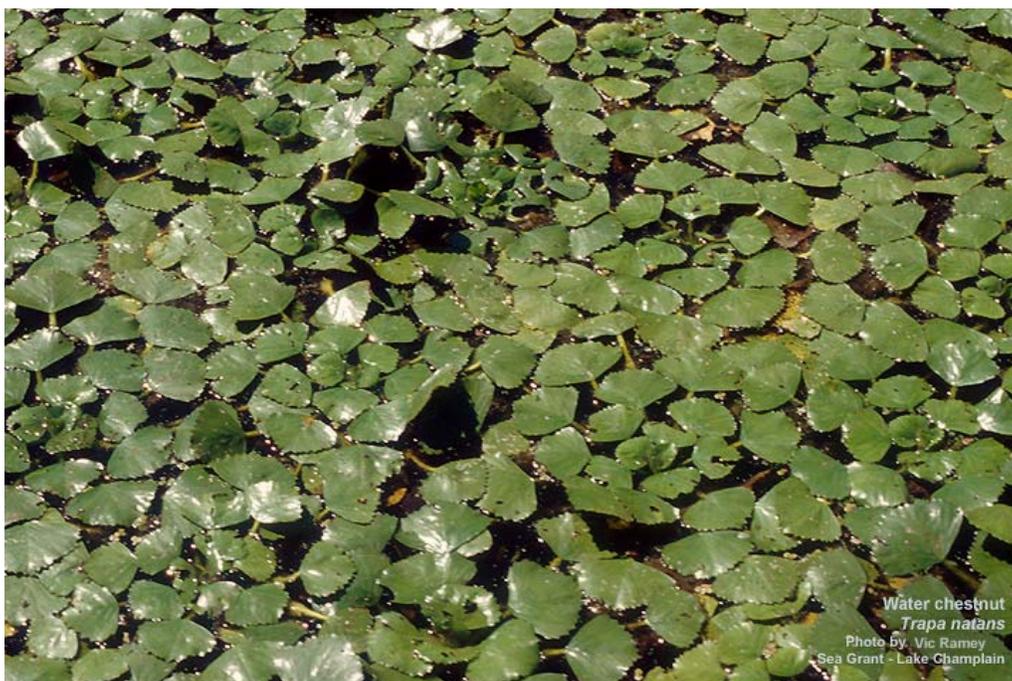


Water Chestnut (*Trapa natans*)

A Technical Review of Distribution, Ecology, Impacts, and Management



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Trapa natans

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Water Chestnut, (*Trapa natans*): A Technical Review of Distribution, Ecology, Impacts, and Management

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Bureau of Science Services

This literature review was commissioned by the nonprofit Centre for Agricultural Bioscience International (CAB International; <http://www.cabi.org/index.asp>) as part of a larger invasive species compendium. We completed eight literature reviews for the project, and due to the large number of requests for this information, we have decided to make the reviews available as DNR miscellaneous publications. Species reviewed include:

- Carolina fanwort (*Cabomba caroliniana*) – [PUB-SS-1047 2009]
- European frog-bit (*Hydrocharis morsus-ranae*) – [PUB-SS-1048 2009]
- Indian swampweed (*Hygrophila polysperma*) – [PUB-SS-1049 2009]
- African elodea (*Lagarosiphon major*) – [PUB-SS-1050 2009]
- Yellow floating heart (*Nymphoides peltata*) – [PUB-SS-1051 2009]
- Curly leaf pondweed (*Potamogeton crispus*) – [PUB-SS-1052 2009]
- Water spangles (*Salvinia minima*) – [PUB-SS-1053 2009]
- Water chestnut (*Trapa natans*) – [PUB-SS-1054 2009]

In completing the literature reviews, we preferentially consulted the peer-reviewed primary literature and supplemented the reviews with secondary sources where necessary. The outline for the reviews is identical for each species and was provided as part of the CAB International commissioning. This effort compliments work conducted during the development of the WDNR's proposed invasive species identification, classification and control rule; a more exhaustive list of species and accompanying literature review summaries can be found on the DNR website at: <http://dnr.wi.gov/invasives/>

Identity

Taxonomy and Nomenclature

The genus *Trapa* L. has been reported as having extremely confusing morphology worldwide; it has previously been classified as 1 polymorphic group or as one genus having up to around 20 different species (Takano and Kadono, 2005). The genus *Trapa* is presently placed in the monogeneric family Trapaceae, Dumort., nom. cons. which is synonymous with family Lythraceae J. St.-Hil., nom. cons. (USDA-ARS, 2008), though it has been placed elsewhere (Hummel and Kiviat, 2004). The genus *Trapa* has been included directly in family Onagraceae (Keng, 1978) as well as in Lythraceae (Watson and Dallwitz, 1992 onwards). Most botanists recognize two species in the *Trapa* genus: *T. bicornis* Osbeck and *T. natans* L. *T. natans* is an important food crop; many regional varieties are grown in different parts of the world. Official accounts recognize two: *T. natans* var. *natans* L. and var. *bispinosa* (Roxb.) (ITIS, 2007). In general, European lines are early flowering, but have lower yield, Asian lines have higher rosette densities and small fruits, while the Chinese and Indian lines have higher yields due to their large fruits (Lalith et al., 2007, Pshennikova, 2007).

Summary of Invasiveness

Trapa natans is a productive, annual, floating-leaved plant which has been cultivated globally for the nutritious nut it produces (Hummel and Kiviat, 2004). It is an extremely important food crop in China and India and is protected in Europe, (Hummel and Kiviat, 2004), but in its introduced range, it grows in thick stands that displace native vegetation and affect water quality. Thick beds of water chestnut can cause significant declines in dissolved oxygen that negatively affect sensitive fauna (Hummel and Findlay, 2006). The nearly impenetrable mats are of virtually no use to wildlife and interfere with boating, fishing and swimming, while the large, spiny nuts can cause injuries to swimmers (ISSG, 2005). *T. natans* sets abundant seed, making it difficult to eradicate once it is introduced (Les and Mehrhoff, 1999).

Distribution, Introduction, and Spread

Distribution

The genus *Trapa* is cultivated worldwide for the harvest of its large, nutritious nut. It currently occupies a wide yet discontinuous range across Europe, Asia, and Africa, and has been introduced to North America and Australia. The variety *T. natans* var. *natans*, with its four-spined nut is widely distributed in Eurasia, Africa and the northeastern United States, whereas *T. natans* var. *bispinosa* (also known as *T. bicornis*, *T. bicornuta*, or *T. japonica*), a two-spined variety, grows in China, Japan, India and Southeast Asia (Hummel and Kiviat, 2006). It is preferentially associated with low-energy, high-nutrient systems (USDA-NRCS, 2008).

History of Introduction and Spread

Trapa natans was first introduced when it escaped cultivation in the late 1800s. Its floating-leaf growth form and edible seeds made it an interesting candidate for aquaculture, and it was likely widely available in the late 19th century (Les and Mehrhoff, 1999). Records show that the gardener for the Cambridge Botanical Garden intentionally planted *Trapa* in area ponds before 1879. It was then introduced to the New York area around 1884; it is likely that it was either planted intentionally for waterfowl food or that it accidentally escaped from a water garden (O'Neill, 2006). The plant was not initially considered aggressive, but by 1899, it had become invasive, requiring control (Les and Mehrhoff, 1999). The first introductions to the Great Lakes region occurred around the 1950s (O'Neill, 2006), where the species likely spreads as a hitchhiker on nets and rope on boats (Les and Mehrhoff, 1999).

Risk of Introduction

T. natans has largely been spread as a result of intentional plantings. There have been many reports of escape from cultivation, and the species was originally introduced as an ornamental (Les and Mehrhoff, 1999). *T. natans* remains well-established in the northeastern United States to this day (Hummel and Kiviat, 2004). The plant annually produces nuts that sink to the sediment and germinate. The rough spines of the fruit make it generally unpalatable to wildlife, reducing the likelihood of the species being spread this way. Instead, seeds disperse passively, being carried by water currents as they drop to the sediment surface (Boylen et al., 2006). The spines of the fruit also allow it to spread over longer distances as a hitchhiker, when it clings to boats and gear (Hummel and Kiviat, 2004).

Biology and Ecology

Description

T. natans is an herbaceous, floating-leaf aquatic species that often grows in water around 60 cm deep (PFAF, 2000). The floating leaves are arranged in a rosette, with leathery upper leaves up to 5 cm wide and broadly rhomboid, triangular, deltoid or broadly ovate (Hummel and Kiviat, 2004). The leaves are sharply serrate, with conspicuous venation and short, stiff hairs. The species also produces submersed leaves that are strikingly morphologically different (Bitonti et al., 1996). The submersed leaves are alternate, finely divided, and can grow up to 15 cm long (Mehrhoff et al., 2003). The petioles of the floating leaves have a spongy section that allows for the flotation of the leaf rosette, and each stem may produce several rosettes (Hummel and Kiviat, 2004). The plant also has white flowers with four 8 mm-long petals and four green sepals. The fruit is a horned nut-like structure that develops underwater and is approximately 3 cm wide (Mehrhoff et al., 2003). Single flowers are produced in axils of floating leaves (Hummel and Kiviat, 2004). The stem of the plant is flexible and from 1 to 5 m long, nodes of the stem have slender linear roots, while the plant is anchored in the sediment by the lower roots that emerged from the propagating seed hull (Hummel and Kiviat, 2004).

Similarities to Other Species

T. natans is unlikely to be readily confused with native plants in its adventive range. The distinctive floating rosette of leathery green leaves and the production of large horned nuts means it is highly morphologically distinct from other floating-leaf species. The two most commonly recognized varieties are distinguished based on the number of spines. The Eurasian/European varieties always have four spines, whereas the Asian varieties (*Trapa natans* var. *bispinosa*) have two spines.

Habitat

T. natans is found world-wide in full sun and low-energy, nutrient-rich fresh waters (Hummel and Kiviat, 2004). It is commonly found in waters with alkalinity ranging from 12 to 128 mg/L of calcium carbonate (O'Neill, 2006), and dislikes calcium-rich waters (PFAF, 2000). Mixed reports exist on the depths of water typically inhabited by *T. natans*. Some sources report the plant can grow in water up to 5 m deep (Pemberton, 2002), others report that *T. natans* can be found in depths ranging 0.3 to 3.6 m (Hummel and Kiviat, 2004), while still others report a maximum depth of 0.6 m (PFAF, 2000). Hummel and Kiviat (2004) report that the species is found most abundantly in water around 2 m deep and in soft substrate. It also prefers slightly acidic water (PFAF 2000), although germination can occur in water with pH ranging from 4.2 to 8.3 (Hummel and Kiviat, 2004). The species is disturbance-tolerant; it has been shown that sewage inputs create favorable conditions of increased alkalinity for the plant, and that increased nitrogen is correlated with increased petiole and fruit biomass. *T. natans* does not tolerate salinity; its seeds will not germinate when NaCl concentrations exceed 0.1% (Hummel and Kiviat, 2004).

Genetics

The taxonomy of the genus *Trapa* is confusing: it has been varyingly considered as part of one polymorphic group, or as a genus with approximately 20 species. Enzyme electrophoresis indicates, for example, three distinct lineages in the Japanese *Trapa*. The analysis indicates that two varieties of *Trapa* have different chromosome numbers ($2n = 96$ and $2n = 48$). However, the authors recognize that despite the distinct genetic

differences, the species *T. natans* and *T. bispinosa* may be a polymorphism of the same single species (Takan and Kadono, 2005). A different study identified genotypic variation as an important factor affecting organogenesis in more than 18 different *T. natans* genotypes drawn from all over the world (Hoque et al., 2007). However, the current tendency is to consider the family Trapaceae a single monogeneric group containing two species that exhibit high genetic and morphological variation.

Reproductive Biology

Trapa natans is an annual species that produces single, bisexual flowers on stalks produced from the center of the floating rosettes. The flower has a two-chambered ovary, four stamens, four petals, and four sepals that eventually become the spines of the fruit (ISSG, 2005). The flowers are generally pollinated by insects, but self-pollination may occur before the flower opens (Hummel and Kiviat, 2004). Once fertilized, the flower stalks droop downward, allowing the ovary to develop underwater into a nut-like barbed fruit (ISSG, 2005). The seed has two unequal cotyledons, one of which is large and starchy. Each rosette produces 10 to 15 nuts, and each nut can give rise to up to 20 additional seeds (O'Neill, 2006). Seeds can remain dormant in the sediments for up to 10 years but do not tolerate desiccation (Hummel and Kiviat, 2004). Vegetative reproduction is also very important to the growth and spread of the plant. The plant produces ramets that can break off and move away from the rest of the clone and survive to produce seeds. This attribute allows for extremely rapid clonal expansion, for example, a 10-fold increase documented in one year in Lake Champlain (Groth et al., 1996). In fact, it has been suggested that this annual plant might act as a perennial in parts of its exotic range, mainly through rapid proliferation from clonal fragments year to year (Groth et al., 1996).

Physiology and Phenology

In spring (May in the northeastern USA), stems bearing leaf rosettes elongate toward the surface of the water. The rosettes flourish and remain green until fall. The plant begins to flower in early summer, and can continue to flower through to fall (June to September in its North American range). The fruits mature mid-summer through fall, after which they sink to the sediment when the plant begins to senesce. The plant quickly decomposes, but the seeds can stay dormant for up to 10 years. The nut overwinters in the sediment, but when water temperature rises to 12 °C, the terminal pore begins to rot, and around one month later, the seed germinates. (Hummel and Kiviat, 2004).

Associations

T. natans is an extremely widespread species and its worldwide distribution means it has a great many associates.

Environmental Requirements

In its alien range, *T. natans* can grow in any freshwater setting (Swearingen et al., 2002) and is found typically in water from .3 to 3.6 m deep (Hummel and Kiviat, 2004). It is restricted to low-energy systems and favours nutrient-rich waters with pH from 6.7 to 8.2 and alkalinity from 12 to 128 mg/L calcium carbonate (O'Neill, 2006).

Movement and Dispersal

Natural Dispersal

T. natans disperses primarily through water flow. The nuts are 20% heavier than the surrounding water, and as the nuts sink downward, water currents carry them a short distance away from the parent plant. Additionally, when ramets break, groups of rosettes can detach from the clone and float a long distance to establish a new population much further away from the parent plant. (Hummel and Kiviat, 2004).

Vector Transmission

Humans may be the primary vector of transmission. *Trapa natans* has been historically valued as an ornamental; its escape from ornamental and botanical gardens likely explains the invasion of the plant in the New World (Les and Mehrhoff, 1999). Although still available from online distributors, current educational efforts aim to decrease the probability that this plant will be intentionally introduced, and hopefully cut down on accidental release in areas where this plant has been declared a noxious weed. Les and Mehrhoff (1999) report observations of nuts attached to the feathers of geese, although they hypothesize that due to the size and weight of the nuts (6 g), it is unlikely that they would remain attached during prolonged flight, so although waterfowl may be a possible vector of transmission, dispersal in this manner likely only occurs over short distances.

Accidental Introduction

Humans can serve as a transmissive vector: the nuts have spines that allow the seed to move as a hitchhiker on boats and attached equipment (Les and Mehrhoff, 1999). This factor has contributed to the spread of *T. natans* in its alien range from the Hudson River to Lake Champlain via interconnected waterways (Les and Mehrhoff, 1999).

Intentional Introduction

T. natans was intentionally introduced into its alien range around the end of the 19th century (Les and Mehrhoff, 1999). The species remains an attractive water garden plant as well as a valuable food crop, and it is possible that intentional introduction will help expand this species' range further.

Natural Enemies

Many natural enemies in the native range of *T. natans* have been documented by Pemberton (1999). The plant is native to the Old World, and many enemies (insects, fungi, viruses) are found throughout its native range. Of the currently explored enemies, he reports that the most common and damaging species in Asia is *Galerucella birmanica*, it causes complete defoliation of entire populations and is also somewhat host-specific (oligophagous). Hummel and Kiviat (2004) report observations on natural enemies in the plant's alien range. *T. natans* is productive and is occasionally a nuisance in its native range; therefore, natural enemies are extremely important to keep populations in check. A major reason behind why the plant is so problematic in its introduced range is precisely because of release from predation (O'Neill, 2006).

Impacts

Economic impact

T. natans is an economic asset in its native range as it is an important food crop and a staple in many areas. However, in its introduced range, the plant is a significant nuisance. The economic cost of *T. natans* in the northeastern United States was not well documented (Pemberton, 2002), but we do know that from 1982 to 2001, \$4.3 million dollars were spent on *T. natans* control in the Lake Champlain basin alone (Naylor, 2003). The largest control program, which takes place in Vermont, was estimated to cost \$500,000 in the year 2000 (Pemberton, 2002).

Social Impact

This plant can cause substantial nuisance to recreational users by impeding navigation and tangling fishing line. This species has little nutritional benefit for fish or waterfowl, and can have detrimental effect on native game species that utilize the area. Additionally, the sharp spines present on the nuts can result in puncture wounds to swimmers (O'Neill, 2006). The plant may have played a role in the drowning deaths of a woman and two children in 2001 on the Hudson River (Hummel and Kiviat, 2004). Some people eat the chestnuts raw and ingest the giant intestinal fluke *Fasciolopsis buski* [Lankaster] that is known to cause fasciolopsiasis, and the beds are known to be good breeding grounds for mosquitoes (Hummel and Kiviat, 2004). However, there is evidence that the *T. natans* nuts have been consumed by humans as early as 8000 B.C. Currently, the nut is valued worldwide for both its nutritional value as well as its medicinal properties.

Impact on Habitat

T. natans can have severe impacts on the environment. When compared to areas vegetated by native species, areas under *T. natans* beds experienced higher variation in dissolved oxygen levels. In a study on the Hudson River, dangerously low DO values (below 5 mg/L) occurred 51% of the time, and levels below 2.5 mg/L occurred 30% of the time, while DO below 5 mg/L *never* occurred in native *Vallisneria* beds (Caraco and Cole, 2002). These observed low levels can be lethal to fish, and consequently cause the migration of small fish from under the canopy to the edges of the beds, which in turn can cause the congregation of game fish at the edges of the beds (O'Neill, 2006). Where the plant is very abundant, up to 50 rosettes can grow within one square meter, covering the water with up to three layers of leaves (Pemberton, 2002). The high density growth of which *T. natans* is capable can result in a decrease in light penetration. In one study that occurred in the Hudson River, only 0.5% of incident light reached a depth of .2 meters underneath large beds of *T. natans* (Caraco and Cole, 2002). Yet other studies report the species' general ability to intercept 95% of incident light (Hummel and Kiviat, 2004).

Impact on Biodiversity

Due to the species' ability to shade out other submersed vegetation, it is generally considered a threat to biodiversity in its introduced range. The species also has an effect on epiphyton communities. In its native range, epiphyton development was shown to be significantly higher on submerged plants than on *T. natans*, while taxonomic composition of epiphytic algae, but not macroinvertebrates, was higher on *T. natans* (Cattaneo et al., 1998). Water chestnut is considered an invasive, destructive species, and has been implicated in the loss of many other plant and animal species. In the Hudson River, for instance, the plant has replaced water celery (*Vallisneria americana* Michx.), clasping

pondweed (*Potamogeton perfoliatus* L.) and nonindigenous Eurasian watermilfoil (*Myriophyllum spicatum* L.). However, the shelter created by the rosettes is beneficial for Duckweeds (*Lemna minor* L., *Spirodela polyrhiza* L. and *Wolffia* spp.) and filamentous algae. Other emergent species that grow above the waterline, including cattail (*Typha angustifolia* L.), pickerelweed (*Pontederia cordata* L.), and spatterdock (*Nuphar advena* [Aiton] Aiton f.) are unaffected by the presence of *T. natans* (Hummel and Kiviat, 2004).

Management

Economic Value

T. natans has long been consumed by humans across the globe (Hummel and Kiviat, 2004). The nuts have a high moisture content and are valued for quenching thirst as well as being used as a source of flour that forms the base for many different food products (Hummel and Kiviat, 2004). The nuts' composition consists of 15% protein, 7.5% fat, 52% starch, 3% sugar and 22.5% water (Hummel and Kiviat, 2004). Singhara nut plants (related subspecies) is highly productive and is capable of high yields (typically 260-370 g/m² and up to 550 g/m²) (Hummel and Kiviat, 2004). As well as being an important food source, the nut has also been recommended for use as paper pulp, fertilizer, fish food, compost and biofuel (Hummel and Kiviat, 2004).

Social Benefit

The plant is used medicinally to treat rabies, poisonous animal bites, diarrhea, amoebic dysentery and other complications (Hummel and Kiviat, 2004). *T. natans* has also been used in an herbal mixture that has proven to provide relief from the symptoms associated with recurrent herpes genitalis and labialis (Hijikata et al., 2007). The rind of the fruit has been discovered to have antibacterial activity, and is primarily effective against gram negative bacteria (Parekh and Chanda, 2007).

Environmental Services

While being widely reported as productive, and as a nuisance in its invasive range, *T. natans* is capable of some environmental services. The plant is able to fix a large quantity of nitrogen and phosphorus (Marion and Paillisson, 2003). This attribute conveys a certain amount of potential for the plant to be used as a tool to reduce eutrophication, however, the vegetation must be removed annually prior to its decay and subsequent release of sequestered nutrients (Hummel and Kiviat, 2004). Water chestnut may also be used in environmental reclamation, as it is capable of accumulating heavy metals, although not at levels as high as other species commonly used in this capacity (Hummel and Kiviat, 2004).

Invasive Species Management

Prevention

Since *T. natans* remains valued for its nutritional and cultural uses, and since it is still a plant of botanical interest, educational programs must be directed to educate the public about the dangers this plant poses outside of its native range. Teaching users how to clean equipment in a way that decreases the chance of transmission is one way to lessen the impact of human-mediated transport. Several states have legislated the regulation of the purchase, transportation, and introduction of this species.

Detection and Inspection Methods

The distinct floating rosette makes this aquatic species easier than most to detect soon after invasion.

Rapid Response

It is much easier and more effective to attempt to control this plant early in its introduction timeline. Small populations are effectively controlled by hand pulling, preferably prior to the production of the propagating nuts. If the infestation is allowed to persist, it will likely grow quickly. It has been reported that this species is capable of increasing its biomass by 10 times in a single year (Groth et al., 1996). Large infestations must be controlled by mechanical harvesters or herbicides and can be quite costly (O'Neill, 2006).

Public Awareness

Numerous educational campaigns have been directed at informing the public about the danger of aquatic invasive species and states in which *T. natans* is particularly problematic commonly distribute informational materials about its identity as well as instructions on how to report new invasions. Other educational campaigns have been directed toward informing the public about how to clean equipment in order to prevent the movement of invasive species.

Eradication

It has been reported that this species was eradicated from the state of Virginia (ISSG, 2005).

Cultural Control and Sanitary Measures

Nuts, though large and not as portable as propagules of other aquatic invasive species can remain dormant for up to ten years, so it is extremely important to decrease the instances of accidental introduction by addressing humans as a vector. Additionally, since the plant is capable of producing ramets and engaging in vegetative clonal expansion via plant fragments, establishing guidelines on how to properly clean equipment, dispose of water, and identify target plants will likely decrease instances of accidental transportation and release.

Physical and Mechanical Control

Since the seeds of *T. natans* can remain dormant for up to 10 years, annual control efforts for at least that long must be undertaken in order for there to be a chance of eradication (O'Neill, 2006). Large beds must be mechanically harvested, but this will provide relief for only one growing season (O'Neill, 2006). Smaller areas of infestation can be addressed with hand pulling, although care must be exercised that all parts of the plant be removed, lest fragments remain to mature and produce fruits (Hummel and Kiviat, 2004). Ultrasound has also been proposed as a possible method of control. After treatment of the stem with ultrasound for 10 seconds, a mortality rate of 97.6% was reported (Wu, 2007).

Movement Control

Plants can spread locally as nuts and fragments drift in water currents, but most attention should be given to addressing forms of human-mediated transport. A number of states have enacted legislation limiting the introduction, sale, transportation and trafficking of the species in an attempt to limit the rate of accidental or intentional introduction (USDA-NRCS, 2008).

Chemical Control

Some control of water chestnut has been documented with subsurface applications of triclopyr and 2,4-D amine. However, the maximum control achieved was only 66% (Poovey and Getsinger, 2007). Due to its limited efficacy, if chemical control is used, it should be accompanied by other forms of physical control and removal.

Biological Control

Much attention has been given to discovering methods of biological control. Grass carp *Ctenopharyngodon idella* [Valenciennes] have been used to control water chestnut (Hummel and Kiviat, 2004). However, grass carp are non-selective herbivores that will almost certainly harm native species. Much research has been forwarded on the use of herbivorous insects from the plant's native range (Pemberton, 1999). Of the explored species, the leaf beetle *Galerucella birmanica* has shown the most promise. Although concerns regarding its specificity were forwarded early on in the research process, it has since been shown that although capable of completing its life cycle using native *Brasenia schreberi*, *G. birmanica* exhibits a strong preference in the laboratory and in the field for *T. natans*, with only occasional "spill-over" of beetles onto *B. schreberi* (Ding et al., 2006).

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Trapa natans
Dimorphic leaves and inflated petioles

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