3 WATER CHESTNUT

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PEST STATUS OF WEED

Water chestnut (*Trapa natans* L.) (Fig. 1), also known as horned water chestnut or water caltrop, is an aquatic weed of the northeastern United States that can dominate ponds, shallow lakes, and river margins (Fig. 2). It displaces native vegetation and limits navigation and recreation. It occurs from the northeast, west to the Great Lakes, and south to Washington, D. C. The plant has the potential to spread into the warm temperate and subtropical regions of the United States, such as Florida, which prohibits importation of the plant (State of Florida, 1996).

Nature of Damage

Economic damage. This weed is difficult and expensive to control, and if unmanaged can increase dramatically (Bogucki *et al*., 1980). When the plant occupies a site, most recreational activities such as swimming, fishing from the shoreline, and the use of small boats are eliminated or severely impeded. The primary economic costs related to *T. natans* are associated with the costs of chemical and mechanical control efforts. Vigorous management efforts by the U.S. Army Corps of Engineers during the 1950s and 1960s brought *T. natans* populations in the United States. largely under control, but these control programs were suspended because the programs' success and because of budgetary constraints (Madsen, 1994). During the 1970s, *T. natans* populations began to increase, and by 1994 the weed infested more areas than before the control programs (Madsen, 1994). The cost of these control programs was not well documented (J. Madsen, pers. comm.). Currently, the largest control program is in Vermont, where $500,000 will be spent for the year 2000 to remove the plants, primarily by use of mechanical harvesters and hand removal. (H. Crosson, pers. comm.).

Figure 1. Single rosette of water chestnut (*Trapa natans*) showing the horned fruits and the inflated leaf petioles that enable the rosette to float. (Photograph by Al Colfancesco, U.S. Army Corps of Engineers.)

Figure 2. Infestation of *Trapa natans* on Lake Champlain, New York. (Photograph by Al Cofrancesco, U.S. Army Corps of Engineers.)

Ecological damage. *Trapa natans* grows best in waters that are nutrient rich and moderately alkaline (Papastergiadou and Babalonas, 1993; Kiviat, 1993). It can grow in water up to 5 m deep, but prefers shallow waters (0.3 to 2.0 m deep) (Papastergiadou and Babalonas, 1993). Where *T. natans* is abundant, up to 50 rosettes can grow in 1 m^2, which enables it to cover the water with up to three layers of leaves

(Tsuchiya and Iwaki, 1984). Heavy shade from *T. natans* suppresses both submersed and other floating plants. The weed's extensive clonal propagation ability enables it to successfully colonize and monopolize aquatic habitats (Groth *et al*., 1996). The Nature Conservancy's (TNC) concern about water chestnut's impact on local flora in the Vermont areas of Lake Champlain has stimulated the TNC to create large teams of volunteers to hand pull the rosettes (S. Crawford, pers. comm.)

Geographical Distribution

Trapa natans was first observed in North America, growing "luxuriantly" in Sanders Lake, Schenectady, New York, in 1884 (Wibbe, 1886). The plant subsequently spread to many other areas in the northeastern United States including Connecticut, Delaware, Maryland, Massachusetts, New Hampshire, Pennsylvania, Vermont, Virginia, and Washington D.C. (Crow and Hellquist, 2000). The plant is now present in the Great Lakes Basin (Mills *et al*., 1993; Groth *et al*., 1996) and recently has been found in Quebec, Canada (C. B. Hellquist, pers. comm.).

BACKGROUND INFORMATION ON PEST PLANT

Taxonomy

Trapa natans often is considered to belong to the Trapaceae, a monogeneric family that is widely distributed in the Eastern Hemisphere (Cook *et al*., 1974). Historically, the genus *Trapa* has been placed in both the Onagraceae (Cronquist, 1981) and the Lythraceae (Fassett, 1957). After being considered part of an independent family for some years, modern molecular research places *Trapa* species once more in the Lythraceae in the order Myrtales (The Angiosperm Phylogeny Group, 1998). Because of the morphological variation in *Trapa* species, there has been little agreement about the number of species in the genus. Various classification schemes have designated from one to 30 *Trapa* species (Cook, 1978). *Trapa* species are determined by fruit morphology and plants with four stout horns on the fruit most often are called *Trapa natans.* The two commonly cultivated species in Asia, *Trapa bicornis* Osbeck and *Trapa bispinosa* Roxburgh, have two horns and are considered by some workers to be agricultural selections of *T. natans* (Kadono, pers. comm.). Unfortunately, an unrelated edible aquatic plant, *Eleocharis dulcis* (Burm.f.) Trin. ex Henschel, a sedge in the Cyperaceae, also is called water chestnut. The corm of *E. dulcis* is the familiar water chestnut, or Chinese water chestnut, sold in cans and commonly served in Chinese restaurants.

Biology

Trapa natans is an annual herb with a floating rosette of leaves around a central stem that is rooted in the hydrosoil. The spongy inflated leaf petioles enable the rosette to float. The plant produces new leaves from a central terminal meristem in the rosette near the surface of the water. The inconspicuous flowers are born in the leaf axils of younger leaves above the water. As the meristem elongates and produces new leaves, the older leaves and developing fruit move, in effect, down the stem and underwater. The single-seeded mature fruit are woody and bear four sharply pointed horns. When mature, the fruits fall from the plant and sink to the bottom of the water body. A seed dormancy period of four months has been found (Cozza *et al.*, 1994). The horns may act as anchors to limit the movement of the seed, keeping them in suitable depths of water. The seeds overwinter at the bottom of the water body and germinate during and throughout much of the warm season to produce shoots that grow to the water surface, where the typical rosette is formed. Seed can remain viable for up to five years (Kunii, 1988).

Analysis of Related Native Plants in the Eastern United States

If *T. natans* is considered to be a member of the mongeneric Trapaceae, a family native to the Eastern hemisphere, then there are no native family members in the New World. If, however, *Trapa* is considered to belong to the Lythraceae, it has confamilial native relatives in North America. The Lythraceae is a small family in North Amercia containing 18 to 20 species in eight genera (*Ammannia, Cuphea, Decodon, Didiplis, Heimia, Lythrum, Nesaea,* and *Rotala*) (Soil Conservation Service, 1982). Six of these genera (all but *Heimia* and *Nesaea*) have species that are broadly sympatric with *T. natans* in North America (Soil Conservation Service, 1982).

HISTORY OF BIOLOGICAL CONTROL EFFORTSIN THE EASTERN UNITED STATES

Area of Origin of Weed

The native area of *T. natans* is from western Europe and Africa to northeast Asia including eastern Russia, China, and southeast Asia, through to Indonesia (Sculthorpe, 1967; Oliver, 1871; Voroshilov, 1982). The starchy nut-like fruit of *T. natans* and its cultivars have been used as food by people in much of the native range and are widely cultivated in Asia (Tanaka, 1976).

Areas Surveyed for Natural Enemies

The specific geographic origins of the *T. natans* genotype(s) that has become a problem in the United States are unknown. The weed usually is thought to be from Eurasia but recent work considers it of Asian origin (Crow and Hellquist, 2000). The two regions surveyed for insect and pathogen natural enemies of *T. natans* are northeast Asia and western Europe, which represent the eastern and western areas of the plant's temperate zone distribution (Pemberton, 1999). China, Japan, eastern Russia, and South Korea were surveyed in 1992 and 1993. These areas were selected because of previous records of damaging insects on wild populations of *Trapa* and published accounts of pest insects of cultivated *Trapa* in the region (Lu *et al.,* 1984; Hayashi *et al*., 1984). Some of these natural enemies on *Trapa* occurred in areas with climates similar to those of the infested areas of North America. In Asia, surveys were carried out on populations of the wild forms of *Trapa japonica* Flerov and *T. natans*, and on the cultivated forms of *T. bicornis* and *T. bispinosa*, which are thought to be agricultural selections of *T. natans*. *Trapa* species and cultivars were locally common in China, South Korea, and Japan, but much scarcer in eastern Russian. *Trapa natans*, the only European *Trapa* (Tutin *et al*, 1968), was surveyed in France, Germany, Italy, Poland, and Switzerland in 1995. *Trapa natans* is a rare plant in Europe and the subject of conservation efforts to preserve and restore populations.

Natural Enemies Found

Tables 1 and 2 list the insects found associated with *Trapa* species in northeast Asia and in western Europe (Pemberton, 1999). Among the insects found, the leaf beetle *Galerucella birmanica* Jacoby was the most common and damaging species found in Asia, causing complete defoliation of whole populations of plants. Nymphuline pyralid moths also were common and at times damaging. Both the beetle and the moths feed and develop on unrelated plants, so have no potential as *T. natans* biological control agents in North America. Because of the possibility of sibling *Galerucella* species with different host plants, *G. birmanica* may warrant additional study. Two *Nanophyes* weevils, which feed in the floating leaf petioles, were found in Asia. They are thought to be specific to *Trapa* but were not observed to be damaging. Low density populations of polyphagous Homoptera were common. Chironomid midges also were frequently associated with the plants, but for the most part were filter feeders, not herbivores. In Europe, a similar insect fauna was found, but no species were very damaging to the plant. One Italian weevil, *Bagous rufimanus* Hoffmann, feeds within the fruit stalk (Mantovani *et al*., 1992) and might be more damaging at higher than observed population levels.

Host Range Tests and Results

To date, this biological control project has been limited to surveys and monitoring of South Korean populations of *T. japonica* for natural enemy activity and damage. No host specificity testing has yet been done.

BIOLOGY AND ECOLOGY OF KEY NATURAL ENEMIES

Galerucella birmanica Jacoby and *Galerucella nymphaeae* L. (Coleoptera: Chrysomelidae)

Galerucella birmanica (= *G. nipponesis* Laboissiere) was abundant in most regions surveyed in northeast Asia, except for Hokkaido in Japan and the Russian Far East. All life stages of the beetle are found on the upper leaf surfaces. The adults and larvae feed on the leaf blades of the plants. Young larvae scrape the upper surface of the leaves, while older larvae and adults consume the blade tissue, often leaving a skeletal leaf comprised of main veins. This beetle can be very damaging, causing whole mats of rosettes to be defoliated. There are several overlapping generations in most areas which enables the populations to rapidly increase. It is the most important pest of cultivated *Trapa* in China and India (Khatib, 1934;

Table 1. Natural Enemies of *Trapa* Species in Northeast Asia (Pemberton, 1999)

Natural Enemy Species	Country	Feeding Site	Host Range
INSECTS			
Aphididae (Homoptera)			
1. *Rhopalosiphum nymphaeae* (L.)	China, Japan, S. Korea	Leaves	Polyphagous
Cicadellidae (Homoptera)			
2. *Macrosteles purpurata* Kuoh et Lu	China, Russia	Leaves	Polyphagous
Chrysomelidae (Coleoptera)			
3. *Galerucella birmanica* Jacoby (=G. nipponensis Laboissiera)	China, Japan, S. Korea, Russia	Leaves	Oligophagous
Curculionidae (Coleoptera)			
4. *Nanophyes japonica* Roelofs	China, Japan	Petiole floats	Stenophagous
5. *Nanophyes* sp.	China, Russia	Leaf blades, petiole floats	Stenogphagous
Pyralidae (Lepidoptera)			
6. *Nymphula interruptalis* (Pryer)	China, Japan, S. Korea,	Leaves and buds	Polyphagous
7. *Nymphula responsalis* (Walker) (=*N. turbata* Butler)	China, Japan, S. Korea	Leaves	Polyphagous
8. *Paraponyx vittalis* (Bremer)	China	Leaves	Polyphagous
Noctuidae (Lepidoptera)			
9. *Spodoptera litura* Fabricius	China	Leaves	Polyphagous
Lepidoptera			
10. Unknown leafminer	China, Japan	Leaves	?
Chironomidae (Diptera)			
11. *Chironomus* spp.	China, Japan, S. Korea, Russia	Petiole floats	Filter feeder
12. Unknown spp.	China, Japan, S. Korea, Russia	Leaves and buds	?
MOLLUSKS			
13. *Radix auricularia* L.	China	Leaves	Broad
FUNGI			
14. *Cercospora* sp.	China	Leaves	Broad
15. *Sclerotium rolfsii* Scaccardo	China	Whole plant	Broad
16. *Botrytis cinerea* Persoon et Fries	China	Whole plant	Broad
OTHER PATHOGENS			
17. Unknown, possible virus	China	Whole plant	?

Table 2. Natural Enemies of *Trapa natans* in Western Europe (Pemberton, 1999)

Natural Enemy Species	Country	Feeding Site	Host Range
Aphididae (Homoptera)			
1. *Rhopalosiphum nymphaeae* (L.)	France, Poland	Leaves	Polyphagous
Cicadellidae (Homoptera)			
2. Unknown leafhopper species	France, Italy	Leaves	Probably polyphagous
Curculionidae (Coleoptera)			
3. *Bagous rufimanus* Hoffman	Italy	Fruit epidermis and peduncle, stem	Stenophagous
Chrysomelidae			
4. *Galerucella nymphaeae* (L.)	France, Italy, Poland	Leaves	Oligophagous
Pyralidae (Lepidoptera)			
5. *Nymphula* sp.	France, Poland	Leaves	Probably polyphagous
Chironomidae (Diptera)			
6. Unknown sp. 1	France, Germany, Italy, Poland	Leaf petiole	Filter feeders
7. Unknown sp. 2	Poland	Apical bud, leaves	?

Lu *et al*., 1984). The beetle also was noted on cultivated *Trapa* along the Mekong River in Vietnam, where farmers use insecticides against it. The beetle eats and develops on unrelated plants, including *Brasenia schreberi* J. Gmelin (Cabombaceae) (Hayashi *et al*., 1984; Lu *et al*., 1984), which gives it its common Japanese name "*junsai mushi,*" which translates as *Brasenia schreberi* insect. It also appeared to be using a floating *Polygonum* sp. (Polygonaceae) as a host plant in northern China. It is possible that *G. birmanica* could represent more than one species with different host plants even though it is a well known pest insect in Asia. Sibling *Galerucella* species with different host plants are known (Blossey, pers. comm.).

Galerucella nymphaeae L. was the most apparent natural enemy of *T. natans* in Europe, occurring in all areas except Germany. This species is very similar to the Asian *G. birmanica*, with regard to appearance, life cycle, and manner of feeding. It was not observed to be very abundant or damaging anywhere in Europe. The beetle feeds on many different unrelated plants, including water lilies. This beetle is a holartic species (Horn, 1893), so already occurs in the United States, where it also feeds on *T. natans*, and unrelated plants (Schmidt, 1985).

Nanophyes japonica Roelofs and *Nanophyes* sp. (Coleoptera: Curculionidae)

Two *Nanophyes* weevils were observed to attack the leaves of *Trapa* spp. in Asia. A brief description of leaf and rosette characteristics is provided here to aid the understanding of the weevils' life cycles. The rosettes of plants float because each leaf stalk (petiole) is enlarged and filled with spongy tissue that forms a float. The leaf position within the rosette changes with age; young leaves expand from the meristem in the center of the rosette, and move outward as the petiole lengthens. As the meristem produces new leaves, it elongates upward, which places older leaves further down on the stem below the surface of the water.

Nanophyes japonica Roelofs is abundant in central Japan and the Nanjing area of China. The adults feed on the upper leaf blades and females lay eggs in the floating leaf petioles. The larvae feed and pupate within these spongy petioles. Attacked petioles are

Table 3. Reported Natural Enemies of *Trapa* of Potential Interest (Pemberton, 1999)

Natural Enemy Species	Country	Feeding Site	Reference
INSECTS			
Curculionidae (Coleoptera)			
Bagous tersus Egorov et Gratshev	Russia	Petiole	Egorov and Gratshev, 1990
Bagous trapae Prashad	India	?, on stem	Prashad, 1960
Bagous vicinus Hustache	India	?	Bharadwaj and Chandra, 1980
Bagous sp.	India	?, reduces crop	Batra, 1962
Nanophyes rufipes Motschulsky	India	?	Bharadwaj and Chandra, 1980
Chrysomelidae (Coleoptera)			
Galerucella singhara Lefroy	India	Leaves	Bharadwaj and Chandra, 1980
Galerupipla sp. near *brunnea* Walker	Thailand	Leaves	Cantelo, 1965
Haltica cyanea Weber	India	Leaves	Batra, 1962
Pyralidae (Lepidoptera)			
Nymphula gangeticalis Lederer	India	Leaves	Bharadwaj and Chandra, 1980
Nymphula crisonalis Walker	Thailand	Leaves	Cantelo, 1965
DISEASE			
Fungus			
Bipolaris tetramera (Mckinney) Shoemaker	India	Leaves	Singh and Lal, 1965

often reddish in color and frequently have indented areas where the eggs have been laid. At times, particularly in smaller plants, the petiole becomes gall-like, with thickened outer walls. Several larvae may occupy an attacked petiole. Blades of leaves with infested petioles are normal in color and appearance, and infested plants produce many fruit, suggesting that the weevil does little damage.

Another unidentified *Nanophyes* species was found in the Harbin area of China and at Hinkanski in Russia. This weevil lays a single egg in the central vein of the upper side of the leaf blade. The newly hatched larva mines the central vein of the leaf blade downward into the petiole float where it finishes feeding and pupates. There is only one larva per leaf, and even though almost all leaves of some plants may be attacked, the leaves and plants remain normal and healthy. Adult feeding on the leaves is minor. The developmental periods (from egg to adult) for both of these weevils appear to be the same as the life span of a single leaf in which the development takes place, which is usually one to two weeks depending on the temperature. The eggs of both weevils are laid in young recently expanded leaves near the center of the rosette and the pupae of both species are found in old submerged leaves on the stem below the water's surface. This synchrony of weevil development with leaf age suggests extreme host specialization. *Nanophyes japonica* has not been recorded from plants other than *Trapa*, and it seems that both of these weevils are limited to *Trapa* species. They are the most specialized natural enemies of *Trapa* species found in northeast Asia.

RECOMMENDATIONS FOR FUTURE WORK

Although *T. natans* continues to be a problem that requires expensive control efforts, no biological control research is being conducted at this time, but future research could help develop biological controls for the weed.

Because the very damaging, Asian leaf beetle *G. birmanica* might be composed of sibling species with different host plants, it would be worthwhile to determine the identities of populations of the beetle associated with different host plants with molecular tools. D2 gene comparisons, which are a useful and inexpensive method for determining species identities of many insect groups (J. Goolsby, pers. comm.), could be used to examine *G. birmanica*.

Surveys for natural enemies have examined widely separated populations of *T. natans* and other *Trapa* spp., but large regions remain unexamined. It is probable, however, that these surveys provide a good indication of what exists in the temperate part of the plant's range, given the similarities in the natural enemies in the far eastern and western parts of the plant's native range. Some temperate areas remain that might contain promising natural enemies. One of the most interesting areas is Kashmir, which has large populations of *Trapa* in an area that is isolated from the rest of temperate Asia by the Himalayan Mountains. There is a diverse fauna of *Trapa* in the warmer areas of India (Table 3), and some of these species might be adapted to the colder climate of Kashmir. The Volga River Delta at the north end of the Caspian Sea also has large *Trapa* populations, and people living there call themselves the *Trapa* eaters (M. Volkovitsh, pers. comm.). *Trapa* populations in this area may lack the isolation needed for them to acquire a natural enemy fauna that is different from that which occurs in temperate Eurasia.

Trapa natans is native also to areas with tropical and subtropical climates including Africa, southern Asia, and southeast Asia. If this weed becomes a problem in the warmer parts of North America, insect natural enemies of the plant from warm areas could become important and might have promise as biological control agents. A number of insects have been reported to attack *T. natans* in warm areas (Table 3), such as India and Thailand. Some of the weevil species are known to reduce fruit yield (Batra, 1962). Insecticides are used against some of these insects, another indication of their impact on the plants (Bharadwaj and Chandra, 1980). Most of these insects are related to species found in surveys in Europe and northeast Asia. They include *Bagous* and *Nanophyes* weevils, Nymphuline moths, a third *Galerucella* sp., and two additional genera of leaf beetles. Some of these may have more specificity and/or ability to damage the plants than the natural enemies encountered to date.

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