Curly-leaf Pondweed (*Potamogeton crispus*)

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

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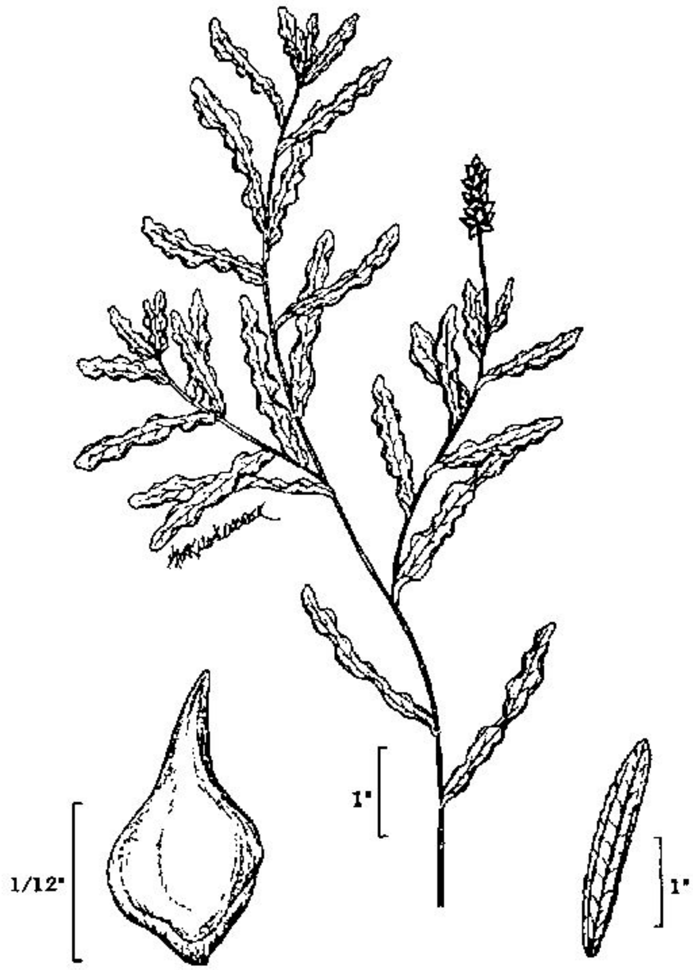

Potamogeton crispus

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Curly-leaf Pondweed (*Potamogeton crispus*)
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
Potamogeton crispus, of order Najadales, family Potamogetonaceae, is a monocotyledonous aquatic forb first described by Linnaeus in 1754. The genus *Potamogeton* contains approximately 100 species (eFloras, 2009) and is cosmopolitan. Historically, the genus has been segregated into several sections and subsections (Hagström, 1916), although more recent examination of collected specimens has led taxonomists to regard these divisions as unnecessary (eFloras, 2009). Within the genus, species have been classified by leaf shape, presence of floating leaves, seed morphology, and chromosome number (Iida et al., 2004). Although there is a high degree of morphological similarity among members of the *Potamogeton* genus, *P. crispus* is generally regarded as one of its more distinctive members. Hybridization among members of this genus is common. Hybrids of *P. crispus* have been reported worldwide, and include *P.* x *cooperi* (Kaplan and Fehrer, 2004), *P.* x *bennetti* Fryer (Wolff et al., 1997), *P.* x *undulatus* (Alix and Scribailo, 2006), and *P. x lintonii* (Neveceral and Krahulec, 1994).

Summary of Invasiveness
P. crispus is a productive submersed macrophyte that is non-native and invasive in temperate

areas of North America, New Zealand, and southern South America (Kaplan and Fehrer, 2004). The species is listed as a noxious or prohibited weed in several areas of the United States (USDA-NRCS, 2009). *P. crispus* is a cold weather strategist, which allows it to establish early in the growing season (Nichols and Shaw, 1986). Unlike most macrophytes, *P. crispus* plants typically die back by early summer and lie dormant until temperatures decrease again in the fall (Bolduan et al., 1994). It is a productive species that tends to form monocultures, thereby decreasing the amount of light available to other species (Engelhardt, 2006). However, its impact on native plant species is disputed in the literature. Some authors state that early emergence helps *P. crispus* out-compete natives, while others aver that its characteristic summer die-back removes it from such competition (Bolduan et al., 1994). The summer senescence and die-back is problematic in its own regard, as the inevitable decay of organic material and resultant nutrient release can stimulate algal blooms and lead to dissolved oxygen depletions. Additionally, this species is particularly difficult to control due to its prolific production of turions (Yeo, 1966).

Distribution, Introduction, and Spread

Distribution

The *Potamogeton* genus is one of the most important, well-represented and cosmopolitan genera of submersed macrophytes; it is extremely important to the structure and function of aquatic ecosystems across the globe (Haynes, 1975). *P. crispus* is widespread throughout much of its native range, which is commonly reported to include Europe, Asia, Africa, and Australia (Bolduan et al., 1994). It is considered non-native and invasive in temperate areas of North America, New Zealand, and southern South America (Kaplan and Fehrer, 2004).

History of Introduction and Spread

The first verified report of *P. crispus* in North America was from Philadelphia, PA in 1841-42, and after initial introduction, the plant began to establish quickly (Stuckey 1979; Bolduan et al., 1994). By the 1860s, its growth in Delaware and Pennsylvania was described as abundant, and it spread rapidly into areas of Massachusetts and New York by the early 1880s (Bolduan et al. 1994). It is likely that inward spread from this eastern population accounts for the first Canadian record in 1891 (Stuckey, 1979). Occurrences were subsequently reported throughout the Western Great Lakes region during the early 1900s (Stuckey, 1979). *P. crispus* was first collected along the western coast of the United States in 1896 (Stuckey, 1979), and slowly spread throughout the southeastern United States during the 1940s (Bolduan et al., 1994). Stuckey (1979) hypothesized accidental introduction during fish stocking activities as the primary vector for spread in New England, and also noted that the plant was at first intentionally planted due to its suitability as habitat and as a food source for wildlife. *P. crispus* currently remains widespread throughout temperate North America, where local populations continue to expand. It has been estimated that *P. crispus* currently occupies anywhere from 30-90% of its potential range (Tomaino, 2004). The first record in New Zealand occurred in 1940, although the first unofficial collection occurred earlier. At least some of the New Zealand introductions can be attributed to accidental or intended plantings (Healy and Edgar, 1980). Sparse information is available on the population reported in South America.

Risk of Introduction

Fragments of *P. crispus* can spread long distances, especially via the dormant apices that are so prolifically produced during summer. Thus, unintentional introduction via fragments transported on boats and equipment is a significant risk (ISSG, 2006). Maki and Galatowitsch (2004) also found that 10% of aquatic plant mailings in horticultural trade contained regulated noxious species, including *P. crispus*, indicating a significant risk of introduction through horticultural activities. *P. crispus* is easily acquired for intentional planting, even in states in which its sale, transportation, and release are regulated (Maki and Galatowitsch, 2004). Additionally, *P. crispus* is spread naturally over long-distances via waterfowl, especially in areas along migratory routes (Boylen et al., 2006). Fragments can locally expand populations by passive spread in flowing water or during flood events.

Biology and Ecology

Description
P. crispus is an herbaceous, submersed aquatic species that can grow over 4m in length (ISSG, 2006). Its sessile, linear leaves are light to dark green, though they can sometimes have a reddish hue. The leaves typically measure from 1.2-9 cm long, 4-10 mm wide and are spirally arranged on flattened stems. Leaves are submersed, often undulate, with obtuse apices and 3-5 veins. Leaf margins are finely serrate. Lacunae are conspicuous and occur in rows of 2-5 along the midrib of the leaf. Stipules are not fused to the leaf and are persistent, though inconspicuous. Leaves and stem are lax; the plant is entirely submersed, though oftentimes some submersed leaves will grow up to and along the waters' surface. Nodal glands are not present. Inflorescences are unbranched and emersed, generally terminal (eFloras, 2009). Flowers are tiny, with four petal-like lobes, and are arranged on spikes 1-3 cm long on stalks up to 7 cm. Sessile reddish-brown fruits are unkeeled and measure 6 x 2.5 mm. Fruits have a small recurved beak that measures 2-3 mm, and the embryo has full spiral. Short, bur-like hardened turions, in which internode length is extremely shortened, measure 1.3-3 x 2 cm, and can be either apical or axillary (eFloras, 2009; USACE-ERDC, 2002).

Similarities to Other Species
P. crispus is easily distinguished from other pondweeds by leaf and fruit morphology, phenological characteristics, and turion production (Iida et al., 2004). *P. crispus* is unique in that its leaf margins are finely serrate. Difficulties in identification may occur very early or late in the growing season when turions are germinating. At these times, the plant develops a winter growth form with very slender, limp, blue-green leaves (Bolduan et al., 1994). Serrations are present in the winter growth form, though are not as conspicuous. Members of the genus *Potamogeton* can hybridize readily and produce individuals with intermediate morphological characteristics (Kaplan and Fehrer, 2004).

Habitat
P. crispus occurs world-wide in rivers, streams, freshwater and brackish lakes, marshes, wetlands, springs, estuaries, and ponds (Iida et al., 2004; ISSG, 2006). It generally prefers alkaline, calcareous, eutrophic waters (Bolduan et al., 1994). It is disturbance-tolerant and is commonly associated with impacted, disturbed, sometimes highly polluted sites (O'Hare et al., 2006). *P. crispus* is also able to survive in a wide range of sediments, from gravel or fine sand with low organic content to loamy mud and clay (Bolduan et al., 1994). This is in part due to the ability shared by many aquatic species to acquire nutrients from the surrounding water as well as through roots. It is also important to note that this cold-tolerant species is evergreen and will grow through winter, often under thick ice cover (Stuckey et al., 1978).

Genetics
The genus *Potamogeton* is highly morphologically and ecologically diverse. Species within the genus have been classified by leaf, seed and pollen morphology, as well as chromosome number. Recent molecular analyses of Japanese *Potamogeton* have allowed for a detailed

exploration of the phylogenic relationships within the genus, indicating this monophyletic group can be split into two major groups (Iida et al., 2004). *P. crispus* is unique in carrying a long deletion in the trnT-trnL sequence; results of allozyme analysis suggests that *P. crispus* is remotely related to and diverse from other taxa in the genus (Iida et al., 2004). Several sources report *P. crispus* as having 2n = 52 chromosomes, although differing chromosome counts have been reported in the literature (Hollingsworth et al., 1998). The species itself has been described as being only moderately genetically variable, with little isozyme genetic diversity within New Zealand populations (Hofstra et al., 1995). Many hybrids have been reported in the literature, including *P.* x *cooperi* (Kaplan and Fehrer, 2004), *P.* x *bennetti* Fryer (Wolff et al., 1997), *P.* x *undulatus* (Alix and Scribailo, 2006), and *P. x lintonii* (Neveceral and Krahulec, 1994).

Reproductive Biology
P. crispus reproduces vegetatively via rhizomatic spread as well as with vegetative propagules called turions. Turions are formed from buds along the stem at or near peak biomass depending on day length, water temperature, and light intensity (Chambers et al., 1985; Bolduan et al., 1994). Production is quite prolific, with Yeo (1966) reporting a single turion of *P. crispus* placed in a 5.9m^2 container yielding 23,520 turions in a single growing season. Densities ranging from 200 – 9600 turions/m^2 have been reported growing in situ (Kunii, 1989; Bolduan et al., 1994). Differences in size, structure, and number of turions produced varied greatly between lentic and lotic environments. Lotic systems were reported as having small but numerous turions produced, while lentic systems produced much larger, but fewer overall turions (Kunii, 1989; Bolduan et al., 1994). High rates of germination have been reported in the lab (100%) and in the field (> 60%) (Bolduan et al., 1994). Turion germination is controlled by temperature and requires a cold (5ºC) or hot (30-35ºC) period to break dormancy (Bolduan et al., 1994). In a South African lake, turion germination was initiated when water temperature fell below 25ºC (Rogers and Breen, 1980) and was inhibited by darkness (Jian et al., 2003).

The species does produce seeds, with Yeo (1966) reporting a single turion producing 960 seeds during a growing season. Hunt and Lutz (1959) estimated in situ seed production at 1110-1394 seeds per square meter, based upon two study plots. However, field germination rates of seeds are extremely low (< 0.001%) (Rogers and Breen, 1980), and most likely do not play an important role in reproduction (Jian et al., 2003).

Physiology and Phenology
P. crispus has a unique life cycle, typically acting as a winter annual. After achieving peak biomass (in May in North America) the plant produces turions and dies back completely (Bolduan et al., 1994). The turions remain dormant through the summer months. As the water cools off near the end of summer the turions germinate, producing the winter growth form. Thus the plant has two periods of peak biomass; once in the spring and once in the fall. After fall germination, the plant spends the winter actively growing; its low light requirements allow it to subsist even under ice (Nichols and Shaw, 1986; Bolduan et al., 1994). The species therefore appears to be a cold-weather strategist. This allows the plant to establish early and either avoid competition or out-compete other macrophytes (Bolduan et al., 1994).

Associations
P. crispus is a cosmopolitan species, with associations reported in the literature for more than 30 plant species, including many other *Potamogeton* species (Bolduan et al., 1994). The species hosts great numbers of invertebrates, with chironomids being the most important group (Nichols and Shaw, 1986).

Environmental Requirements
P. crispus is a cold-weather and low-light adapted species (Tobiessen and Snow, 1984), allowing it to exist in deeper or more turbid waters than many other species (Jian et al., 2003). It has been reported to typically grow in water from 1m to 3m deep, though can be found in water up to 7m deep. Photosynthetic rate is highest at 30ºC (Saitoh et al., 1970), but vegetative growth has been reported to survive temperatures of 1-4ºC in the field (Stuckey et al., 1978; Tobiessen and Snow, 1984). USDA-NRCS (2009) reports an absolute minimum temperature of -33ºF (0.5ºC), with active growth stopping when temperatures drop below 5ºC. *P. crispus* is typically associated with eutrophic, alkaline sites, and is extremely tolerant of high nutrient systems (7.5 mg P L^{-1}, 75 mg N L^{-1}) (Mulligan et al., 1976). Its main phosphorus source is the sediment, whereas it acquires nitrogen and potassium from the surrounding water (Rogers and Breen, 1980; Nichols and Shaw, 1986). A study in Wales shows that *P. crispus* lakes all had conductivity >150μS and Ca+Mg/Na+K hardness ratios >3 (Bolduan et al., 1994).

Movement and Dispersal

Natural Dispersal
P. crispus spreads vegetatively via rhizomes and turions. Turions can be distributed passively via water flow (ISSG, 2006).

Vector Transmission
Turions are likely spread long distances by wildlife such as waterfowl. Dispersal via waterfowl has been documented along major migratory routes in New York (Boylen et al., 2006).

Accidental Introduction
Propagules of *P. crispus* are easily transported by recreational users (ISSG, 2006). There have been reports of accidental introduction through fishery stocking activities (Les and Mehrhoff, 1999; Tomaino, 2004), as well as documented accidental inclusion in aquaculture mailings (Maki and Galatowitsch, 2004).

Intentional Introduction
Some populations of *P. crispus* were intentionally planted as waterfowl and wildlife habitat (Les and Mehrhoff, 1999; Tomaino, 2004). In addition, *P. crispus* has been recognized as a 'useful' aquaria plant, and some localities may have originated from intentional plantings (Les and Mehrhoff, 1999).

Natural Enemies
P. crispus is heavily grazed by waterfowl throughout its range (Boylen et al., 2006). Non-indigenous red swamp crayfish have a pronounced effect on populations of *P. crispus* in Italy (Gherardi and Acquistapace, 2007). In addition, herbivorous fish will commonly graze on this species (Wang et al., 2007).

Impacts

Economic Impact
Monotypic stands of *P. crispus* can be quite a nuisance, presenting significant navigational difficulties to recreational users (Bolduan et al., 1994). *P. crispus* can also stimulate algal blooms (Nichols and Shaw, 1986) which can decrease the aesthetic value of a waterbody. These factors have a significant impact on the recreational and real estate value of a water

body, and may also have an impact on the tourism industry. Impacts are greatest in the species' introduced range, where it is considered a noxious weed (USDA-NRCS, 2009).

Social Impact

P. crispus can be a substantial nuisance to recreational users by impeding navigation and tangling fishing line. This species can also reduce swimming access and stimulate unsightly, possibly toxic algal blooms. Its environmental effects can decrease the aesthetic value of a waterbody as well as affect property values and tourism.

Impact on Crops and Other Plants

Given this species' tendency to grow in monocultures with high productivity, it has been reported to cause decreases in biodiversity by outcompeting native plants (Tomaino, 2004). However, it should be noted that the impact of this species on the native plant community is disputed, with some authors concluding that the fact that the plant acts like a winter annual removes it from negatively impacting native species (Bolduan et al., 1994). In its native range it can be productive, but is not generally reported as a nuisance.

Impact on Habitat

Massive stands of *P. crispus* substantially alter a waterbody's internal loading, and can also reduce the fetch of a lake, sometimes inducing stratification in normally unstratified systems (Bolduan et al., 1994). In a comparative study that evaluated four related macrophyte species, *P. crispus* produced the highest shoot growth rate and biomass (Engelhardt, 2006). It can grow in dense monotypic stands and affect habitat structure, which may have impacts on commercially and recreationally sought after fish species (Crowder and Cooper 1982). *P. crispus* has been reported to decrease the amount of light reaching the sediment surface (Engelhardt, 2006). However, the plant may have positive effects in extremely degraded systems. Feng et al. (2002) report that planting of *P. crispus* in enclosures improved water transparency, decreased electric conductivity, increased pH, and was shown to have an inhibitory effect on green algae.

Impact on Biodiversity

Several sources report that *P. crispus* has a negative effect on macrophyte biodiversity and often outcompetes native plants (Bolduan et al., 1994; ISSG, 2006). *P. crispus* is found at sites where *P. ogdenii,* a critically impaired species, exists. *P. crispus* likely competes with *P. ogdenii* and may be having a significant impact on it (Tomaino, 2004). In studies conducted in its native range of Poland, the variety of fungus species reported growing on dead fragments of *P. crispus* was greater in relation to other plant species (Czeczuga et al., 2005).

Management

Economic Value

P. crispus can be used in the treatment of industrial and domestic aqueous waste, obviating the need for chemical treatment (Hafez et al., 1992; Hafez et al., 1998).

Social Benefit

P. crispus has been proven to be a good resource for carotenoids, which are often used in medicine and cosmetics for their antioxidation, immunity-regulation, and tumor proliferation-slowing properties. Carotenoids like the ones extracted from *P. crispus* plants are also used as colorants and antioxidants in food additives (Ren and Zhang, 2008). *P. crispus* has been examined as an ethnobotanical treatment against cancer (Duke, 2008).

Environmental Services
P. crispus can aid in the self-purification of waterbodies over the winter by aiding in resettlement of suspended mud and sand (Cao and Wang, 2007). The plant has also been shown to improve water transparency, decrease electric conductivity, and increase pH in eutrophic systems (Feng et al., 2002). Given the species' pollution tolerance, it is a viable candidate for the revegetation and restoration of extremely impacted sites (Zhou et al., 2006; Samecka-Cymerman and Kempers, 2007). The plant may also provide adequate habitat for small fish and invertebrates, and can be a valuable food source to some aquatic herbivores (ISSG, 2006).

Prevention
The vegetative propagules of this species are very easy to spread. Therefore, educational programs are usually necessary to decrease this form of human-mediated spread. Teaching users how to clean equipment in a way that decreases the chance of transmission is one way to lessen the impact of humans as a vector. Several states have legislated regulation of the purchase, transport, and introduction of this species.

Detection and Inspection Methods
Formal aquatic plant surveys are generally necessary for the early detection of *P. crispus*. Due to the species' ability to "top out" in monotypic stands, riparian owners may also notice and report new infestations (ISSG, 2006).

Rapid Response
Because *P. crispus* prolifically produces turions which can remain viable for at least two years, rapid response to decrease turion deposition is integral to successful management (Tomaino, 2004; ISSG, 2006). Early spring treatments before turion production may be the best time for management activities (Netherland et al., 2000; Woolf and Madsen, 2003).

Public Awareness
Numerous educational campaigns have been directed at informing the public about the danger of aquatic invasive species. Agencies in areas in which *P. crispus* is particularly problematic commonly distribute informational materials about its identity as well as 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 transportation and spread of invasive species.

Eradication
No reports of eradication exist in the literature.

Cultural Control and Sanitary Measures
Turions are easily transportable and can remain dormant for at least two years, and possibly longer (Tomaino, 2004). Thus, it is extremely important to decrease the instances of accidental introduction by addressing humans as a vector. By establishing guidelines on how to properly clean equipment, dispose of water, and identify target plants, it is likely that instances of accidental transportation and release will decrease.

Physical and Mechanical Control
Mechanical harvesting may be used to obtain some nuisance relief, but reviews of efficacy of control are mixed. In Michigan, the dominance of *P. crispus* over native species was only reinforced by harvesting (Bolduan et al., 1994). In other instances, early season cutting at the sediment surface has been shown to prevent turion production (ISSG, 2006). Some have used

winter drawdowns as a means of control, but the literature reports no significant impact of overwinter drawdown on *P. crispus* (Nichols and Shaw, 1986). Shallow dredging has mixed reviews as well; in some instances there seems to be little effect, and in some cases lasting control has been achieved (Tobiessen and Snow, 1984; Tomaino, 2004). Other mechanical methods including benthic barriers, hand removal, rotovation, and shading have been reported as successful (USACE-ERDC, 2002).

Movement Control
Screening has been used to stop the passive movement of turions. However, since plants can spread via fragments, much attention has been given to decrease human-mediated dispersal. The plant is on a number of state noxious lists, and some states have put in place legislation to regulate the sale, transportation, and introduction of *P. crispus*.

Biological control
No information exists in the literature.

Chemical control
P. crispus is sensitive to 2,4-D, especially during early spring (Woolf and Madsen, 2003; Belgers et al., 2007). *P. crispus* is susceptible to endothall-based herbicides (Skogerboe and Getsinger, 2002). It is suggested that treatments which occur in early spring may help lessen the impacts on the native plant community (ISSG, 2006). The herbicides fluridone and diquat have also been used, and in general may provide relief for one growing season (ISSG, 2006).

Research Needs
More research should be directed to evaluate the impacts *P. crispus* has on natives, as well as further evaluate the impacts of nutrient release during the summer.

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