australia, there is evidence from herbarium records that potentially five species have naturalized: *S. platyphylla* (Engelmann) J.G. Smith, *S. calycina* Engelmann, *S. filiformis* J.G. Smith, *S. macrophylla* Zuccarini, and an uncertain sagittate-leaved species. Of these five species, only two (*S. platyphylla* and *S. calycina*) were found to be well represented in herbaria and thus firmly naturalized. The other three species may or may not be established well enough to be considered naturalized. Historical reports of other species, *S. graminea* Michaux, *S. montevidensis* Cham. & Schltdl. and *S. brevirostrata* Mack. & Bush appear to be in error. Reports of *S. sagittifolia* L. in New South Wales have not been substantiated and may have been confused with *S. montevidensis* (Harden 1993), as both species possess a purple spot at the base of the petals.

Figure 1. Inflorescence of *Sagittaria platyphylla*.

Species

***Sagittaria platyphylla* (Engelmann) J.G. Smith., Missouri Bot. Gar. Rep. 6:29 (1894).** Type. Based on *Sagittaria graminea* var. *platyphylla* Engelmann in A. Gray. Man. Bot. ed. 5: 494. 1867. (The epithet *platyphylla* is a combination of the Greek words *platys* meaning 'broad', and *phyllon* meaning 'leaf'.)

Synonyms for S. platyphylla*:*

- *Sagittaria graminea* Michaux var. *platyphylla* Engelmann in A. Gray. Man. Bot. ed. 5: 494. 1867.
- *Sagittaria recurva* Engelmann ex Patterson, Checklist 130. 1887.
- *Sagittaria mohrii* J.G. Smith, Mohr Bull. Torrey Club 24: 19, 1897.

Perennial, glabrous herbs, to 150 cm; rhizomes absent; stolons present; tubers present. **Leaves** phyllodial and petiolate; phyllodial leaves submersed or emersed, flattened, 5–28 × 0.5–2.7 cm; emersed leaves petiolate; petioles 10–70 cm long, blades linear to ovate, 4–18 × 0.4–8 cm, occasionally with 1–2 short basal auricles. **Scapes** erect, emersed; peduncles 15–54 cm long; inflorescences racemose bearing 3–8 nodes, each node with 2–3 flowers, 4.5–18 × 2–9 cm; lower nodes bearing carpellate flowers; upper nodes bearing staminate flowers; nodal bracts scarious, connate more than 1/4 total length, lanceolate, tip acute, 3–6 mm long. **Flowers** carpellate flowers pedicellate; pedicels spreading to ascending, to 3 cm long, cylindric, not distinctly thicker than upper staminate pedicels in flower but becoming so in fruit, cylindric, spreading to recurved in fruit; sepals spreading to reflexed, lanceolate, 3.7–5.5 × 2–3.5 mm. Staminate flowers pedicellate; pedicels ascending, cylindric, to 2 cm long; sepals lanceolate 4–5 × 1.5–3 mm; filaments dilated, longer than to more or less equal to anthers, pubescent; anthers yellow (Figure 1). **Fruiting heads** to 1.5 cm diameter, not enclosed by sepals; achenes oblanceolate, 1.5–2.2 × 0.8–1.2 mm, beaked; adaxial margin slightly keeled, keel entire; abaxial margin slightly keeled, keel entire; faces ridged to slightly winged, wing entire, resin canals absent; beak laterally attached, obliquely emerging, to 1 mm long (Keener 2005).

Sagittaria platyphylla is native to North America, primarily to the south central United States of America (USA), with sporadic distribution in eastern USA and Central America. *S. platyphylla* was previously considered one of seven varieties of *S. graminea* Michaux (*S. graminea* var. *platyphylla*) (Bogin 1955), but was later assigned to specific rank based on the studies of Wooten (Wooten 1973). *S. platyphylla* can be distinguished from *S. graminea* by the presence of fruiting heads on recurved pedicels which are distinctly thicker in diameter than the staminate pedicels. *S. graminea* produces erect to spreading carpellate pedicels which are more or less the same diameter as the staminate pedicels (Godfrey and Wooten 1981).

The leaf shape and size of *S. platyphylla* are highly variable and are influenced by a range of environmental and management factors (Sainty and Jacobs 1981, Flower 2004). Three main leaf forms are recognized: broad-leaf emergent, narrow-leaf emergent, and the submersed phyllodial leaf form (Flower 2004). The broad-leaf emergent form produces erect linear to ovate, acuminate blades. This type of leaf morphology tends to occur in slow moving water bodies in which plants produce vigorous stolons. The narrow-leaf emergent form produces erect, narrowly tapered blades. Plants of this form generally produce weaker, depleted stolons, usually after herbicide application. The submersed phyllodial leaf form produces linear strap-like leaves and is mostly found in deeper water than emergent plants.

***Sagittaria calycina* Engelmann *in* Torrey, Bot. Mex. Bound. 212. 1859.** (The epithet *calycina* is Latin for 'with reference to the calyx'.)
The plants of Australia are represented by *Sagittaria calycina* var. *calycina*.

Synonyms for S. calycina *var.* calycina:

- *Sagittaria calycina* var. *fluitans* Engelmann in Torrey, Bot. Mex. Bound. 212. 1859.
- *Sagittaria calycina* var. *maxima* Engelmann in Torrey, Bot. Mex. Bound. 212. 1859.
- *Sagittaria calycina* var. *media* Engelmann in Torrey, Bot. Mex. Bound. 212. 1859.
- *Sagittaria calycina* var. *grandis* Engelmann in A. Gray, Man. Bot., ed. 5. 494. 1867.
- *Lophiocarpus calycinus* (Engelmann) Micheli in A. & C. DC., Monogr. Phan. 3: 61. 1881.
- *Lophotocarpus calycinus* (Engelmann) J.G. Smith, Mem. Torrey Club 5: 25. 1894.
- *Lophotocarpus californicus* J.G. Smith, Missouri Bot. Gard. Rep. 11: 146. 1899.
- *Lophotocarpus depauperatus* Engelmann ex J.G. Smith, Missouri Bot. Gard. Rep. 11: 148. 1899.
- *Lophotocarpus fluitans* (Engelmann) J.G. Smith. Missouri Bot. Gard. Rep. 11: 145. 1899.
- *Sagittaria montevidensis* subsp. *calycina* (Engelmann) Bogin, Mem. New York Bot. Gard. 9: 197. 1955.

Annual or perennial, glabrous herbs to 80 cm tall; rhizomes present or absent; stolons absent; tubers present. **Leaves** phyllodial and petiolate; phyllodial leaves submersed or emersed, flattened, linear, 2.5–45 × 0.5–2 cm; petiolate leaves emersed, rarely floating; petioles, 8–55 cm long; blades sagittate, hastate or elliptic, 3–20 × 2.5–12.5 cm. **Scapes** erect, recurved or decumbent, emersed or partly submersed; peduncles 1.5–40 cm long; inflorescence racemose, bearing 2–12 nodes, each node with 1–3 flowers, 1–17.5 × 1–15 cm; lower nodes bearing perfect flowers; upper nodes rarely bearing staminate flowers or functionally staminate with rudimentary carpels; nodal bracts opaque with scarious margins or scarious, distinct or connate at base less than 1/4 of total length, lanceolate to ovate, tip obtuse to acute, 2–34 mm long. **Flowers** carpellate flowers pedicellate; pedicels spreading to erect, to 7 cm long, cylindric, distinctly thicker than upper staminate pedicels, cylindric, recurved in fruit; sepals erect, appressed, ovate, 5–12 × 4–9 mm. Staminate flowers pedicellate; pedicels ascending, cylindric, to 4 cm long; sepals lanceolate to elliptic, 2.5–4.5 × 3–5 mm; filaments cylindric, longer than anthers, glabrous or pubescent; anthers yellow. **Fruiting heads** to 2.5 cm diameter, enclosed by sepals; achenes oblanceoloid, 1.8–2.5 × 0.8–2 mm, beaked; adaxial margin keeled, keel entire; abaxial margin keeled, keel entire; faces smooth to slightly ridged, resin canals present or absent; beak laterally attached, horizontally emerging, to 0.5 mm long (Keener 2005).

Sagittaria calycina is native to central North America in the USA, ranging south into Mexico. In Bogin's (1955) monograph, *S. calycina* was treated as one of four subspecies of *S. montevidensis* Cham. & Schltdl. (*S. montevidensis* subsp. *montevidensis*, *S. montevidensis* subsp. *chilensis* (Cham. & Schltdl.) Bogin, *S. montevidensis* subsp. *calycina* (Engelmann) Bogin, and *S. montevidensis* subsp. *spongiosa* (Engelmann) Bogin). This treatment was maintained by Haynes and Holm-Nielsen (1994) and Haynes and Hellquist (2000). Using molecular data, Keener (2005) elevated *S. montevidensis* subsp. *calycina* to specific status as *S. calycina* Engelmann *in* Torrey, recognizing two varieties, *S. calycina* var. *calycina* and *S. calycina* var. *spongiosa* Engelmann *in* Gray.

Historic reports of *Sagittaria montevidensis* Cham. & Schltdl. in Australia may stem from the previous taxonomic treatment of *S. calycina* as a subspecies of *S. montevidensis*. The two species share similar morphology and can sometimes be mistaken for each other. *S. montevidensis* is native to tropical and subtropical areas in south central and western South America and has naturalized in south eastern USA and western Africa. It is usually more robust, with purple spots at the base of the petals. These spots are absent or clear in *S. calycina*. Some herbarium records of larger *S. calycina* specimens could be confused with *S. montevidensis* without adequate flowering material to examine for the purple spots. Until a specimen is discovered in Australia that clearly has a purple spot on the petal, *S. montevidensis* should be excluded from the Australian flora.

***Sagittaria filiformis* J.G. Smith, Missouri Bot. Garden Rep. 6: 46. 1894.** (The epithet *filiformis* is Latin for 'thread-like' and refers to the narrow leaves of this species.)

Synonyms for S. filiformis*:*

- *Sagittaria natans* Michaux, Fl. bor.-am. 190. 1803.
- *Sagittaria natans* var. *lorata* Chapman, Fl. So. States 449. 1860.
- *Sagittaria natans* var. *gracillima* S. Watson *in* A. Gray, Man. Bot. ed. 6, 556. 1890.
- *Sagittaria subulata* var. *gracillima* (S. Watson) J.G. Smith, Mem. Torrey Club 5: 26. 1894.
- *Sagittaria subulata* var. *natans* (Michaux) J.G. Smith, Missouri Bot. Garden Rep. 6: 44. 1894.
- *Sagittaria lorata* (Chapman) Small, N. Am. Fl. 17(1): 52. 1909.
- *Sagittaria stagnorum* Small, Man. SE. Fl. 24. 1933.
- *Sagittaria subulata* var. *lorata* (Chapman) Fernald, Rhodora 42: 409. 1940.
- *Sagittaria subulata* subsp. *lorata* (Chapman) Clausen, Torreya 41: 161. 1941.

Perennial, glabrous herb to 120 cm tall; rhizomes absent; stolons present; tubers present. **Leaves** phyllodial and petiolate; phyllodial leaves submersed, flattened to lenticular, linear, 5–120 x 0.1–1.5 cm; petiolate leaves floating or rarely emersed, when floating petioles 3–40 cm long; blades linear to ovate, rarely sagittate, 1.5–5.5 x 1–3 cm; when emersed; petioles 5–10 cm long; blades linear to ovate, rarely sagittate, 2–5.5 x 0.8–3 cm. **Scapes** floating or rarely emersed; peduncles 5–40 cm long; inflorescence racemose or rarely umbellate or paniculate, when racemose or paniculate bearing 2–10 nodes, each node with 2–3 flowers, 5–25 x 2–15 cm; lower nodes bearing 1–3 carpellate flowers and 0–2 staminate flowers, or bearing 2–3 branches; upper nodes bearing staminate flowers; nodal bracts scarious, connate less than to more than 1/4 total length, lanceolate, tip acuminate, 3–10 mm long, often caducous with only basal remnants present. **Flowers** carpellate flowers pedicellate; pedicels spreading, to 13 cm long, cylindric, not distinctly thicker than staminate pedicels, cylindric, ascending in fruit; sepals spreading to appressed, ovate to elliptic, 3–4.5 x 1.2–2.5 mm. Staminate flowers pedicellate; pedicels ascending, cylindric, to 8 cm long; sepals lanceolate, 2.3–4 x 1.5–2.5; filaments dilated, longer than anthers, glabrous; anthers yellow. **Fruiting heads** to 0.7 cm diameter, appressed by sepals at base but not enclosed; achenes obovoid, 1.5–2.1 x 0.8–1.3 mm, beaked; adaxial margin keeled, keel entire to scalloped; abaxial margin slightly keeled, keel entire; faces winged or sometimes tuberculate, or merely ridged, wing margin scalloped to toothed, resin canals present; beak laterally to apically attached, vertically to obliquely emerging, to 0.3 mm long.

Only a single specimen of *S. filiformis* was discovered in Australian herbaria. This specimen was collected in Tasmania by S.P. Welsh in 2000 and deposited at the Hobart Herbarium. The locality provided was "on a property 1 km north east of Stella Glen, 41° 38′ 43″ S; 146° 44′ 31″ E" with a habitat given "in a small pond". This area should be explored for additional naturalized populations.

Sagittaria filiformis is native to the southeastern USA and has become naturalized in other parts of North, South and Central America. The linear to ovate floating leaves and floating inflorescence are very distinctive from other species naturalized in Australia. However, when water levels drop, the species may produce only very narrow phyllodial leaves.

***Sagittaria macrophylla* Zuccarini, Ahb. Math.–Phys. Cl. Königl. Bayr. Akad. Wiss. 1: 289. 1832.** (The epithet *macrophylla* is a combination of the Greek word *macros* meaning 'large, long or tall', and *phyllon* meaning 'leaf'.)

Synonyms for S. macrophylla:

- *Sagittaria mexicana* Steudeudal, Nom. ed. 2. 2: 491. 1841. *Nomen superfluum*.

Perennial, glabrous herbs, to 100 cm; rhizomes absent; stolons present; tubers present. **Leaves** petiolate, emersed; petioles 15–30 cm long; blades elliptic or less commonly sagittate to hastate, 8–25 x 0.7–8 cm, lobes when present, shorter than remainder of the blade. **Scapes** erect, emersed; peduncles 35–52 cm long; inflorescences racemose to corymbose, bearing 3–5 nodes, each node with 3 flowers, 5–17 x 3–11.5 cm; lower nodes bearing carpellate flowers; upper nodes bearing staminate flowers; nodal bracts scarious, distinct or connate at base less than 1/4 total length, lanceolate, tip obtuse, 7–13 mm long. **Flowers** carpellate flowers pedicellate; pedicels ascending, to 11 cm long, cylindric, distinctly thicker than upper staminate pedicels, cylindric, spreading in fruit; sepals spreading to reflexed, lanceolate, 7–8 x 4–6 mm. Staminate flowers pedicellate; pedicels ascending, cylindric, to 3 cm long; sepals lanceolate 6–8 x 2–4 mm; filaments cylindric to slightly dilated at base, longer than to more or less equal to anthers, glabrous; anthers yellow. **Fruiting heads** to 2 cm diameter, not enclosed by sepals; achenes oblanceolate, 3.1–3.5 x 2–2.5 mm, beaked; adaxial margin keeled, keel entire; abaxial margin not keeled; faces smooth to slightly ridged, resin canals present or absent; beak laterally attached, obliquely emerging, to 1.2 mm long.

Sagittaria macrophylla is native to southern Mexico where it is endemic.

Even though there are herbarium specimens collected in Australia identifiable with *S. macrophylla*, the inclusion of it in the Australian flora is tentative and requires further research. Keener (2005) suggests *S. macrophylla* and *S. platyphylla* are closely related. They possess natural ranges that do not overlap, but are near each other. Slightly dilated, glabrous filaments and extremely long, spreading carpellate pedicels distinguish *S. macrophylla* from *S. platyphylla,* which has dilated, pubescent filaments and spreading to recurved, shorter carpellate pedicels. In their native range, both species have a propensity to produce the occasional basal lobe on emersed leaves, with *S. macrophylla* producing much longer ones. From herbarium specimens collected in Australia, there were clear examples of individuals with long carpellate pedicels and glabrous filaments which match *S. macrophylla*. However, specimens from the same localities or nearby were identifiable with S. *platyphylla* as well as intermediates between the two. It is possible both species are naturalized and were able to hybridize. Genetic studies are required to resolve the taxonomy of these populations.

Sagittaria sp.

The fifth species of *Sagittaria*, collected in a natural environment at Woomargama in southern New South Wales, could not be identified to species. The collection (E.J. McBarron 652) was made in 1947 and is lodged with the Royal Botanic Garden Herbarium in Sydney. It is a sagittate-leaved species without mature fruit necessary for identification. Currently it is identified as *S. sagittifolia* L., a native of Europe.

Key to species of *Sagittaria* naturalized in Australia

1a. Leaf blades present.

2a. Leaf blades of larger leaves sagittate.

3a. Pedicels of carpellate flowers, distinctly thicker in diameter than pedicels of staminate flowers; sepals of carpellate head tightly appressed in fruit.

4a. Petals uniformly white or with a translucent spot at base. ***S. calycina***

4b. Petals with a distinct brownish-purple spot at base. **[*S. montevidensis*]**

3b. Pedicels of carpellate flowers more or less the same thickness in diameter as pedicels of staminate flowers; sepals of carpellate heads spreading to reflexed in fruit. ***Sagittaria* sp.**

2b. Leaf blades ovate, elliptic, or lanceolate (rarely may have a small basal lobe).

5a. Filaments glabrous.

6a. Leaf blades and inflorescence emersed; sepals of fruiting heads spreading to reflexed. ***S. macrophylla***

6b. Leaf blades and inflorescence usually floating; sepals of fruiting heads appressed. ***S. filiformis***

5b. Filaments pubescent (at least at base). ***S. platyphylla***

1b. Leaves phyllodial without expanded blade.

7a. Filaments pubescent; sepals of fruiting heads spreading to reflexed. ***S. platyphylla***

7b. Filaments glabrous; sepals of fruiting heads appressed. ***S. filiformis***

Taxonomy and related species in Australia

Class Liliopsida, Subclass Alismatidae, Order: Alismatales, Family Alismataceae (Cronquist 1981).

The Alismataceae is a primitive family closely related to the Butomaceae and Limnocharitaceae, with 11 genera and just over 100 species (Mabberley 1990). In Australia there are eight genera in the Alismataceae: *Limnophyton* (1 sp.), *Astonia* (1 sp.), *Damasonium* (1 sp.), *Alisma* (2 spp.), *Caldesia* (2 spp.), *Echinodorus* (1 sp.), *Hydrocleys* (1 sp.), and *Sagittaria* (4 spp.) (Jacobs 1997). Five alismataceous species indigenous to Australia include: *Alisma plantago-aquatica* L., *Astonia australiensis* (Aston) S.W.L.Jacobs, *Caldesia oligococca* (F.Muell.) Buchenau, *C. parnassifolia* (L.) Parl. and *Damasonium minus* (R.Br.) Buchanan (Jacobs 1997). Species of *Sagittaria* are distinguished from the closely related genera *Echinodorus* and *Alisma* by the presence of unisexual flowers; the latter genera have wholly bisexual flowers.

At least six additional species of *Sagittaria* are utilized and traded in Australian ornamental horticulture, and although none has been recorded as naturalized, they have considerable potential to become so. Non-naturalized *Sagittaria* in Australia include: *S. graminea* Michaux, *S. lancifolia* L., *S. latifolia* Willdenow, *S. natans* Pallas, *S. sagittifolia* L. and *S. subulata* (Linnaeus) Buchenau (Hibbert 2000, 2002, 2004). *S. brevirostrata* is reported from only one location in the Goulburn River near Nagambie, Victoria (Aston 1967), but appears to have become extinct.

Sagittaria sinensis Sims (a synonym of *S. trifolia* L.) and *S. montevidensis* were used in ornamental horticulture in Brisbane and Sydney in the late 1880s. *Sagittaria* and arrowheads were also utilized as aquarium plants as early as 1933 in New South Wales, Western Australia and Victoria, although there are few details on which taxa were involved (NLA 2012).

History

Sagittaria platyphylla was reported as naturalized in Ekibin Creek near Brisbane in 1959 (Aston 1973). In 1962, infestations were reported in the northern Victorian irrigation district, but may have been present some time before then (Aston 1973). Specimens were first collected in Victoria in 1964 at Nine Mile Creek at Wunghnu in north-central Victoria (Aston 1967) and, in the same year, at Liverpool and Casula on the banks of the St Georges River in New South Wales. During the early 1970s, the distribution of *S. platyphylla* increased rapidly (Aston 1973) and its spread into irrigation districts of Victoria caused concern (Parsons and Cuthbertson 1992). *S. platyphylla* is now a dominant weed in channels and drains in the Murray Valley and Shepparton irrigation areas and an emerging weed in the Central Goulburn irrigation area of Victoria.

In New South Wales, *S. platyphylla* was first reported as a weed in the Murrumbidgee irrigation area in 1990 (Eastern and Western Riverina Noxious Weed Advisory Group 2009). The first record for South Australia was in 1980 (Reddy 2005) and in Western Australia in 1999 at the Canning River (Sage *et al*. 2000). *S. platyphylla* occurs in Queensland around Brisbane (Figure 2). Most previous records from far north Queensland are erroneous due to misidentification with *Echinodorus* spp.

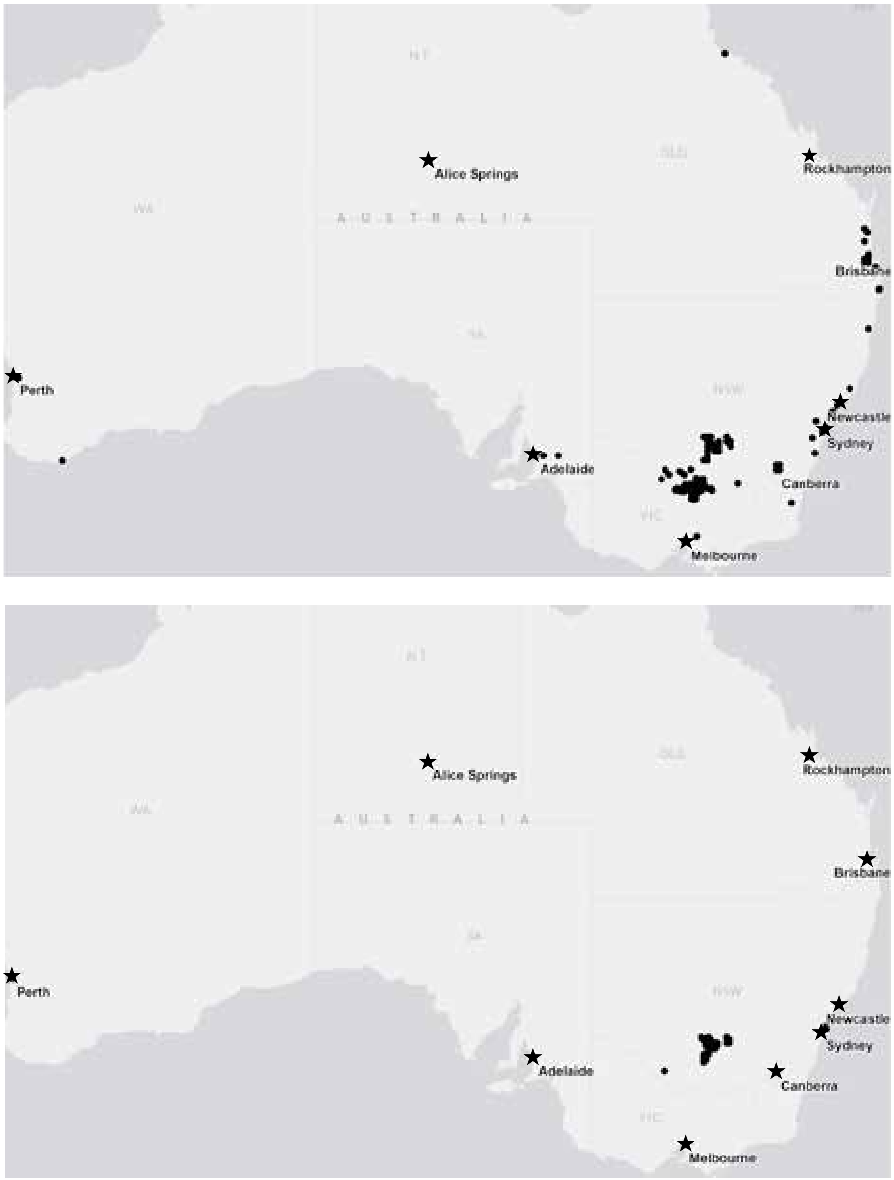

Figure 2. Australian distribution of *S. platyphylla* (top) and of *S. calycina* (bottom).

Sagittaria montevidensis was first reported as a garden escape near Sydney in 1926 and *S. montevidensis* subsp. *montevidensis* was first identified in the Murrumbidgee irrigation district in 1962 (Parsons and Cuthbertson 1992). However, there are no herbarium specimens to validate these reports and it appears misidentification with *S. calycina* has occurred. *S. calycina* was first reported in 1966 (Parsons and Cuthbertson 1992) and has since spread southwards into the Murray Valley region, where it occurs mostly in drainage channels and rice crops (McIntyre and Newnham 1988).

Distribution

World

The Alismataceae is distributed within the tropical, subtropical and sub-temperate regions of the eastern and western hemispheres (Rataj 1972a, b). *Sagittaria* is cosmopolitan, occurring in temperate and tropical regions of both hemispheres. The total number of *Sagittaria* species remains undetermined. However, most described species occur in North America, where there are 24 species (Lot and Novelo 1992, Cook 1996, Haynes *et al*. 1998, Haynes and Hellquist 2000). Up to four species occur in Europe and Asia (Haynes and Holm-Nielsen 1994).

Sagittaria platyphylla occurs naturally in southern North America from Kansas to Texas across to Georgia and western Florida (Wooten 1973, Godfrey and Wooten 1981), where it inhabits streams and lakes from sea level up to 900 m (Haynes and Hellquist 2000). The species is also native to Mexico. *S. platyphylla* is naturalized in the former USSR (Rubstov 1975), Indonesia (Rataj 1972a), Panama, where it is well established in

Figure 3. *S. platyphylla* invading a natural wetland in central Victoria.

Figure 4. *S. platyphylla* established in an irrigation channel in Tatura, Victoria.

the canal zone (Bogin 1955), and along the Gulf of Mexico coast. *S. platyphylla* was first recorded as naturalized in South Africa in KwaZulu Natal, and is now considered a new and emerging weed threat to aquatic ecosystems (P. Ivey personal communication 2011).

Sagittaria calycina is native to central North America, ranging south into Mexico, where it can be regarded as problematic, particularly in California (McIntyre and Newnham 1988). The species is naturalized in New Zealand (Owen 1996), but is referred to as *S. montevidensis*.

Australia

Sagittaria platyphylla inhabits shallowly flooded or marshy areas associated with rivers and streams (Parsons and Cuthbertson 1992) (Figure 3) and is a weed of drainage channels, ditches and permanent swamps associated with irrigation and drainage systems in south-eastern Australia (Figure 4). The main infestations occur in the Murray, Goulburn, Ovens and Edward Rivers, and irrigation and drainage networks in northern Victoria and southern New South Wales (Chapman and Dore 2009). Isolated occurrences of *S. platyphylla* occur in South Australia on the Murray River from Mannum to the Younghusband and Bowhill areas, and in Western Australia's south west at Albany and the Canning River in Perth (Sage *et al*. 2000, Reddy 2005) (Figure 2). The rate and extent of spread of *S. platyphylla* is increasing, particularly in south-eastern Australia (Sagliocco *et al*. 2007). The species' potential distribution includes waterways and wetlands throughout eastern and southern Australia. Records for *S. platyphylla* occur in near-coastal areas of Queensland and the species is reported as locally common in the Brisbane and Noosa areas (K. Stephens personal communication 2009, G. Sainty personal communication 2009). The species is currently absent from Tasmania, the Australian Capital Territory and the Northern Territory.

Sagittaria calycina is known from the Murrumbidgee and Coleambally irrigation areas of New South Wales (Flower 2003, Australia's Virtual Herbarium 2010), where it occurs in permanent freshwater to c. 1 m deep and is mostly found in rice fields, drainage ditches and the Barren Box swamp west of Griffith (Harden 1993, Parsons and Cuthbertson 1992).

An isolated and old reputed record of *S. montevidensis* occurs from Centennial Park in Sydney (Beadle *et al*. 1972), but specimens are lacking and the species appears to be no longer present in the area.

Naturalization and weed threats

Four species of *Sagittaria* other than *S. platyphylla* and *S. calycina* are naturalized outside their native ranges and can threaten agricultural production or natural ecosystems. *S. lancifolia, S. rigida* Pursh and *S. subulata* are native to the New World, but are naturalized in Europe. *S. trifolia* is native to Europe, but is now naturalized in the southern Ukraine (Tutin *et al*. 1980). Endemic species, e.g. *S. montevidensis*, *S. aginashi* Makino, *S. guayanensis* Kunth, *S. lancifolia* L., *S. pygmaea* Miq. and *S. trifolia* L. (Bogin 1955, Rataj 1972b, Godfrey and Wooten 1979, Randall 2002), can also be problematic, particularly in rice production systems.

Habitat

Climatic requirements

No quantitative data are available on the climatic requirements of *S. platyphylla* and *S. calycina*. In its native and introduced range, *S. platyphylla* has a broad ecological tolerance, but is generally restricted to warm-temperate regions. Frosts may kill or damage top growth, but regrowth occurs from submerged or subterranean organs.

Waterways protected by stands of trees provide shelter from damaging frosts. *S. calycina* has a broad climatic range within its native distribution, where it occupies temperate to subtropical wetland habitats in the nearctic region.

Substratum

In Australia, *S. platyphylla* occurs mostly in irrigation channels where it establishes on berms and flat shoulders that are shallowly inundated (Flower 2004). As irrigation channels divide and become smaller than main channels, the environment becomes more suitable for establishment of *S. platyphylla*. Shallow channels and spurs have slower moving, warmer water, and are often less turbid than deeper faster moving channels. Fluctuating water levels allow greater access of *S. platyphylla* to shallow water and favour its establishment. Achenes tend to germinate and grow on silty sediment rather than clay. Silt accumulates where water movement is slow, particularly on the inside of bends of larger channels, rivers and creeks, which are frequently colonized by *S. platyphylla*. Once established, populations trap more sediment, thereby increasing habitat availability. In North America, substrates high in potassium and organic matter were associated with *S. platyphylla*, suggesting specificity for certain soils amongst *Sagittaria* taxa (Wooten 1986).

Plant associations

No data are available from Australia on the composition of vegetation communities invaded by *Sagittaria*. An analysis of floristic co-associates and the ecological vegetation classes occupied by both *Sagittaria* species, but particularly *S. platyphylla*, would improve predictions of potential impact and distribution.

Growth and development

Physiology

The photosynthetic pathway utilized by *S. platyphylla* and *S. calycina* is unknown, but the CAM photosynthetic pathway is utilized by a range of submersed aquatic plants (Keeley 1998). The CAM photosynthetic pathway was suggested for *S. subulata* (Keeley 1998), but more recent studies indicate a C_4 mechanism, similar to that used by *Hydrilla*, may be involved (Cooper-Driver 1980, Bowes *et al.* 2002). Validation of the photosynthetic pathways of *Sagittaria* would be beneficial as there may be management implications, particularly in relation to herbicide options.

Starch is commonly found in the rhizomes of *Sagittaria* and along the larger vascular bundles in the petiole. High starch content has favoured cultivation and consumption of *S. latifolia* as a human food source in China and Japan. Leaves of *Sagittaria* commonly contain C-glycoflavones, a secondary metabolite which may have a role as a protective agent against predation and disease (Gornall and Bohn 1978, Cooper-Driver 1980). Amino acids are reported to accumulate in the base of leaves of *Sagittaria* and translocation of these substances occurs in *S. graminea* (Schenk 1972). In some circumstances, release of methane gas, attributed in part to pressure-induced flow through air spaces of roots embedded in methane saturated anaerobic sediments, may occur (Parsons and Cuthbertson 1992).

The optimal temperatures for germination and growth of *S. platyphylla* are between 21°C and 24°C, respectively (Parsons and Cuthbertson 1992, Flower 2004).

Phenology

In south-eastern Australia, flowering of *S. platyphylla* commences from around August-September and finishes around May (Flower 2004), with peak flowering usually from November to February. Fruit production occurs from December. In Queensland, *S. platyphylla* flowers from November to January (Stephens and Dowling 2002), but flowering may extend through to March. In Australia, *S. calycina* flowers during summer. Flowering of *S. graminea sens. lat.* is usually associated with the presence of emergent leaves; however, submerged plants exposed by lowering of water levels can occasionally produce inflorescences, a process governed by the availability of photosynthetically active radiation (Wooten and Lamotte 1978). Plants of *S. graminea* exposed to day lengths between 7–15 h initiate flower production (Wooten and Lamotte 1978).

Reproduction

Seed production and dispersal

Pollination of *Sagittaria* is by flies, short-tongued bees, generalist bees, syrphids or other small insects that are attracted to nectar rewards (Lovell 1898, Rogers 1983, Muenchow and Delesalle 1994). Flowers of *S. graminea sens. lat.* excluded from access by pollinators do not produce seeds, indicating plants are not agamospermous (Wooten 1973) and are likely to be self-incompatible.

Sagittaria platyphylla and *S. calycina* produce aggregate fruits of 1-seeded carpels. In northern Victoria, *S. platyphylla* produces an average of 850 achenes per fruit and 6900 achenes per inflorescence (Flower 2004), while *S. calycina* produces 800–2000 achenes per inflorescence and 15–32 inflorescences per plant, with an average of 20 000 achenes per plant (Flower 2003). Achene dispersal is by animals (birds) or floatation (Turner 1981). Seeds of most Alismataceae are adapted to aquatic dispersal. The spongy pericarp, wings and resin ducts or glands on the lateral faces of the achenes provide buoyancy (Kaul 1978, Rogers 1983). The seeds of *S. lancifolia* are known to float on the surface of undisturbed water for more than two months (Collon and Velasquez 1989). However, the achenes of *S. platyphylla* sink in seven days (R. Kwong unpublished data), while achenes of *S. calycina* float for a little less than two weeks (Flower 2003). Most *Sagittaria* achenes drop within the infestation area, but some are eaten by ducks and are believed to be viable when excreted (Parsons and Cuthbertson 1992). Enhanced germination of *Alisma* seeds after ingestion by ducks has been reported (Rogers 1983). Achenes of *Sagittaria* can adhere to animals via a sticky outer surface, or become attached to mud and machinery (Rogers 1983, Flower 2003).

Seed longevity, dormancy and germination

In the laboratory, the optimal temperature for germination of *S. platyphylla* is 21°C. Achenes do not germinate in darkness, but remain viable (Flower 2004). The duration of viability of *S. platyphylla* achenes is undetermined. However, achene viability of *S. calycina* is highest (54%) in the first year and declines to 45% by the third year (Flower 2003). The threshold for germination of *S. calycina* is <10°C, but germination increases substantially above 11°C, with an optimal germination temperature between 12–24°C (Flower 2003). Germination of Alismataceae may be enhanced by ethylene production under anaerobic conditions (Graham 1996, Flower 2003). Seeds of *S. calycina* require light for germination, which is inhibited by burial in soil at any depth (Flower 2003).

Vegetative

Tubers are produced by most perennial species of *Sagittaria*. In the case of *S. platyphylla*, both ramets and tubers are produced at the terminal end of stolons, with most tubers produced by mature plants just before winter (Figure 5). Tubers are round, fleshy starch-storing organs with an average weight of 1.2 g (R. Kwong unpublished data). Stolons are produced by both emergent and submerged forms of *S. platyphylla*, but stolon production is suppressed at water depths greater than 50 cm (Flower 2004). Stolons eventually senesce, breaking the connection between clonal plants, but the rate of senescence is unknown. *S. montevidensis* is perennial and produces rhizomes, but no tubers. *S. calycina* is capable of producing both rhizomes and tubers.

Hybrids

Hybridization occurs in *Sagittaria*, but is inadequately investigated. Plasticity of morphological characters and related taxonomic confusion makes recognition of hybrids difficult. Bogin (1955) suggests the origin of *S. graminea* var. *platyphylla* (= *S. platyphylla*) was hybridization between *S.*

Figure 5. Juvenile *S. platyphylla* with stolon and tubers.

montevidensis and *S. graminea*, followed by introgression with *S. graminea*. However, subsequent hybridization experiments do not strongly support this hypothesis. Crossing experiments show varieties of *S. graminea* (varieties *graminea*, *weatherbiana*, *chapmanii*) are highly interfertile with each other and with *S. platyphylla*, but *S. platyphylla* shows low crossability with *S. fasiculata* E.O.Beal and no fertile crosses were obtained when combined with *S. isoetiformis* J.G.Sm., *S. rigida* Pursh, *S. cristata* Engelm., *S. teres* S.Watson and *S. montevidensis* subsp. *calycina* (Wooten 1973).

Cytology and genetic diversity

Sagittaria is reported to have a relatively uniform chromosome number of $2n = 22$ (Olsen 1941, Baldwin and Speese 1955, Beal 1960, Love and Love 1961, Sharma 1972, Les and Philbrick 1993), but polyploid cytotypes are reported (Les and Philbrick 1993). *Sagittaria* species have one long pair of chromosomes with nearly median centromeres, nine pairs of intermediate length with subterminal centromeres, and one short pair with submedian centromeres (Baldwin and Speese 1955). Specific cytological details for *S. platyphylla* and *S. calycina* are not available.

Phylogenetic reconstruction of Victorian *S. platyphylla*, based on the nuclear *rpb2* gene and two regions from the chloroplast genome, *psbD-trnT* and *rpl32-trnL* (UGA), detected very low sequence variation and strong resolution that Victorian populations represent a single taxonomic entity, suggesting a single genetic source pool at the time of introduction into southern Australia (Chong and Broadhurst 2009). However, more recent research has shown a more heterogeneous gene pool exists in Australia (Broadhurst and Chong 2011). Further molecular phylogenetic analysis is required to determine the genetic composition of *S. platyphylla* populations from Western Australia and Queensland (Chong and Broadhurst 2009).

Population dynamics

Population dynamics data for *Sagittaria* are not available for Australian habitats. Information on mortality rates between life stages, especially relating to seed survival following dispersal, and the transition from seedling to juvenile stages, is required for the development of weed management strategies, including the potential application of classical biological control.

Importance

Detrimental

Agricultural impacts. The most significant impacts of *S. platyphylla* invasions arise from reduced flow paths in drains and channels, which cause increased water levels, particularly during periods of high flow or rainfall, and inefficiencies in water delivery. Infestations in irrigation channels affect the reliability of water delivery to farms, reducing capacity to deliver the right amount of water at the right time, which can lead to production losses or increased costs (Parsons and Cuthbertson 1992, Chapman and Dore 2009). Damage to irrigation infrastructure can also be significant (Chapman and Dore 2009). In the channel system administered by Goulburn–Murray Water, up to 85% of 14 000 km of creeks, drains and channels have infestations of *S. platyphylla*, requiring an annual expenditure of \$A250–\$500K y^{-1} depending on the season (Flower 2004, Chapman and Dore 2009). In the Shepparton and Murray Valley irrigation areas, more than \$A2 million y^{-1} is spent on control of *S. platyphylla* (Chapman and Dore 2009). In New South Wales, *S. platyphylla* is recognized as a serious problem in channel systems of the Griffith area (Eastern and Western Riverina Noxious Weeds Advisory Group 2009).

Similarly, in the southern central area of New South Wales, *S. calycina* reduces water delivery efficiencies by blocking channels and drainage ditches. In southern rice production areas, *S. calycina* is a major crop competitor, along with several other Alismataceae (*Alisma plantago-aquatica*, *A. lanceolatum* With., *Damasonium minus*), causing yield reductions of up to 75%, increased production costs and reductions in rice quality (Flower 2003, Seal *et al.* 2004). Aerial sowing of rice into flooded bays exacerbates the impact of several alismataceous weeds, including *S. calycina* (Seal *et al.* 2004), by prolonging the inundation period. In North America, *Sagittaria* is an alternative host to the aster leaf hopper, *Macrosteles fascifrons* Stål, (Hemiptera: Cicadellidae), a vector of aster yellows phytoplasma, oat blue dwarf virus and clover phyllody virus. While the leaf hopper is not present in Australia, infestations of *Sagittaria* present a potential biosecurity risk to Australian agricultural and floricultural industries.

Natural waterway impacts. *Sagittaria platyphylla* threatens native aquatic flora and fauna by invading shallow water bodies, where it competes with native species and reduces plant biodiversity (Chapman and Dore 2009). However, quantitative data demonstrating such impacts are lacking. The endangered Lower Murray Ecological Community, iconic wetland areas of Barmah and Gunbower Forests, and northern RAMSAR sites such as the Kerang wetlands and Chowilla flood plain are at risk from invasions by *S. platyphylla* (Gehrke and Harris 2001, DSE 2003a, b, Feehan *et al.* 2005, Nitschke 2008, Chapman and Dore 2009). Environmental water allocations to Murray wetlands could benefit invasive species such as *S. platyphylla* by increasing abundance and the rate of spread (Howell and Benson 2000, Merrin *et al.* 2005). Meta-population modelling indicates that reaches of the Murray River from Albury to below Mildura could be occupied by *S. platyphylla* in the absence of proactive management intervention (Feehan *et al.* 2005, Nitschke 2008, Chapman and Dore 2009). In coastal New South Wales, *S. platyphylla* invades wetlands and is expanding rapidly in the Porters Creek wetlands, where it causes loss of understorey species in *Melaleuca linariifolia* Sm. forests (G. Sainty personal communication 2009).

Sagittaria platyphylla is reported to have negative impacts on recreational activities, particularly fishing, boating and passive recreation. In shallow streams, *S. platyphylla* may act as a barrier to the movement of native fish and provide habitat to populations of European carp (*Cyprinus carpio* L.) (Chapman and Dore 2009). Again, quantitative data on these impacts are lacking.

In natural waterways, *S. calycina* appears to have minimal ecological impacts, although formal evaluation is also warranted.

Beneficial

In Australia, few beneficial outcomes are associated with *S. platyphylla* and *S. calycina*. Both species are utilized as aquatic ornamentals in jurisdictions where they are not listed under relevant noxious weed legislation (Victoria, Northern Territory, Australian Capital Territory, Queensland), but are of negligible economic value. Other *Sagittaria* species are freely traded as aquatic ornamentals.

Preparations involving *Sagittaria* have been attributed with diverse medicinal benefits, primarily in eastern Asia, but also in North and South America. Most are applications to soothe and cleanse afflictions of the skin. Anti-inflammatory activity is observed in extracts of *S. sagittifolia* (Sharma *et al*. 1975, Parsons and Cuthbertson 1992). Throughout most of their range, *Sagittaria* spp. are utilized as a source of food. Tubers of several species are consumed baked, boiled, fried, ground into flour, sweetened or dried. Therefore, human activity has historically played a role in the distribution of *Sagittaria* (Rogers 1983).

In situations where *Sagittaria* and the aquatic weed *Hydrilla verticillata* (L.f.) Royle co-occur, *Sagittaria* competes strongly with *Hydrilla*, substantially reducing its dry weight and number of tubers and shoots (Parsons and Cuthbertson 1992).

Legislation

Sagittaria platyphylla and *S. montevidensis* are declared species under State noxious weed legislation in Western Australia, Tasmania, South Australia and New South Wales (Weeds Australia 2012). In South Australia, both species are listed as Class 1 weeds and generally require notification and destruction throughout the State. In Western Australia, both species are P1/2 weeds which are subject to eradication and prevented from trade, sale or movement. In Tasmania, both species are declared weeds and restriction measures are in place to prevent introduction and establishment. In New South Wales, *S. platyphylla* and *S. montevidensis* are Class 5 state-wide restricted species and require notification on detection. *S. platyphylla* is also a Class 4 locally controlled weed in New South wales. Revision of legislative listings will be required to accommodate the elevation of *S. calycina* to specific rank. *S. platyphylla* is also a Class 4 locally controlled weed. No *Sagittaria* species are declared in Victoria, Australian Capital Territory, Queensland and the Northern Territory, but in some cases (e.g. Victoria, Queensland) are under review.

Weed management

Herbicides

In Australia, there are no label recommendations specifically for *S. platyphylla*, but minor usage permits have been issued by the Australian Pesticide and Veterinarian Medicines Authority (APVMA). Several herbicides are registered for the control of *S. montevidensis*. Use of herbicides in or near water bodies is strictly regulated by label recommendations, and maximum residue limits are recommended in the national water quality management strategy *Australia and New Zealand Guidelines for* 'Fresh and Marine Water Quality' (ARMCANZ 1995). Use of herbicides for control of *Sagittaria* in aquatic habitats should not exceed maximum residue limit guidelines or conditions specified under minor use permits. In billabongs where shallow water and lack of flow generally occur, herbicide application can be difficult without exceeding specified limits and may require progressive application in sections of the invaded water body.

Herbicide applications for the control of *S. platyphylla* often result in variable levels of control that are not consistent between locations and time of application (Flower 2004). Under permit, 625 g L^{-1} 2,4-D present as dimethylamine and diethanolamine salts can be used at 10–40 L ha^{-1} to control *Sagittaria* in drainage systems and specified creeks and irrigation areas (APVMA 2012). Also under permit in specified irrigation areas and creeks, including the Murray River, 360 g L^{-1} glyphosate as the isopropylamine and mono-ammonium salts are utilized for control of *S. platyphylla* (listed as *S. graminea*) and *S. montevidensis*. In lockable irrigation supply channels and tail drains that lead to recirculation dams or settling ponds, 150 g L^{-1} imazapyr present as isopropylamine salt and 150 g L^{-1} glyphosate as isopropylamine salt up to 5 L ha^{-1} is used under permit for control of *Sagittaria*. In the Goulburn Murray Irrigation area, 2,4-D dimethylamine and diethanolamine salts and amitrole are also utilized under permit for control of *Sagittaria* in drains. Use of 2,4-D frequently causes abscission of leaves before translocation, resulting in 'chemical mowing', where regrowth usually occurs within 6–12 weeks. In Western Australia, the triazolone herbicide carfentrazone-ethyl 400 g L^{-1} at 250 g ha^{-1} has been advocated for suppression of *S. platyphylla*.

Early experimentation with dichlobenil (a granular, residual herbicide registered in some aquatic situations) appears to be promising. Dichlobenil is a systemic herbicide used for selective control of aquatic weeds in New Zealand (Hofstra and Clayton 2001). Dichlobenil kills seedlings of *S. platyphylla* at rates of 23–230 kg ha^{-1}, but takes longer at lower rates. The effectiveness of dichlobenil at 23 kg ha^{-1} on underground organs is unknown. Dichlobenil also prevents growth from tubers and rhizomes, but is not registered for use in water that is used for crop irrigation or, livestock and human consumption (Chapman and Dore 2009).

Applications of glyphosate kill seedlings of *S. platyphylla*, but even at maximum label rates of 9 L ha^{-1}, applications to larger plants tend to burn the ends of leaves without clear control benefits. Higher rates of application can decrease the level of foliar cover, but may take up to 10 weeks for full impact to be expressed. Time of application appears to influence efficacy of glyphosate, as greater levels of foliar cover reduction are obtained with applications in March and June rather than December (Flower 2004). Manipulation of water levels can also improve impacts by increasing exposure of foliage to herbicides. Wave wash can reduce the efficacy of glyphosate applications if this occurs within the 4 h rain-fast period. Spot spraying at rates of 36–40 L ha^{-1} can suppress plants in waterways, provided 60% of the plant is exposed to herbicide. However, follow-up applications are often necessary. There is anecdotal evidence of glyphosate resistance in areas where repeated applications have occurred (Nitschke 2008). Applications of glyphosate at 9–72 L ha^{-1} reduce *S. platyphylla* wet tuber weight, with greatest impacts occurring at the higher rates of application.

In the Australian rice growing industry, more than 90% of the crop is sown with pre-germinated seed distributed into flooded bays or flooded permanently within one week of sowing (Whitworth *et al.* 2003). This cultural practice helps suppress the invasive grass *Echinochloa*, but provides a favourable environment for *S. calycina* and other alismataceous weeds (Seal *et al.* 2004). Three main herbicides are utilized for suppression of alismataceous weeds in rice crops: benzofenap at 300 g L^{-1}, dichlobenil and a dry flowable formulation of bensulfuron (Parsons and Cuthbertson 1992). MCPA at 250 g L^{-1} is utilized to a limited extent on mature *Sagittaria* infestations in rice crops. Herbicide resistance is reported for alismataceous weeds in rice crops (Cother 1999). Thirty-five percent of *S. calycina* accessions are reported as herbicide resistant, with the potential to cause escalating economic losses (Broster *et al*. 2001, Seal *et al*. 2004).

Herbicide application remains a major component of current *Sagittaria* management and therefore the risk of generating herbicide resistance requires further investigation. Research is required to improve our understanding of the physiological effects of herbicides, particularly the rates and pathways of herbicide translocation throughout single and multiple plants. Understanding the effects of herbicide application on demographic processes (i.e. mortality of different life stages and fecundity) will provide useful information with respect to optimal application timing for effective control. Additional herbicide techniques that target submerged plant parts, such as the use of gel adjuvants, warrant further investigation.

Other treatments

Mechanical control of *Sagittaria* is utilized in channels and drains when the hydraulic capacity of water delivery infrastructure needs to be restored quickly. The technique, which mostly uses excavation machinery, is particularly useful where herbicide application is inappropriate, such as near sensitive crops or where channels are in continual use and cannot be shut down for applications of herbicides. Mechanical control methods can be costly due to high labour and transport costs. They may also fragment *Sagittaria* plants, which may then disperse through water delivery infrastructure. Viable propagules such as seed, tubers, stolons, rhizomes or crowns may also remain after treatment by mechanical methods, necessitating follow-up suppression activity (Flower 2003, Nitschke 2008, Chapman and Dore 2009). In irrigation systems, mechanical control can damage or re-profile drains and channels, leading to leakage or ponding, which can affect water delivery.

The design of irrigation channels can influence colonization patterns of *Sagittaria*. Where water levels can be maintained at depths greater than the transition point from submersed to emergent forms of *S. platyphylla* (50 cm), water delivery benefits are obtained. Steeper slopes decrease infiltration of *S. platyphylla* into deeper parts of a channel and reduce the impact of damaging emergent forms.

Flower (2003) found that various stubble management practices, such as retention, burning or incorporation have no immediate effect on establishment and growth of *S. calycina*, while nitrogen applications at rates similar to those used for rice (between 20 and 200 kg N ha $^{-1}$) enhanced growth. In rice crops, allelopathic potential to selectively inhibit the development of *Sagittaria* exists in rice germplasm, offering the possibility of integrated weed management practices (Seal *et al*. 2004).

Response to other human manipulations

The roles of fire, grazing by domestic stock and slashing have not been evaluated in Australia for suppression of *Sagittaria*, but are unlikely to be of great benefit due to the asexual modes of reproduction in *S. platyphylla* and non-target impacts in rice-growing areas. In natural ecosystems, competitive and desirable native aquatic vegetation may offer potential for the suppression of *S. platyphylla*, particularly if combined with other forms of control such as selective use of herbicides or classical biological control, but formal evaluation is required.

Natural enemies

In an evaluation of the potential for classical biological control of *S. platyphylla* in Australia, a number of arthropods were reported to be associated with *Sagittaria* spp. but no phytophagous insects or plant pathogens were specifically recorded associated with *S. platyphylla* in North America (Sagliocco 2005). The first systematic survey for natural enemies in the USA commenced in August 2010, through Mississippi, Tennessee and Alabama, with a follow-up survey conducted in Texas and Louisiana in September 2011 (Kwong and Sagliocco, unpublished data). Four species of *Listronotus* (Curculionidae: Brachycerinae: Rhytirrhinini) were collected and identified as *L. appendiculatus* (Boheman), *L. frontalis* LeConte, *L. sordidus* (Gyllenhal) and *L. tuberosus* LeConte. The most common and abundant weevil encountered was *L. appendiculatus*. Adults feed on flowers and fruits, while larval feeding in fruits caused significant destruction of the receptacle and developing achenes. Larvae were observed pupating at the base of flower stalks and petioles (N. Harms personal communication 2011). While 18 species of *Listronotus* are known to be associated with *Sagittaria* in North America, limited information on the biology and host plants of these species is available. In some species, larvae develop in flower stalks, receptacles, petioles, leaves, root collars and tubers, and may cause stems galls in some instances. Feeding sites often develop conspicuous globules of hardened latex. At least some species pupate in peduncles, where teneral adults may also be found. Adults are largely nocturnal and appear to feed mainly on fruiting heads, fruits or leaves (O'Brien 1981, Muenchow and Delesalle 1992, Center *et al*. 2002, Sagliocco 2005). Adults have also been observed to swim using dog-paddle like strokes (O'Brien 1981), a useful trait to assist dispersal should they be selected for classical biological control. The impact of *Listronotus* on their hosts varies depending on the species. In Ohio, larvae of *L. caudatus* (Say) destroyed up to half of the tubers of *S. latifolia*, while the larvae of *L. appendiculatus* and *L. echinodori* both fed within the fruit, with *L. appendiculatus* causing the most damage (Muenchow and Delesalle 1992). Larvae of *Listronotus frontalis* LeConte develop in leaf petioles of *S. graminea*, while *L. neocallosus* O'Brien pupate in root collars of *S. engelmanniana* (O'Brien 1981). Other curculionids such as *Brachybamus electus* Germar, *Barinus bivittatus* (LeConte), *Anchodemus angustus* LeConte, *Onychylis nigrirostris* (Boheman), and *O. angustus* LeConte occur on *Sagittaria*, but little information is available on their host range (Leng 1913, Blatchley and Leng 1916, Blatchley 1920, Tanner 1943).

Nine species of donacid beetles (Coleoptera: Chrysomelidae) are found on *Sagittaria* (Brigham *et al*. 1982). Adult *Donacia* usually spend their life above the water surface while larvae feed on the roots, rhizomes and submersed stems and extract oxygen from the stems. Although their specificity is not well documented (Jolivet and Hawkeswood 1995), Hoffman (1940) suggests a high degree of host preference. While no donacid beetles were collected on *S. platyphylla* during surveys conducted in 2010, root, crown or tuber-feeding arthropods are of interest as potential biological control agents for *Sagittaria* in Australia due to their potential capacity to damage growth apices and carbohydrate storage organs. During the 2011 survey, larvae of a large *Listronotus* sp. were found causing considerable damage to root crowns leading to plant death.

The dipteran family Ephydridae, consisting of predominantly aquatic species, has two species recorded from *Sagittaria* in the USA: *Hydrellia deceptor* Deonier (Deonier 1971, Deonier 1998) and *H. griseola* Fallen (Lange *et al.* 1953), the latter being a pest of rice and other crops. The chloropid fly, *Eugaurax* sp. (Diptera: Chloropidae) was the only dipteran collected from *S. platyphylla* during recent surveys. Larvae were observed in flowers and young fruits. Little is known of the food habits of *Eugaurax*, although *E. floridensis* Malloch has been reared from *S. lanceolata* (Sabrosky 1974).

The aquatic larvae of the pyralid moths *Munroessa icciusalis* (Walker) and *Parapoynx obscuralis* (Grote) have been recorded on *S. latifolia* in South Carolina (Herlong 1979) but are known to feed on a range of aquatic plants (McCafferty and Minno 1979). Neither of these species was observed on *S. platyphylla* in recent surveys. However, caterpillars of *Spilosoma virginica* (Fabricius) (Lepidoptera: Arctiidae) were commonly seen feeding on leaves, but this species is also polyphagous and of little value for classical biological control.

Seven species of plant parasitic nematodes are recorded from *Sagittaria* and have potential as classical biological control agents. The bud nematode *Aphelenchoides* sp. occurs in the leaves of *Sagittaria* and *Elodea*. Similarly, the polyphagous *Aphelenchoides fragariae* (Ritzema Bos) feeds on apical buds of the submerged aquatic weed *Hydrilla verticillata*, while *Hirschmanniella caudacrena* Sher is pathogenic on the floating aquatic *Ceratophyllum demersum* L., where it can cause death of the host, and is also associated with *Sagittaria*, *Cabomba* and *Ludwigia* (Sher 1968, Esser and Harkcom 1982, Esser *et al*. 1985, Gerber and Smart 1987). In Australia, the waterlily aphid (*Rhopalosiphum nymphaeae* (Linnaeus)) feeds on a range of aquatic and terrestrial plants, including *S. sagittifolia* (Eastop 1966). In North America, this aphid is also recorded feeding on *S. montevidensis* (Smith 1992) and is a vector of abaca mosaic virus, cabbage black ringspot virus, cauliflower mosaic virus, cucumber mosaic virus and onion yellow dwarf virus (Oraze and Grigarick 1992, Center *et al*. 2002).

Records of plant pathogens from *S. platyphylla* are uncommon, but may reflect limited sampling effort rather than a depauperate mycoflora. *Doassansia* leaf smuts (Doassansiales: Doassansiaceae) are recorded from *Sagittaria* in North America and Japan (Fischer 1953, Tanimoto and Kusakari 2000). *Doassansia sagittariae* (Fuckel) J.C. Fisch., known from at least six *Sagittaria*, is recorded from *S. graminea* (Fischer 1953), a species closely related to *S. platyphylla*, and from *S. montevidensis* (Templeton 1962, Farr *et al*. 2006). Additional pathogens from unspecified species of *Sagittaria* include *Puccinia* (Uredinales), *Burilla*, *Pseudodoassansia*, *Pseudodermatosorus sagittariae* (Vánky & C.Vánky) Vánky (Ustilaginales), *Cercospora alismatis* Ellis & Holw. and *Ramularia* (Hyphomycetes), *Colletotrichum*, *Gloeosporium*, *Marssonia*, *Pestalotia* (Coelomycetes) and *Sclerotium* (Deuteromycotina) (Farr *et al.* 1989, Vánky 1999, Farr *et al.* 2005). *Plectosporium alismatis* (Oudem.) W.M.Pitt, W.Gams & U.Braun (Phyllachorales) (= *Rhynchosporium alismatis*) (Pitt *et al*. 2004) was investigated for the control of *Alisma lanceolatum* and *Damasonium minus* in Australian rice growing areas (Cother and Gilbert 1994b, Cother 1999), and although this pathogen is known from *Sagittaria* (Cother and Gilbert 1994a), *S. platyphylla* and *S. montevidensis* were resistant non-hosts (Pitt *et al*. 2004). Nine species of fungi are recorded from *S. montevidensis* in Brazil, with four (*Cercospora sagittariae* Ellis & Kellerm., *Colletotrichum gloeosporioides* (Penz.) Penz. & Sacc., *Plectosporium alismatis* and *Pseudocercospora arthrospora* D.J. Soares, R.W. Barreto & U. Braun) having potential for use as biological control agents (Soares and Barreto 2009). Leaf spots were commonly found on *S. platyphylla* during surveys conducted in 2010-11. Twenty-nine fungus species were isolated from *S. platyphylla* leaf spot lesions. However, these were generalist pathogens or secondary invaders with no potential for biological control (J. Shearer personal communication 2011).

As *Sagittaria* is not native to Australia and provides virtually no beneficial contribution to the national economy, invasive species, particularly *S. platyphylla* and *S. calycina*, are attractive targets for classical biological control. The wide native distribution of these *Sagittaria* would allow for selection of appropriate species or biotypes of biological control agents suited to climatic situations in Australia. While the economic impact of *S. platyphylla* in Australia warrants nomination as a target for classical biological control, consideration should also be given to the inclusion of *S. calycina* based on the species' large potential distribution in Australia. Detailed field surveys of the phytophagous biota, particularly plant pathogens, and herbivory loads associated with *Sagittaria* in Australia and within the native distributions of *S. platyphylla* and *S. calycina*, would substantially contribute to an informed evaluation of potential control prospects.

Acknowledgments

We thank Linda Broadhurst (CSIRO) and participants of the Canberra 2010 *Sagittaria* workshop for assisting in the identification of knowledge gaps. We thank Charles O'Brien, Nathan Harms and Judy Shearer for assistance with the collection and/or identification of organisms associated with *Sagittaria* in the USA. We thank Pat Feehan and Gavin Rose for comments on an earlier draft of this paper. Paula Bosse, Fiona Ede, Richard Maxwell, Geoff Sainty, Barry Powells, Kathy Stephens, Dorean Erhart, Lisa Mitsch, Tim Nitschke and Phil Moran contributed data records on the distribution of *Sagittaria* in Australia. Franz Mahr kindly prepared the maps. Data from the Australian Virtual Herbarium was also used to help prepare Figure 2.

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