State of Michigan's Species Profile for Calligraphy Sedge (*Carex kobomugi*) Management

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Introduction and Scope

Calligraphy sedge (*Carex kobomugi* Ohwi.) is a perennial, clonal graminoid in the family *Cyperaceae* native to coastal China, Korea, Japan, and Russia (eFloras, 2022). In North America it is a shoreline- and dune-invading plant currently ranging from Massachusetts to North Carolina along the Atlantic coast (Standley, 1983; USDA, 1983; Lea & McLaughlin, 2005; Johnson, 2011; Charbonneau et al., 2017), as well as being present in Oregon on the Pacific coast (University of Washington Burke Museum, 2011). Calligraphy sedge was introduced to North America on two separate occasions: first in Oregon around the year 1900 under the name *Carex macrocephala* (Soil Conservation Service, 1941) and again in 1929 at Island Beach State Park, New Jersey, now under *Carex kobomugi*. It is hypothesized to have spread to North America in the form of solid ballast or packing material from ships and cargo from Asia as seeds or rhizomes (Small, 1954; Wootton, 2007; Halsey, 2002). Calligraphy sedge is an aggressive dune invader and may negatively impact threatened and endangered dune species such as piping plover (*Charadrius melodus*) and Pitcher's thistle *(Cirsium pitcheri*). It may also subject dunes to increased erosion by being a shorter-statured plant compared to native dune-binding plants such as American beachgrass (Lea & McLaughlin, 2005; Wooten et al, 2005; Charbonneau et al., 2017).

Synonyms

Scientific Name: *Carex macrocephala* (may have been lumped with *Carex kobomugi* prior but is separate now)
Common Name: Japanese sedge, Asiatic sand sedge, sea isle Japanese sedge

Common name notes:

The common name used in this document, calligraphy sedge, was selected after an assessment following the University of Minnesota's Invasive Species Common Name Practices (Gupta & Weber, 2022) after discussion with regional colleagues. Efforts were made to avoid place-based, name-based, and derogatory names in favor of descriptive names that better help identify the species or it habitat or communicate its history. When no existing common names met the criteria, work with the Michigan State University Translation Center and Japanese Studies Program revealed that the specific epithet, "kobomugi," refers to *mugi* (meaning wheat, rye, barley, and oats) and a mis-transliteration of the calligrapher Koo Boo Taishi. Further exploration revealed the base of *Carex kobomugi* stems were used for calligraphy brushes in medieval Japan.

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- Consolidating current science-based knowledge relative to the biology and ecology of calligraphy sedge.
- Summarizing scientific literature and research efforts that inform management options for calligraphy sedge in Michigan.
- Identifying future directions for research relative to successful calligraphy sedge prevention and management in Michigan.

Credit

This document was written by Nathan Veres under the direction of Dr. Megan Butler and was reviewed by the Michigan Departments of Natural Resources and Agriculture and Rural Development. This document references peer-reviewed journals and publications. Any chemical, company, or organization that is mentioned was included for its involvement in peer-reviewed, published, publicly shared information, not to imply endorsement of the chemical, company, or organization.

Biology and Ecology

I. Identification

Calligraphy sedge is a short and sturdy plant, approximately 0.3 m in height (Swearingen, 2009; USDA, 2023a). Its shoots grow in semi-rosette form, with small petiole angles and leaf blades touching close to its surface. It is typically found in nearly complete monocultural mats occupying 140 m^2 (Charbonneau et al., 2020), but mats may range in size from a single shoot to 10,000 m^2 (about 2.5 acres) (Wootton et al., 2005).

Figure 1: Juxtaposition of seed head (left) and flower spike of calligraphy sedge (Carex kobomugi). Photograph by Leslie J. Mehroff, 2005

The leaves are stiff and V-shaped with sharp serrations; there are 5 to 10 blades per mature shoot (Wootton et al. 2005, EDDMAPS 2023). The leaf shade is yellow-green, and leaves are 3 to 8 mm wide. Calligraphy sedge leaves tend to be longer than the shoots and often curl out and under (Swearingen 2009, eFloras 2022).

Calligraphy sedge flowers early in the growing season, starting in April and going on until June. The flower spikes themselves (Fig. 1) are numerous within the sedge mats. They are dioecious and arranged in spikes with brown scales at the end of a triangular stalk approximately 30 cm

tall, transitioning to sharp green scales when it goes to seed (Swearingen, 2009**;** Native Plant Trust, 2023). Female inflorescence is slightly larger than the male inflorescence and produces fruits (achenes) (eFloras, 2022). The flowers are the most conspicuous identifying feature of the plant; however, it is crucial to be able to identify the plant in its sterile form as it readily reproduces by rhizomes (Swearingen, 2009).

The most common lookalike of calligraphy sedge, as well as its native ecological counterpart, is the American beachgrass (*Ammophila breviligulata*). American beachgrass can be distinguished from calligraphy sedge in several ways (Fig. 2), including that the native grass typically has much longer leaves (0.3-0.9 m, often >1 m), and much longer flower spikes (~0.75 m) (Coffin and Pfannmuller, 1988; Wootton et al, 2005). The leaves of American beachgrass are also a blue-green shade, compared to the yellow-green cast of calligraphy sedge (Lea & McLaughlin, 2005).

Figure 2: Calligraphy sedge growing in native habitat (left; by Σ64 CC BY 4.0) vs American beach grass growing in native habitat (right; Royalbroil, CC BY-SA 3.0)

Another species that could be mistaken for calligraphy sedge is largehead sedge (*C. macrocephala*). Both plants have been found invading North American Pacific and Atlantic coasts (USDA, 1983; USDA, 2023b). They are so biologically similar that calligraphy sedge was once classified as a variety of largehead sedge, but they are now considered to be separate species (CABI, 2015). There are currently no reports of the two species hybridizing (CABI, 2015; Wootton, 2007). Several differences help distinguish these two species in the field: calligraphy sedge has a higher shoot density, while largehead sedge shoots are sturdier and seed heads are noticeably larger and darker (CABI, 2015).

Additionally, sedges of the genus *Cyperus* may sometimes grow on dunes and strongly resemble calligraphy sedge except they have no serrations and flower in late summer/early fall. Other species that may be misidentified as calligraphy sedge include beach panicgrass (*Panicum amarum*) and little bluestem (*Schizachyrium scoparium*) (Lea & McLaughlin, 2005; Bahkta and Bohling, 2016). Beach panicgrass can be differentiated from calligraphy sedge by being taller, having a bluish hue to the blades, and having long, arching seed heads. Little bluestem can be differentiated from calligraphy sedge by having red or blue colored blades that are much narrower than those of calligraphy sedge.

II. Detection

Calligraphy sedge is a dune-obligate species, typically found in foredunes between 40m and 100m from oceanic shorelines (Ishizuka, 1962; Ishikawa and Kachi, 1998; Min, 2004). It is highly conspicuous and easily identifiable when growing as mats (EDDMaps, 2023). It is also possible for calligraphy sedge to grow as individual plants. For lone individuals, height can be used as a quick reference: calligraphy sedge can grow to a foot tall at maximum, while native American beachgrass typically grows anywhere from 1 to 3 feet tall (USDA, 2023a). In its native range, calligraphy sedge can also be found on sandy lakeshores and riverbanks (eFloras, 2022). However, it has not yet been reported occupying any inland habitats in its invasive range as of the writing of this report (EDDMaps, 2022; iNaturalist, 2023). Ground surveys are the most efficient method for detecting calligraphy sedge, but spatial imagery/aerial photography may be used as well (Shisler et al., 1987; Burkitt & Wootton, 2011; Charbonneau et al., 2017; Charbonneau et al., 2020).

III. Life History and Spread/Dispersal

The primary method of reproduction in calligraphy sedge is through vegetative means via rhizomes (Ishikawa and Kachi, 1998; Lea & McLaughlin, 2005; Charbonneau et al., 2020). The rate at which calligraphy sedge stands expand is estimated to be between 1 and 3 m per year, even without new seedlings, and has been described as exhibiting a “guerilla” growth-form where the rhizomes of a clonal plant grow aggressively fast, yet with high mortality (Wootton, 2003; Wootton et al., 2005; Lea & McLaughlin, 2005; Charbonneau et al., 2020). Calligraphy sedge is thought to be able to spread quickly due to the large quantity of internodes growing from the rhizomes (Small, 1954; CABI, 2015). The low internodal space of calligraphy sedge rhizomes led Charbonneau et al. (2020) to suggest that interconnecting stands are unlikely. Calligraphy sedge stands become increasingly dense as the age of the stand increases, eventually outcompeting native flora and developing a monoculture (Burkitt and Wootton 2011). The rhizomes are able to grow 20 cm deeper than American beachgrass rhizomes, although calligraphy sedge rhizomes experience high mortality rates at this depth; a recent study by Charbonneau et al. (2020) found that the majority of shoots analyzed at the maximum depth calligraphy sedge can occupy (>60 cm) were dead.

Although seeds aren’t necessary for a calligraphy sedge stand to expand, they are the main mechanism of spread into new ranges and establishing new stands (Lea & McLaughlin, 2005; Charbonneau et al., 2020). Calligraphy sedge is a dioecious flowering plant and requires the presence of both male and female flowers to sexually reproduce. Pollen may be carried long distances by wind, but no research has confirmed this as of the writing of this report (Lea & McLaughlin, 2005). Flowering occurs early in the growing season, from April to June (Lea & McLaughlin, 2005). Three conditions are required for germination: a chilling period, scarification, and optimal soil depth. A chilling period, followed by a subsequent temperature above 10 °C was found to be required for calligraphy sedge germination. Seed scarification (the chipping/nicking/breaking of seed coating) occurs naturally by the sand grains found in calligraphy sedge habitat. Seeds are found to germinate only at depths around 10cm (Ishikawa

et al., 1993). The seeds are buoyant and immersible, which allows the seed to be transported long distances by wave action (Ishikawa et al., 1993).

Native Range:

Calligraphy sedge is native to coastal regions in East Asia (eFloras, 2022). In its native range, the plant is a perennial dune grass reproducing asexually (rhizominously) and sexually (Ishikawa et al., 1993; Ishikawi and Kachi, 1998). Asexual, rhizominous reproduction is the dominant reproduction mechanism and mainly contributes to the local expansion of established stands (Lea & McLaughlin, 2005). Seed germination rate is low and, due to the special adaptations of the seeds, is mainly utilized for the colonization of new stands (Ishikawa et al., 1993). Calligraphy sedge seeds are found to be buoyant and immersible in salt water. Utilizing wave action, calligraphy sedge can be transported long distances to new colonization sites (Ishikawa et al., 1993; Lea & McLaughlin, 2005; Charbonneau et al., 2020).

In its native range, calligraphy sedge is highly adapted to foredune habitats between 40 and 100 m from oceanic shorelines (Ishizuka, 1962; Ishikawa and Kachi, 1998; Min, 2004). Calligraphy sedge*'s* niche fulfillment restricts its habitat to low-nutrient sand sites adjacent to bodies of water (Ishikawa and Kachi, 1998). The spread of calligraphy sedge in its native habitat is limited by two constraining forces. First, the increasing inhospitality of the dune environment with closer proximity to ocean waters. Ishikawa and Kachi (1998) found that in Japan, calligraphy sedge most commonly grows around 40 m from ocean water but plants closer to the ocean were more likely to exhibit injuries most likely due to inundation events and exposure to highly saline water. Factors such as salt spray, erosion and burial, temperature extremes, inundation, etc. all limit the ability of calligraphy sedge to establish and spread (Kim, 2004; Ishikawa et al., 1993; Ishikawa and Kashi, 1998; CABI, 2015). Second, farther from the shoreline, the competitive superiority of other plants compared to calligraphy sedge prevents this species from spreading inland within its native range (Ishikawa and Kachi, 1998). For example, Ishikawa and Kachi (1998) found that in Japan, calligraphy sedge became less abundant farther from the ocean water likely due to competition with *Oenothera laciniata* (cutleaf evening-primrose) and *Imperata cylindrica* (cogongrass). These species have denser root systems and more aggressive growth that allow them to out-compete calligraphy sedge for resources such as non-saline water. These vegetative patterns that confine species to specific habitat niches are commonly found in dune ecosystems (Cowles, 1899).

Invasive Range:

As in its native range, calligraphy sedge primarily utilizes rhizominous growth for local expansion and establishes new stands from seed in invasive ranges (Small, 1954; Wooton, 2003; Lea & McLaughlin, 2005; Wooton et al, 2005; Charbonneau et al., 2020). In North America, the calligraphy sedge growing season varies slightly depending on local climatic conditions but generally starts in April and peaks in June or July (USDA, 2023a; Daneshgar et al., 2017; Lea & McLaughlin, 2005). Due to the frequent oceanic storms that cross the eastern seaboard, it is hypothesized that once calligraphy sedge is introduced to a new range the main mode of distant expansion for this species is utilizing transportation from storm wave action

(Lea & McLaughlin, 2005; Charbonneau et al., 2020). In the United States, human-driven spread is largely attributed to intentional planting for dune stabilization (CABI, 2015). Several recent studies have found that unlike many invasive species, Human traffic does not seem to significantly influence calligraphy sedge spread (Wootton et al., 2005; Charbonneau et al., 2020) perhaps due to the fact that seeds are not readily adhesive (Wootton et al., 2005).

Figure 3: Global distribution of calligraphy sedge (Carex kobomugi O.). Source: http://www.discoverlife.org

IV. Habitat

Native Range:

Calligraphy sedge is native to East Asia (Fig. 3). It is found in Taiwan, in China on the East Coast from Zhejiang up to Liaoning, Heilongjiang, and Tibet (Zhang et al., 2010), along the coasts of Korea and Japan, and along the coast of both Primorsky Krai and in Khabarovsk Krai on Sakhalin Island in Russia (Khan et al., 2008; eFloras, 2022; Kim, 2004; Lea & McLaughlin, 2005; Burkitt & Wootton, 2011; Tsuyuzaki, 2015; GBIF, 2022; MISIN, 2022). It is abundant in its range on coastal dunes (especially the dune crests), sandy lakeshores, and rarely on riversides, typically growing 40 to 100 m from shore (Ishizuka, 1962; Ishikawa and Kachi, 1997; Min, 2004; Khan et al., 2008). The conservation status of calligraphy sedge has not been designated globally nor nationally by any entity (NatureServe Explorer, 2023).

In China, calligraphy sedge is a foredune inhabiting plant co-dominant with *Calystegia soldanella* (sea bindweed or kidney leaf). Interestingly, even in its native habitat, calligraphy sedge has been found to negatively affect community diversity through inhibiting the colonization of other native species (Ishizuka, 1962; Yang et al., 2011). Yang et al. (2011) hypothesize that storms with a one-year period of intensity keep the growth of dominant species such as calligraphy sedge in check. However, in Korea, calligraphy sedge was found to

be outcompeted by terrestrial invasives such as Japanese mugwort (*Artemisia princeps*), hairy crabgrass (*Digitaria sanguinalis*), and seashore zoysia grass (*Zoysia sinica*) (Kim, 2004).

Associated species commonly found growing with calligraphy sedge include kidney leaf (*Calystegia soldanella*), duckbill (*Ischaemum bartatum*), beach silvertop (*Glehnia littoralis*), dwarf carex (*Carex pumila*), sand grass (*Messerschmidia sibirica*), cogongrass (*Imperata cylindrica*), strand grass (*Leymus mollis*), beach vitex (*Vitex rotundifolia*), sea pea (*Lathyrus japonicus*), okahijiki (*Salsola komarovii*), New Zealand spinach (*Tetragonia tetragonioides*), Bermuda grass (*Cynodon dactylon*), and buckbush (*Kali collinum*) (Khan et al., 2008; Yang et al., 2011).

Invasive Range:

Calligraphy sedge's invasive range includes both the east and west coasts of the United States. Initially, calligraphy sedge was introduced to North America on the Pacific coast in 1900. At the time it was categorized under the taxon *Carex macrocephala,* as it was believed that it was a variety of largehead sedge (Small, 1954). Today the invasion of calligraphy sedge on the Pacific coast is localized along the Columbia River on the Oregon-Washington border (Fig. 4) with the only reporting of the species coming from a Multnomah County (EDDMaps, 2023).

Figure 4: Calligraphy sedge reports on the West Coast (EDDMapS, 2023)

The invasion on the Atlantic coast has been more extensive compared to the Pacific coast. Calligraphy sedge was first identified on the Atlantic in 1929 under its current classification. There is uncertainty as to how exactly it was introduced into this part of the country. Some researchers hypothesize that the plant was used as packaging material on ships inbound from Asia (Small, 1954; Halsey, 2002; Lea & McLaughlin, 2005). Many researchers, however, dispute this by attesting that calligraphy sedge is an unlikely source for packaging materials and was more likely used as dry ballast (Wootton, 2007; Burkitt & Wootton, 2011). On the Atlantic coast, calligraphy sedge was initially sparse but was planted intentionally by land managers and homeowners beginning in the 1930s as a substitute for American beachgrass in stabilizing dunes (Shisler et al., 1987; VA DCR, 2011; Charbonneau et al., 2020; CABI, 2015; USDA, 2023a). By the time the invasiveness of Calligraphy sedge was

realized (Standley, 1983; USDA, 1983), it had become established in the region and began colonizing new sites as well as further expanding existing stands (Reo, 2014). Tropical storms have further facilitated the expansion of calligraphy sedge (Sigren et al., 2014), especially from Hurricane Sandy (Charbonneau et al., 2017). Calligraphy sedge has been detected on the East Coast (Fig. 5) in North Carolina, Virginia, Maryland, Delaware, New Jersey, New York, Connecticut, Rhode Island, and Massachusetts, (EDDmapS, 2013; Lea & McLaughlin, 2005; University of Washington Burke Museum, 2011). Due to its ability to spread quickly and outgrow native plants, it is listed as invasive, and its sale and distribution are prohibited by statute in Connecticut and Massachusetts. It is on state invasive species lists in Rhode Island, New York, Virginia, New Jersey, and Delaware. It is currently on North Carolina's Invasive Species watch list. The expansion of calligraphy sedge on the East Coast is expected to increase exponentially over time. (Reo, 2014).

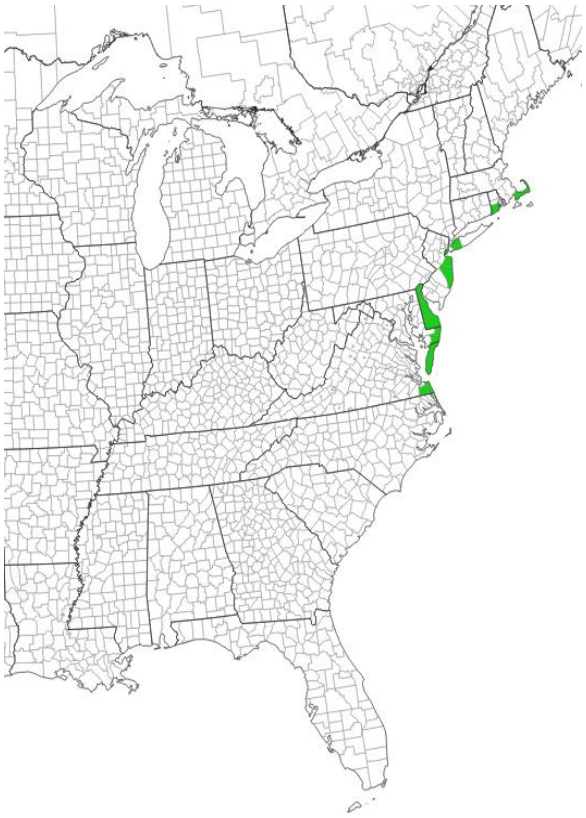

Figure 5: Distribution of calligraphy sedge on the East Coast (EDDmapS, 2023)

V. Effects of *Carex kobomugi*

Overview of Existing Research

The understanding of calligraphy sedge*'s* negative impacts on North American dune ecosystems has been well established (Burkitt and Wootton, 2011). These primarily include the reduction of native species diversity, reduction of native species richness, and alteration of dune ecomorphology.

Negative Effects

Ecological

In its invasive range, calligraphy sedge is an aggressive clonal species that dominates dune habitats, reducing native biodiversity (Lea & McLaughlin, 2005; Charbonneau et al., 2017; Charbonneau et al., 2020), density (Burkitt and Wootton, 2011), and shoot densities (Wootton et al., 2005). Once calligraphy sedge stands become established, native species richness and diversity sharply decrease (Wootton et al., 2005; Charbonneau et al., 2017). American beachgrass is particularly vulnerable to calligraphy sedge (Charbonneau et al., 2017). Calligraphy sedge has deeper rhizomes (Charbonneau et al., 2020) and more shoots per node (Small, 1954; Ishikawi and Kachi, 1998), which translates to increased nutrient uptake (Johnson, 2011) and faster, denser growth patterns (Wootton et al., 2005). Sand burial is shown to further propagate calligraphy sedge and allow it to out-compete native species as burial stimulates its

growth (Lea & McLaughlin, 2005; Burkitt and Wootton, 2011; Daneshgar et al., 2017; Charbonneau et al., 2020). While many invasive species thrive in disturbed habitats, calligraphy sedge is more likely to become established in undisturbed areas; recent studies have noted that areas with the least amount of disturbance, natural and anthropogenic, show the highest calligraphy sedge growth (Wootton et al., 2005; Charbonneau et al., 2020).

Another detrimental effect from the presence of calligraphy sedge to dune habitats is the reduction of arbuscular mycorrhizal fungi (AMF) from dune soils. Calligraphy sedge does not utilize AMF in the uptake of phosphorus like American beachgrass does. The more established a calligraphy sedge stand becomes, the more difficult it will be for native plants to recolonize sites after invasive species management (Johnson, 2011).

Damage to dune ecology caused by calligraphy sedge can alter vertebrate and invertebrate species composition and alter habitat suitability (Reo, 2014). For example, the monarch butterfly (*Danaus plexippus*), recognized as endangered by the International Union for Conservation of Nature (IUCN, 2022), relies on the seaside goldenrod (*Solidago sempervirens*) as a food source on migration routes (Reo, 2014). Thick monoculture mats of calligraphy sedge also threaten endangered shorebirds such as the Piping plover (*Charadrius melodus*) which rely on open space between dune plants for nesting (Reo 2014).

Economic:

Coastal dunes play an important role in mitigating storm damage (Sigren et al., 2014; Sigren et al., 2018). Maintaining stable, functional coastal dunes is found to be an economically viable method of mitigating storm damage (Reo, 2014; Burkitt and Wootton, 2011). Typically, this is done through dune nourishment, the addition of compatible sediments to a dune from off-site sources (Passeri et al., 2021). However, dune nourishment can also inadvertently spread calligraphy sedge (Daneshgar et al., 2017). While calligraphy sedge has been found to be an effective dune-stabilizing plant (Small, 1954; Wootton, 2003; Reo, 2014; Lea and McLaughlin, 2005; Charbonneau et al., 2020), there is evidence that calligraphy sedge-dominated dunes are shorter, more compact (Lea & McLaughlin, 2005; Wootton et al., 2005), and accumulate less sediment (Zarnetske et al., 2012), which may result in increased erosion and reduced storm mitigation abilities (Lea & McLaughlin, 2005; Charbonneau et al., 2017). The ensuing defoliation through erosion and storm outwash may reduce the scenic and recreational value of coastal dunes (Wootton et al., 2005).

Human Health and Wellbeing:

There are no known major detrimental effects that calligraphy sedge may have on human health. Beachgoers may be injured by the spiked flowers, as was observed in New Jersey (Wootton et al., 2005), which can be a deterrent to recreation.

Positive Effects

Calligraphy sedge has been found to be an effective dune-stabilizing plant (Small, 1954; Wootton, 2003; Lea and McLaughlin, 2005; Reo, 2014; Charbonneau et al., 2020). While some

studies attest that it is unclear whether calligraphy sedge is a more effective dune-stabilizing plant than American beachgrass (Wootton et al., 2005; Daneshgar et al., 2017), Reo (2014) found that dunes in New Jersey that were fronted with calligraphy sedge suffered less erosion than American beachgrass fronted dunes during Hurricane Sandy. Wootton et al. (2005) also hypothesize that the spiky flowers of calligraphy sedge act as a natural deterrent to human foot traffic (2005), a desirable trait for erosion prevention dune restoration activities.

Current Status and Distribution in Michigan

Calligraphy sedge is currently listed as a Michigan Watch List invasive species (State of Michigan, 2023a). Currently, calligraphy sedge has not been detected in Michigan. A report was made to MISIN in 2021 about the sedge being found at Guernsey Lake in Kalkaska County (MISIN, 2022), but early reconnaissance by the DNR indicates this is likely to be a misidentification (K. Grzesiak, 2022). Michigan has listed this species as a Watch List invasive plant due to its ability to dominate and outcompete native flora (State of Michigan, 2023a). As calligraphy sedge is an obligate dune species, shorelines should be prioritized when surveying.

Due to the plant's reputation as an effective dune-stabilizer and the lack of regulation regarding its sale, calligraphy sedge is likely to invade Michigan by intentional plantings, therefore all populated lakeshores should be monitored for this species. Being at a considerable distance from the species' invasion range on the Atlantic coast makes a natural invasion origin highly unlikely. While there is a direct maritime shipping route that directly links the Great Lakes to the Atlantic coast via the Hudson River and Erie canal, the Hudson River flows southward and thus away from the Great Lakes. The seeds are not found to be adhesive, making "hitchhiking" an unlikely transmission route as well (Ishikawa et al., 1993).

Management of Calligraphy Sedge

I. Prevention

Hypothetically, calligraphy sedge is able to spread to most of the Atlantic and Pacific coasts. Despite an earlier introduction date on the West Coast, calligraphy sedge has failed to expand there as it has on the East Coast. This may be due to the fact that it was intentionally planted throughout the 1960's and 1970's along the East Coast for dune-stabilization purposes. Since there was little to no anthropogenic influence like this on the West Coast population, this evidence indicates that avoiding purposeful planting is key to preventing the continued spread of this species. Connecticut and Massachusetts have both already taken steps in this direction by prohibiting the sale and distribution of calligraphy sedge (CABI, 2015; University of Connecticut Invasive Plants Working Group, 2018).

Apart from intentional planting, calligraphy sedge mainly spreads locally through rhizomes, while the seeds are specialized for long-distance establishment of new stands (Ishikawa et al.,

1993) through storm events (Ishikawa and Kachi, 1998). Human traffic does not seem to significantly influence calligraphy sedge spread (Wootton et al., 2005; Charbonneau et al., 2020) perhaps because people avoid calligraphy sedge patches due to the spikey seed heads and because seeds are not readily adhesive to passing animals.

II. Management/Control

Key Considerations

Management plans for calligraphy sedge should consider the fragility of dune environments in their execution. Calligraphy sedge forms a monoculture out-competing native species, removing established stands can increase the risk of erosion. Because the species acts as a dune stabilizer, special care should be taken in removal (Wootton et al., 2005). Letting calligraphy sedge stands remain has been preferential to some land managers if storm protection of adjacent landowners is considered. In these circumstances, it is best to conduct a planting immediately after removal (Charbonneau et al., 2017).

Mechanical and chemical methods have been used to successfully manage calligraphy sedge. In either case, it is crucial that broken rhizomes are not left after treatment as they will re-colonize the area (Lea & McLaughlin, 2005). Because of this potential, it is important to monitor sites post-treatment for any new growth and re-treat as necessary (LHPRISM, 2022).

Most researchers, including Daneshgar et al. (2017) recommend a broad approach utilizing multiple methods to manage calligraphy sedge, such as initial targeted herbicide applications followed by nourishments (sand burials) and native plantings. The Lower Hudson Partnership for Regional Invasive Species Management (LHPRISM) recommends hand-pulling or spraying new growth (2022). Wooten et al. (2005) recommend removing small stands first, due to calligraphy sedge*'s* rhizominous growth patterns.

Physical Control

Manual removal has only been successful when controlling small populations. However, it is economically and logistically infeasible to treat larger established populations manually. Infestations of less than 200 shoots have been effectively managed by hand-pulling (Small, 1954; Daneshgar et al., 2017). Shovels can be used to efficiently dig under each individual shoot to expose the rhizomes. Shoots are extensively interconnected by ¼-inch thick roots (Lea & McLaughlin, 2005). Loose shoots and rhizomes should then be hand-excavated with care to not break the plant into fragments, following the rhizomes through the sand. Any rhizome fragments left over will likely sprout. Gloves are recommended to be worn, as the terminal points of the rhizomes are sharp (Lea & McLaughlin, 2005; LHPRISM, 2022). Excavated plants should be fully desiccated in unsuitable habitats (grass, concrete) and then composted or disposed of in black plastic (Lea & McLaughlin, 2005).

Mechanical methods of removal that do not remove the entire plant and rhizomes from the area have been shown to be either ineffective or detrimental to calligraphy sedge

management. Mowing is ineffective, as the rhizomes quickly re-sprout when cut. Soil tilling also fragments the rhizomes, which encourages further growth (LHPRISM, 2022). Repeatedly burying calligraphy sedge in sand has been suggested as an alternative treatment method to chemical control given the fragility of dune environments (Wootton et al., 2005; Reo, 2014). However, Daneshgar et al. (2017) suggest that burial is not an effective method due to the potential for damage to native flora. In addition, fill used to bury plants has the potential to inadvertently introduce additional invasive species. New management techniques should be explored.

Chemical Control

Currently, glyphosate is the only herbicide used for the management of calligraphy sedge, in 2% to 3% solutions (Lea & McLaughlin, 2005; CABI, 2015). Applications are effective starting during the early growing season (April through May) and lasting until fall (October) (Lea & McLaughlin, 2005). Glyphosate should be applied to calligraphy sedge*'s* leaves. Since the leaves are so narrow, liberal coverage of leaves is needed to make up for run-off (Lea & McLaughlin, 2005). One or two spot-spray re-treatments afterward are usually required. Since a colony's rhizomes can be so extensive, the ability to conduct follow-up treatments and monitoring for multiple years after treatment is necessary (Lea and McLaughlin, 2005; University of Connecticut Invasive Plants Working Group, 2018). However, for the larger invasion sites, repeated herbicide applications beyond the 1-2 treatments recommendation may be required to control calligraphy sedge (Wooton et al., 2005).

Extra precautions should be taken when applying herbicides to sandy soils, particularly those near surface water or with high water tables. Aggressive applications can cause excessive erosion (Daneshgar et al., 2017), and transportation of herbicides is more rapid in sand compared to other soil types. In addition, soil microbes that would typically break down herbicides are likely either insignificant or absent in sandy soils typical of dune ecosystems (Lea & McLaughlin, 2005). Finally, glyphosate brands formulated with surfactant (such as Roundup) should not be applied in or near water because the surfactant can be toxic to fish and aquatic life. When applying glyphosate in aquatic conditions, it is important to use formulations without adjuvants (e.g. Rodeo, AquaNeat) and utilize aquatic-approved surfactants (NDSU, 2023).

Wootton (2003), Wootton et al. (2005), and Daneshgar et al. (2017) recommend pursuing alternative methods to chemical control, noting expenses, damage to native flora, and failure to eradicate stands for their stance. In 1999, during a removal program in New Jersey, repeat glyphosate applications of calligraphy sedge were not shown to eliminate the species from the treated sites. Meanwhile, native species richness and diversity were negatively affected (Matarczyk et al., 2002).

Biological Control

Seven species of arthropods and 71 species of fungi have been associated with the genus Carex in Asia (Zheng et al., 2005). However, there is no biological control agent in use against

calligraphy sedge at the time of this report, nor have any been currently proposed (LHPRISM, 2022).

Indirect Management

Currently, there are no indirect methods of managing calligraphy sedge being utilized. Due to the fluid nature of dune geomorphology, implementing significant landscape alterations in this environment would likely be detrimental.

Re-establishing native vegetation

Once calligraphy sedge has been removed from a dune ecosystem, it is important to establish native vegetation to prevent re-colonization and protect vulnerable dunes from storm damage, blowouts, and erosion (Lea & McLaughlin, 2005). In Michigan, American beachgrass (*Ammophila breviligulata*) is a common dune plant used for dune stabilization and restoration (EGLE, 2022). When identifying plants to use in restoration, it is important to consider where each species is found in dune ecosystems. For example, American beachgrass is also commonly planted in foredunes (Lea & McLaughlin, 2005; EGLE, 2022), while species like sand reed grass (*Calamovilfa longifolia*) are well adapted to erosional areas (Cohen et al., 2023) and species like sea-rocket (*Cakile edentula*) and little bluestem (*Schizachyrium scoparium*) are more common in back dune areas (Lea & McLaughlin, 2005; Cohen et al., 2023).

Research Needs

I. Biology and Ecology

While research has shown that calligraphy sedge has deeper rhizomes (Charbonneau et al., 2020) and more rhizome shoots per node (Small, 1954; Ishikawi and Kachi, 1998) compared to native flora like American beachgrass, other mechanisms that facilitate the calligraphy sedge's competitive success over native flora remain unclear (Daneshgar et al., 2017). For example, it is not known whether calligraphy sedge produces allelopathic chemicals (USDA, 2023a); further investigation on allelopathic possibilities and rhizome competition would improve our understanding of invasions (Callaway and Ridenour, 2004). Further research is also needed to fully understand the long-term negative impacts of established calligraphy sedge stands (Burkitt and Wootton, 2011), including calligraphy sedge's influences on soil chemistry (Daneshgar et al., 2017) and local, broad-scale environmental. In addition, more research is necessary to understand the effects of calligraphy sedge on native invertebrate and vertebrate species.

It is known that calligraphy sedge influences the ecomorphology of dunescapes, but to what extent remains unknown (Charbonneau et al., 2017). The species effectiveness as a dune stabilizer is also contested (Wootton et al., 2005; Rio, 2014), as dunes invaded by calligraphy sedge have been hypothesized to be lower in profile than dunes occupied by American beachgrass (Pronio, 1989) due to the shorter stature of calligraphy sedge (Shisler et al., 1987). From this, it could be concluded that calligraphy sedge dunes are more prone to erosion, but no evidence has come from this (Lea and McLaughlin, 2005; Wooten et al., 2005). It has also been

speculated that--due to the stouter nature of its leaves, the density of its shoots, and the density of its root structures—calligraphy sedge is more effective than American beachgrass at capturing sand particles and therefore dune-building (Zarnetske et al., 2012; Keijsers et al., 2014). Further research needs to be conducted to form a consensus.

II. Detection and Prevention

Current research indicates that human traffic does not seem to significantly influence calligraphy sedge spread (Wootton et al., 2005; Charbonneau et al., 2020). Direct planting seems to be the main source of human-related spread. However, no studies have looked into the potential for seeds to be transported in soil on recreational vehicles like dune buggies. More research on the relationship between recreation and invasive dune species such as the calligraphy sedge is necessary to help managers develop best management practices for the prevention, detection, and control of this species.

While ground surveys are currently the most common method of identifying calligraphy sedge, spatial imagery/aerial photography can be used to identify established populations growing as mats (Shisler et al., 1987; Burkitt & Wootton, 2011; Charbonneau et al, 2017; Charbonneau et al., 2020). Research that helps improve methods for using remote sensing to monitor for calligraphy sedge will be very valuable. Research that explores the use of eDNA in monitoring for new populations could also help states like Michigan improve monitoring for watchlist species like calligraphy sedge.

III. Management

More research into effective calligraphy sedge management should be explored. The efficacy of herbicides outside of glyphosate should be tested as well as application methods beyond foliar sprays such as hand-swiping and wicking. In addition, several studies have emphasized the need to identify alternative methods to chemical control for this species citing expenses, damage to native flora, and failure to eradicate stands (Wootton, 2003; Wootton et al., 2005; Daneshgar et al., 2017).

Currently, there has not been any research published on the biological control of calligraphy sedge (LHPRISM, 2022). There are several arthropods and fungi species native to Asia that are known to interact with the genus Carex in Asia that might hold potential as biological control agents (Zheng et al., 2005). There is also currently little understanding of species that parasitize or consume calligraphy sedge in North America (Maron and Villa, 2001).

While repeated sand burial has been hypothesized as a low-impact alternative to chemical control (Wootton et al., 2005) burying may cause more damage to native flora (Daneshgar et al., 2017) or even stimulate rather than suppress calligraphy sedge growth (Lea & McLaughlin, 2005; Burkitt and Wootton, 2011; Daneshgar et al., 2017; Charbonneau et al., 2020). More research is needed to understand under what conditions repeated sand burial is effective.

Practically, it is unclear at what depth the calligraphy sedge would need to be buried and how many burials would be needed to suppress rather than stimulate growth. Prescribed burnings are another potential alternative management method that has yet to be explored, although damage to native vegetation might be similar to sand burials. There is also the question of whether there is sufficient fuel to in dune ecosystems to carry sufficient fire for prescribed burns to be effective. The use of physical barriers to prevent the spread of calligraphy sedge seeds and rhizomes has also not been explored.

Future Directions for Michigan and Management

If given the opportunity to become established, calligraphy sedge could potentially thrive on Michigan's globally-rare freshwater dunes. Two common constraints for coastal dune-obligate plants are salt spray (Maun, 2009) and the competitive superiority of inland plants (Ishikawa and Kachi, 1998). The absence of salt spray in the Great Lakes could give calligraphy sedge a competitive advantage over native dune plants, as it is specialized for harsher environments. In addition, spotted knapweed (*Centaurea stoebe*), another invasive species common on dune ecosystems, has dominated and subsequently diminished native flora diversity and richness throughout the state (Marshall, 2021; State of Michigan, 2023b). Given this already weakened state of Michigan's sand dune ecosystems, calligraphy sedge may proliferate due to the lack of intraspecific competition by native plants. In addition, due to the plant's rhizominous growth pattern, sedge stands can grow exponentially if left untreated (Reo, 2014; Charbonneau et al., 2020). Therefore, prevention, early detection and rapid response are the best strategies that land managers in Michigan can employ on dune habitats concerning calligraphy sedge.

I. Prevention

Because of the plant's historical reputation and use as a dune-stabilizing plant, intentional plantings have been the main vector by which this species has spread in the United States. As such, avoiding purposeful planting is key to preventing the continued spread of this species. Today, there is still a risk that well-intentioned homeowners aiming to engage in local dune restoration efforts will purchase and plant calligraphy sedge in Michigan. Preventative efforts should focus upon preventing the intentional planting of sand sedge through policy, education, and collaboration.

The distribution and sale of calligraphy sedge is currently prohibited in Massachusetts and Connecticut (CABI, 2015). Adopting policies that prevent the sale and distribution of calligraphy sedge in the state can be an effective means of preventing the species' spread. In addition to direct policies, it is important to educate homeowners, nurseries, communities near dune ecosystems and natural resource managers about the risk that calligraphy sedge poses to native ecosystems and provide information on native alternatives such as American beachgrass that can be utilized for dune stabilization. Michigan's Cooperative Invasive Species Management Areas are an excellent resource that can facilitate educating the public and preventing the spread of this species.

II. Early Detection

It is imperative that Michigan continue to monitor and prevent the spread of calligraphy sedge into the state. Adding calligraphy sedge to existing dune monitoring programs is an important step to take. State natural resource managers should be trained to detect any initial outbreaks early and coordinate a rapid response to treat and eradicate small populations before the species becomes established. Monitoring for this species should focus on foredunes between 40m and 100m from shorelines (Ishizuka, 1962; Ishikawa and Kachi, 1998; Min, 2004). Ground surveys are the most efficient method for detecting calligraphy sedge. Surveyors should be on the lookout for both thick mats typical of established populations as well as lone individuals. Connecting homeowners and communities near dune ecosystems with resources such as MISIN can also help improve early detection efforts.

Collaboration and networking between natural resource management agencies across state lines is also an important factor that will help Michigan to continuously improve and target monitoring for this species. Systems that provide direct open access to data on species location and resources that facilitate their detection are invaluable resources (such as MISIN). Efforts to standardize, contribute to, and use these databases will ensure that these tools are as helpful to natural resource managers in Michigan as they have the potential to be.

III. Rapid Response

If new populations of calligraphy sedge can be detected and treated early, managers will have more control options and a greater chance at success. While chemical treatment with glyphosate is the most commonly used treatment, small populations (under 200 shoots) can be treated manually. Management may require a combination of physical and chemical methods and repeated applications are often necessary. After treatment, it is crucial that broken rhizomes are not left in the area as they will re-colonize the area (Lea & McLaughlin, 2005). Because of this potential, it is important to monitor sites post-treatment for any new growth and re-treat as necessary (LHPRISM, 2022).

When managing this species, it is also important to consider the fragility of the dune environment. Special care should be taken in removal to prevent erosion and harm to native dune and aquatic species (Wootton et al., 2005). Once calligraphy sedge is removed from the ecosystem, it will be necessary to immediately plant native species in order to prevent erosion, storm damage, and the re-establishment of invasive populations (Charbonneau et al., 2017).

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