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Overcoming Barriers to Aquatic Plant Restoration: Addressing Gaps in Species Identification and Planting Techniques in the Intermountain West

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OVERCOMING BARRIERS TO AQUATIC PLANT RESTORATION: ADDRESSING GAPS IN SPECIES IDENTIFICATION AND PLANTING TECHNIQUES IN THE INTERMOUNTAIN WEST

by

Kate A. Sinnott

A thesis submitted in partial fulfillment
of the requirements for the degree

of

MASTER OF SCIENCE

in Ecology

Approved:

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ABSTRACT

Overcoming barriers to aquatic plant restoration: Addressing gaps in species identification and planting techniques in the Intermountain West

by

Kate A. Sinnott, Master of Science

Utah State University, 2023

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Department: Watershed Sciences

Aquatic plants play a keystone role in inland waters through their impact on critical ecosystem functions such as primary production, nutrient cycling, habitat for aquatic organisms, and hydrologic regime. However, global assessments show an accelerated decline of aquatic plants in inland waters, largely due to anthropogenic stressors. Restoration of aquatic plant communities can help reverse this degradation, though it is not widely practiced due to capacity-related knowledge gaps. To overcome these gaps, I identified and addressed two fundamental barriers to aquatic plant restoration with an objective to increase capacity for aquatic plant restoration in the Intermountain West: 1) lack of confidence in aquatic species identification among wetland professionals, and 2) underdevelopment of planting techniques that are scalable and result in successful plant establishment. To address the first barrier, I produced the “Floating and Submerged Plants of Utah: Pocket ID Guide.” The guide contains identification information and images for 36 aquatic species and a key to the Pondweed family. To address the second barrier, I conducted two field experiments to compare the relative performance of different planting methods (how plants are introduced to a site) and planting designs (how plants are arranged within a site) across two plant material types (the form in which the plant arrives at the site) for three aquatic species. I selected planting methods that reduce planting effort and therefore can more easily be scaled up. I found that planting methods had a significant effect on establishment for one of the native species tested, *Ruppia cirrhosa*. However, effects of planting methods were not significant for the other two species, *Potamogeton nodosus* and *Stuckenia pectinata*. I found little evidence of the effects of planting design across species and plant material types. Based on these findings, I suggest that planting methods be paired intentionally with species identity to promote both establishment and efficiency, and that logistical considerations, rather than potential ecological differences, can guide planting design choices. Given the urgent need to reestablish the ecosystem functions associated with aquatic plant communities, addressing these barriers is timely and imperative to improve restoration success and reverse the degradation of inland waters.

(97 pages)

PUBLIC ABSTRACT

Overcoming barriers to aquatic plant restoration: Addressing gaps in species identification and planting techniques in the Intermountain West

Kate Sinnott

Aquatic ecosystems provide many critical and economically valuable benefits, including drinking water, food, recreational opportunities, and water supply for irrigation and agriculture. However, the health of these systems has been severely impacted by human activities such as pollution, land conversion, and introductions of harmful species. Restoring native aquatic plants can help reverse this damage and reestablish benefits, though it is not a common practice. With an objective to increase capacity for aquatic plant restoration in the Intermountain West, I identified and addressed two major barriers: 1) a lack of confidence in aquatic species identification among wetland professionals, and 2) underdeveloped planting techniques that can be used over large scales and result in successful plant establishment. To address the first barrier, I produced the "Floating and Submerged Plants of Utah: Pocket Field Guide." The guide contains identification information, images, and interesting facts about 36 aquatic species, as well as a key to the Pondweed family. To address the second barrier, I conducted two field experiments to identify successful and scalable planting techniques in a river delta in the Intermountain West. In these experiments, I examined the performance of different planting methods (how plants are introduced to a site) and planting designs (how plants are arranged within a site; clumped and dispersed designs) for two types of plant materials (stem fragments and plugs—adult plants in soil). I found that planting methods had a significant effect on plant establishment across the plant material types for one of the native species tested, *Ruppia cirrhosa*, but not the other two species, *Potamogeton nodosus* and *Stuckenia pectinata*. I did not find significant effects of planting design. Based on these findings, I suggest that wetland professionals carefully pair different species with planting methods to balance scalability and plant establishment. I also suggest that logistical considerations (such as site accessibility), rather than potential ecological differences (such as species-specific traits that may affect plant establishment), can guide planting design choices. Addressing these barriers will increase the capacity for aquatic plant restoration in the Intermountain West and subsequently support the health of aquatic ecosystems.

ACKNOWLEDGMENTS

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Kate A. Sinnott

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CHAPTER I

INTRODUCTION

Submerged and floating plants (hereafter, "aquatic plants") play a keystone role in aquatic ecosystems through their impact on several major ecosystem functions: habitat for fish and macroinvertebrates, primary production, nutrient cycling, and hydrologic regime (Carpenter & Lodge, 1986; Janssen et al., 2021; Jeppesen et al., 2012; Schriver et al., 1995). Humans receive critical and economically valuable services from functioning aquatic systems, including provisioning of drinking water and food, recreational opportunities, and water supply for irrigation and agriculture (Hilt et al., 2017; Janssen et al., 2021). However, environmental alterations are increasingly putting pressure on inland aquatic ecosystems, resulting in widespread change and habitat loss.

Quantitative global assessments of aquatic vegetation dynamics in lakes show an accelerated decline, likely caused by multiple stressors such as eutrophication, land conversion, and global climate change (Fleming & Dibble, 2015; Hilt et al., 2006; Zhang et al., 2017). Additionally, altered environmental conditions and species introductions may result in the spread of invasive aquatic plant species, which can fundamentally change wetland structure by impacting flow, displacing native species, and changing the nutrient cycle (Fleming & Dibble, 2015; Havel et al., 2015; Rahel & Olden, 2008). These environmental shifts can result in the loss of the important ecosystem services associated with aquatic ecosystem functioning (Zhang et al., 2017).

Restoration of submerged and floating plants can help reestablish ecosystem services. However, aquatic plant communities may take decades to passively recolonize after stressors are removed (Hanson & Butler, 2011; Jeppesen et al., 2005), and often the taxa that establish are non-native and invasive (Knopik & Newman, 2018). Active revegetation of aquatic plants is necessary in sites where rapid native passive recovery is unlikely or optimal conditions for natural recolonization are unachievable (Hilt et al., 2006). Despite the need for active revegetation of aquatic species, their restoration is not widely practiced due to gaps in theoretical and applied knowledge pertaining to restoration practices and community dynamics. To address these knowledge gaps, I identified two barriers to aquatic plant restoration in the Intermountain West: 1) a lack of confidence in aquatic species identification among wetland professionals, and 2) underdevelopment of planting techniques that are scalable and result in successful plant establishment.

In this thesis, I seek to attenuate these two barriers with an objective to increase the capacity for aquatic plant restoration in the Intermountain West. Through informal discussions with wetland professionals in this region, I recognized a lack of confidence in the identification of aquatic plant species. Proper species identification is critical to the competent management and restoration of aquatic plant communities, though identification of aquatic plants is particularly challenging due to their reduced flowers and shared leaf characteristics (Moody et al., 2008). Field guides that are easy to interpret and can be used in the field support basic plant identification skills (Farnsworth et al., 2013). In Chapter II, I address the lack of confidence in species identification through the production of the “Floating and Submerged Plants of Utah: Pocket Field Guide.” This guide includes 36 species and will be produced as a 4” × 6” booklet with waterproof, tearproof pages optimized for use in field conditions.

Chapter III focuses on identifying planting methods and designs that may promote successful establishment in a river delta in the Intermountain West across two plant material types. Species investigated in this chapter include *Potamogeton nodosus* (longleaf pondweed), *Ruppia cirrhosa* (spiral ditchgrass), and *Stuckenia pectinata* (sago pondweed). Results show that scalable planting methods (methods that expedite the planting process by allowing plugs to be dropped from the surface of the water) are not significantly different from hand planting plugs and that added preparation of stem fragments did not improve plant establishment across species for the species *P. nodosus* and *S. pectinata*. However, effects of planting methods were significant for *R. cirrhosa*. Thus, I suggest that planting method be paired carefully with species identity to promote both plant establishment and efficiency. I did not find significant effects of planting design (dispersed vs. clumped arrangements).

As the effects of anthropogenic stressors become more pronounced, reversing the degradation of inland waters is an increasingly urgent endeavor (Finlayson et al., 2019). Addressing barriers to aquatic plant restoration by identifying successful and scalable planting techniques and promoting recognition of native and non-native species can improve restoration success and help restore critical ecosystem functions and services to threatened aquatic ecosystems.

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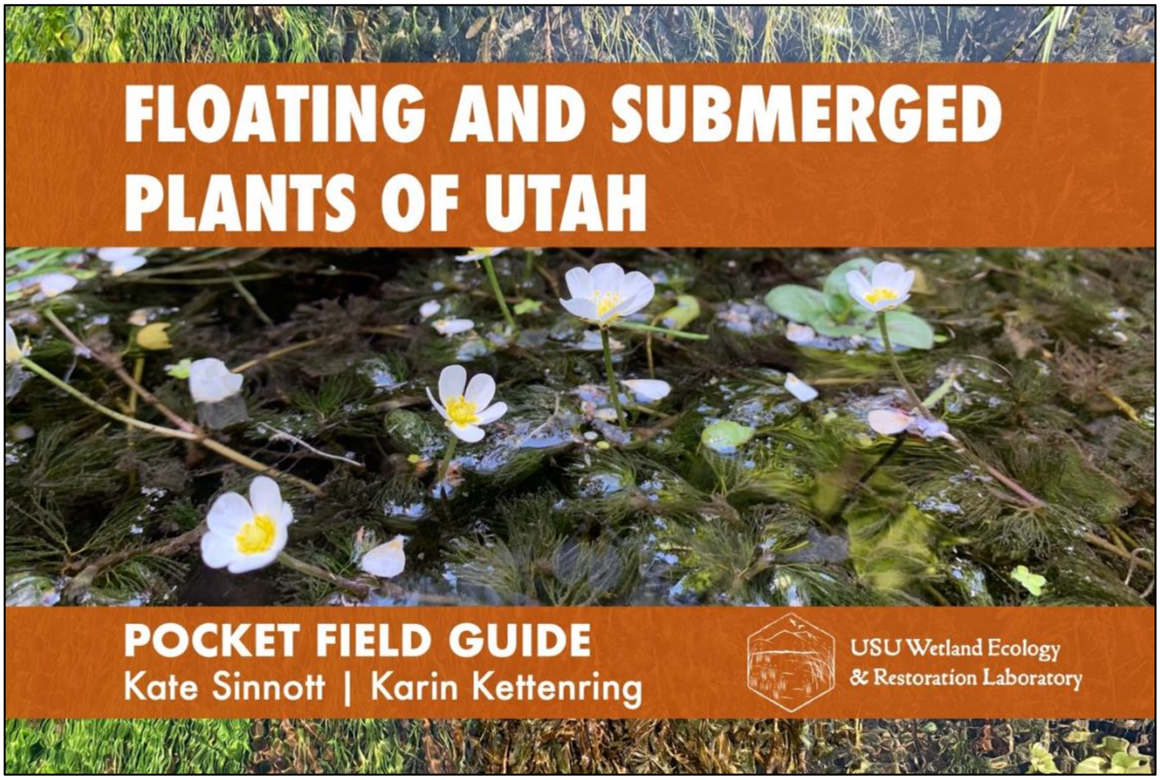
CHAPTER II

FLOATING AND SUBMERGED PLANTS OF UTAH: POCKET FIELD GUIDE

ABSTRACT

Species identification and recognition is a vital requirement to researching, managing, and restoring plant species. In informal discussions with wetland managers, restoration practitioners, and researchers in the Intermountain West, I identified species recognition as a significant barrier the research and restoration of aquatic plant communities. Guides to aid identification could help address this barrier, but available guides were incompatible with field conditions due to their large size or inability to get wet. To fill this gap, I created a list of aquatic plant species that can be found throughout Utah and compiled and consolidated information from plant keys, field guides from other regions or larger systems, online databases, and personal observations to create a field guide that would be both accessible and informative. The resulting “Floating and Submerged Plants of Utah: Pocket Field Guide” contains identification information, images, and interesting facts about 36 aquatic species, as well as a key specific to Pondweed family. It is 4” × 6” and constructed of waterproof, tear-proof pages to allow for use in a variety of field conditions.


FLOATING AND SUBMERGED PLANTS OF UTAH
POCKET FIELD GUIDE
Kate Sinnott | Karin Kettenring
USU Wetland Ecology
& Restoration Laboratory

Contents

Introduction

Submerged and floating plant species play critical roles in aquatic ecosystems. They provide habitat to aquatic organisms, improve water clarity by trapping sediment, and absorb excess nutrients from the water column, amongst many other vital services. However, they have been threatened and degraded by pollution, land conversion, and introductions of harmful species. Identifying both native and non-native plants is an important component of tackling this degradation and promoting the conservation and restoration of aquatic plant communities. We hope this book finds a home in the pocket of your waders or the bottom of your kayak and guides you in the process of getting to know these fascinating species.

Resources

Many plant identification sources were used to compile the descriptions of each species: *Aquatic and Wetland Plants of Southwestern United States,*[1] *Wetland Plants of Great Salt Lake,*[2] the U.S. Forest Service,[3] *Aquatic and Wetland Plants of Southeastern United States,*[4] the Biota of North America Program (BONAP), [5] *Aquatic Plants of the Upper Midwest,*[6] AquaPlant,[7] the PLANTS Database,[8] and *A Utah Flora.*[9] These sources may be consulted for additional information.

Acknowledgments

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DUCKS UNLIMITED

HOW TO USE THIS GUIDE

Each of the plant identification pages in this guide contains information on the species' habitat and characteristics.

Duration

Annual (A): completes life cycle in one growing season
Perennial (P): part of the plant persists year to year
Annual or perennial (AP): depends on local conditions

Nativity

Native (N): naturally occurring in Utah
Introduced (I): introduced from outside Utah
Aquatic Invasive Species (AIS): not native and a known invasive species

FAMILY

Genus species

Common name

Habitat
This plant lives in these sorts of conditions.

Stems and roots
These are the characteristics of the stems and roots.

Leaves
These are the characteristics of the leaves. We may describe them using technical words.

Flowers and seeds
These are the characteristics of the flowers and seeds.

Additional facts
This is where you'll find fun facts, synonyms of species names, and look-alike species.

Nativity:	Duration:	Commonness:
N	AP	C

The color of the plant information box indicates where this species grows in the water column:

= Most of the plant is floating on or above the surface of the water
= The plant is both on/above the water's surface and submerged
= The plant is entirely submerged

Definitions of underlined words can be found in the glossary (pg. 39).

Commonness

Common (C): found abundantly in Utah
Uncommon (U): found less abundantly in Utah
Occasional (O): found infrequently in Utah

(Commonness defined in glossary on pg. 39.)

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SALVINIACEAE

Azolla microphylla

Mexican mosquito fern

Habitat
Surface of lakes, ponds, and quiet waters of streams and canals.

Stems and roots
Plants are flattened, forming free-floating mats ①. 1–3 cm across. Small roots reach into water.

Leaves
Scale-like, green to red, lobes that are somewhat irregular in shape, small hairs on upper lobe.

Reproduction
Pitted spores located on underside of leaves.

Additional facts
Synonym: *A. mexicana*
Fixes atmospheric nitrogen.

Nativity:	Duration:	Commonness:
N	AP	U

1

CERATOPHYLLACEAE

Ceratophyllum demersum

Coontail

Habitat
Entirely submerged in quiet waters of lakes, ponds, and streams.

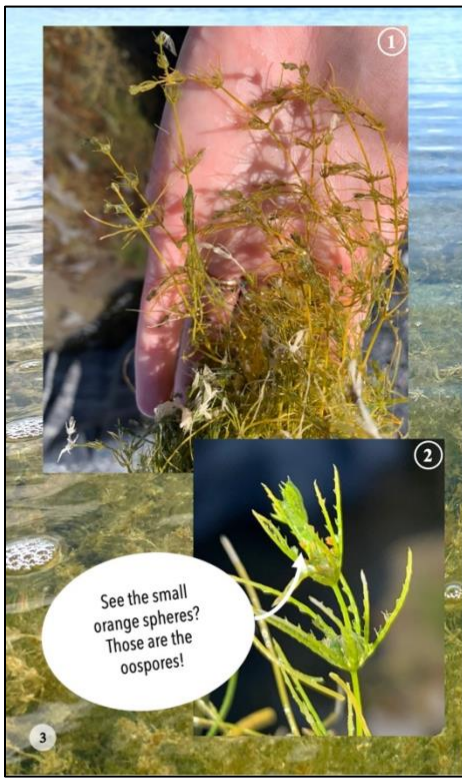
Stems
Not rooted. Stems up to 3 m long, branched and forming large masses ①-②. Brittle.

Leaves
In whorls of 6 to 12. Leaves are variable in length, typically around 15 mm. Forked ③. Serrate.

Flowers
Inconspicuous flowers in leaf axils ④.

Additional facts
Provides habitat for aquatic animals such as shrimp and fish as well as food for waterfowl.

Nativity:	Duration:	Commonness:
N	P	C



CHARACEAE

Chara spp .

Muskgrass, stonewort

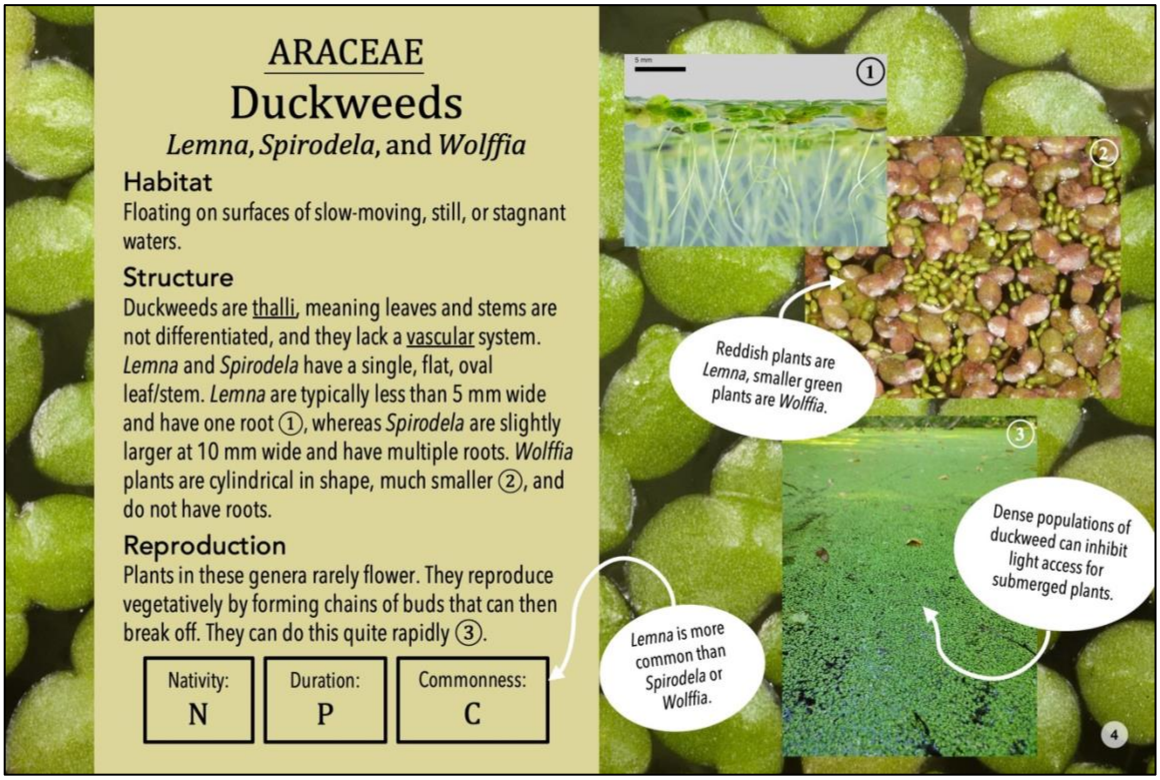
Habitat
Entirely submerged in shallow to deep hard or alkaline water.

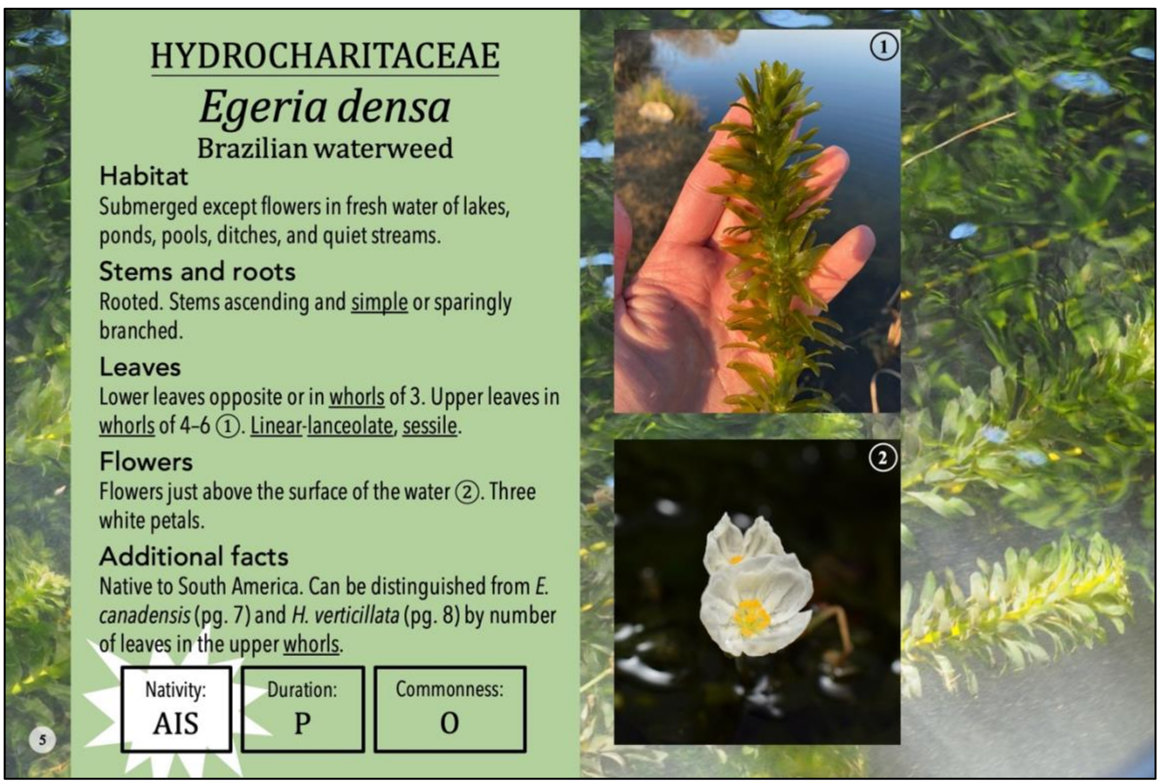
Structure
Although it looks a lot like a vascular plant ①, *Chara* is a genus of algae. It is highly branched and has 6 to 16 branchlets around each node. These branchlets often have spine-like appendages. It does not have roots but can attach itself to the substrate with root-like appendages.

Reproduction
Does not have flowers or seeds. Reproduces via fragments or oospores (a thick-walled cell formed by fertilization) ②.

Additional facts
Easily distinguished by its foul, musty smell. It often has a grainy or crunchy texture from calcium deposits.
Chara is commonly considered an indicator of high water quality.

Nativity:	Duration:	Commonness:
N	AP	C


ARACEAE
Duckweeds
Lemna, Spirodela, and Wolffia
Habitat
Floating on surfaces of slow-moving, still, or stagnant waters.
Structure
Duckweeds are thalli, meaning leaves and stems are not differentiated, and they lack a vascular system. Lemna and Spirodela have a single, flat, oval leaf/stem. Lemna are typically less than 5 mm wide and have one root ①, whereas Spirodela are slightly larger at 10 mm wide and have multiple roots. Wolffia plants are cylindrical in shape, much smaller ②, and do not have roots.
Reproduction
Plants in these genera rarely flower. They reproduce vegetatively by forming chains of buds that can then break off. They can do this quite rapidly ③.
Nativity: N
Duration: P
Commonness: C
5 mm
①
②
③
Reddish plants are Lemna, smaller green plants are Wolffia.
Lemna is more common than Spirodela or Wolffia.
Dense populations of duckweed can inhibit light access for submerged plants.
4


HYDROCHARITACEAE
Egeria densa
Brazilian waterweed
Habitat
Submerged except flowers in fresh water of lakes, ponds, pools, ditches, and quiet streams.
Stems and roots
Rooted. Stems ascending and simple or sparingly branched.
Leaves
Lower leaves opposite or in whorls of 3. Upper leaves in whorls of 4–6 ①. Linear-lanceolate, sessile.
Flowers
Flowers just above the surface of the water ②. Three white petals.
Additional facts
Native to South America. Can be distinguished from E. canadensis (pg. 7) and H. verticillata (pg. 8) by number of leaves in the upper whorls.
Nativity: AIS
Duration: P
Commonness: O
①
②
5

PONTEDERIACEAE

Eichhornia crassipes

Common water hyacinth

Habitat
Floating on the surface of ponds, streams, and ditches.

Roots
Roots purplish and dangling in water below leaves.

Leaves
Leaves round and in clusters. Petiole is distinctively spongy and inflated ①.

Flowers
Showy purple to light blue flowers on spike. Top petal has purple or blue spot with yellow center ②.

Additional facts
Synonym: *Pontederia crassipes*
Native to South America. Extremely aggressive. Not yet spreading in Utah, but if found, report it to the county weed supervisor for that area.

Nativity:	Duration:	Commonness:
AIS	P	NA

6

HYDROCHARITACEAE

Elodea canadensis

Canadian waterweed

Habitat
Submerged except flowers in lakes, ponds, and slow-moving streams, especially calcareous areas.

Stems and roots
Rooted. Long, slender stems. Dichotomously branched ①.

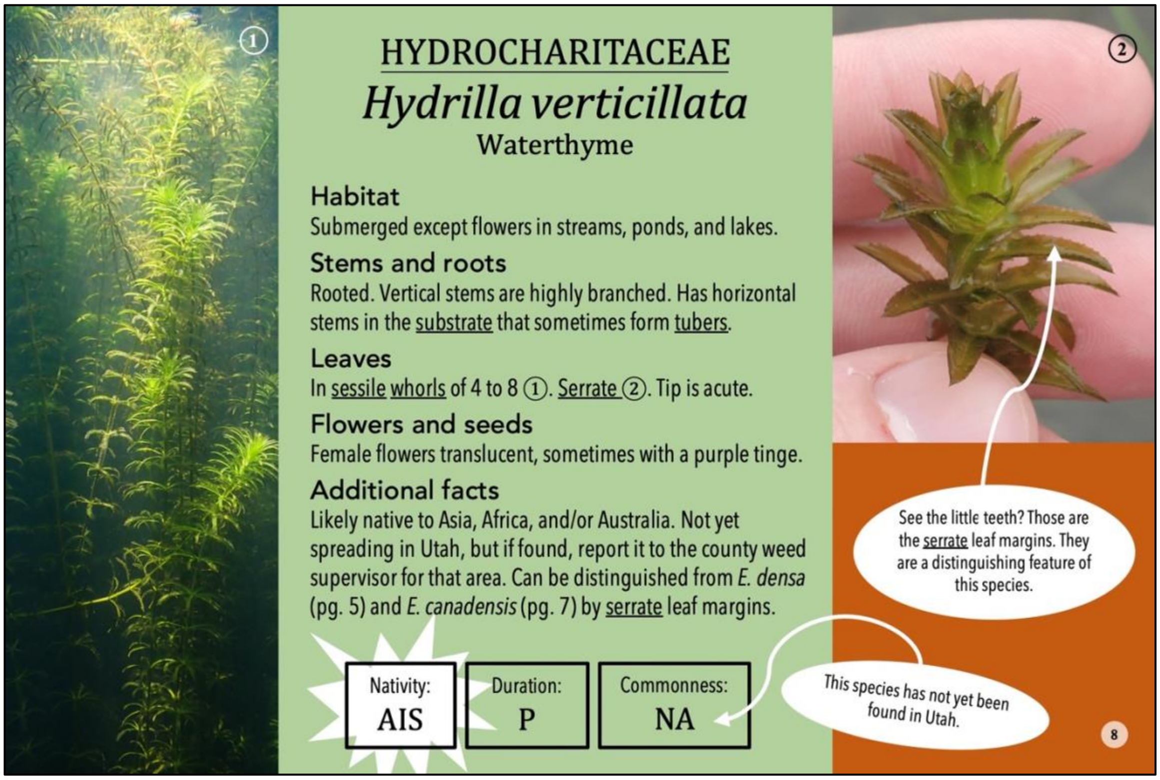
Leaves
Middle and upper leaves are in whorls of 3. Linear to tapering oblong. Thin, finely serrate.

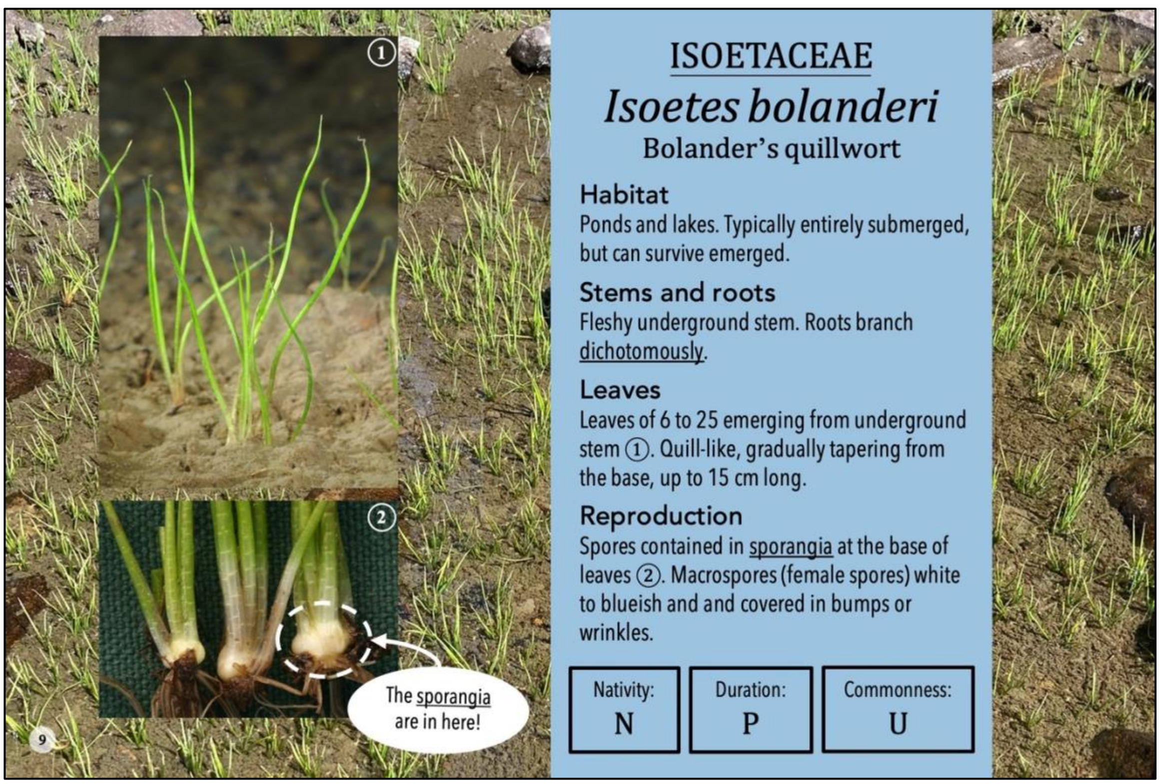
Flowers and seeds
Flowers bloom above the surface of the water. Three white petals.

Additional facts
Can be distinguished from the invasive species *E. densa* (pg. 5) and *H. verticillata* (pg. 8) by the number of leaves in each whorl.

Nativity:	Duration:	Commonness:
N	P	C

7


HYDROCHARITACEAE
Hydrilla verticillata
Waterthyme
Habitat
Submerged except flowers in streams, ponds, and lakes.
Stems and roots
Rooted. Vertical stems are highly branched. Has horizontal stems in the substrate that sometimes form tubers.
Leaves
In sessile whorls of 4 to 8 ①. Serrate ②. Tip is acute.
Flowers and seeds
Female flowers translucent, sometimes with a purple tinge.
Additional facts
Likely native to Asia, Africa, and/or Australia. Not yet spreading in Utah, but if found, report it to the county weed supervisor for that area. Can be distinguished from *E. densa* (pg. 5) and *E. canadensis* (pg. 7) by serrate leaf margins.
Nativity: AIS
Duration: P
Commonness: NA
See the little teeth? Those are the serrate leaf margins. They are a distinguishing feature of this species.
This species has not yet been found in Utah.
1
2
8


ISOETACEAE
Isoetes bolanderi
Bolander's quillwort
Habitat
Ponds and lakes. Typically entirely submerged, but can survive emerged.
Stems and roots
Fleshy underground stem. Roots branch dichotomously.
Leaves
Leaves of 6 to 25 emerging from underground stem ①. Quill-like, gradually tapering from the base, up to 15 cm long.
Reproduction
Spores contained in sporangia at the base of leaves ②. Macrospores (female spores) white to blueish and and covered in bumps or wrinkles.
Nativity: N
Duration: P
Commonness: U
The sporangia are in here!
1
2
9

ISOETACEAE

Isoetes echinospora

Spiny-spored quillwort

Habitat

Ponds and lakes in shallow, clear water. Typically entirely submerged, but can survive emerged.

Stems and roots

Fleshy underground stem. Roots branch dichotomously.

Leaves

Wide rosette of leaves emerging from the underground stem ①. Lighter green at base. Quill-like, up to 10 cm.

Reproduction

Spores contained in sporangia at the base of leaves. Macrospores (female spores) spiny ②.

Additional facts

Synonym: *Isoetes tenella*

Can be distinguished from *I. bolanderi* (pg. 9) by spines on macrospores (requires magnification).

Nativity:	Duration:	Commonness:
N	P	O

10

HALORAGACEAE

Myriophyllum sibiricum

Northern watermilfoil

Habitat

Submerged except flowers in lakes and streams, shallow to deep water ①.

Stems and roots

Rooted. Stem whitish or tan, sometimes with reddish tint.

Leaves

Leaves in whorls of four. Simply pinnate with 4 to 11 segments on each side of the central leaf axis ②.

Flowers and seeds

Whorled spike that emerges from the water ③.

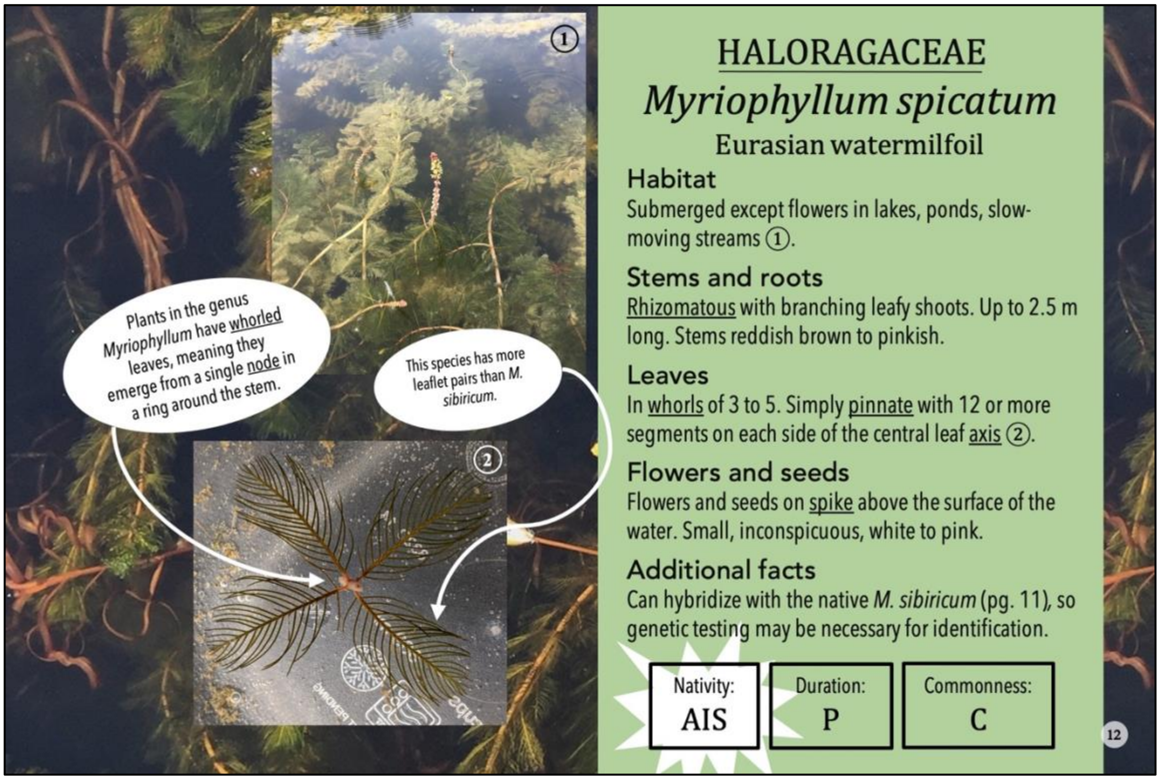
Additional facts

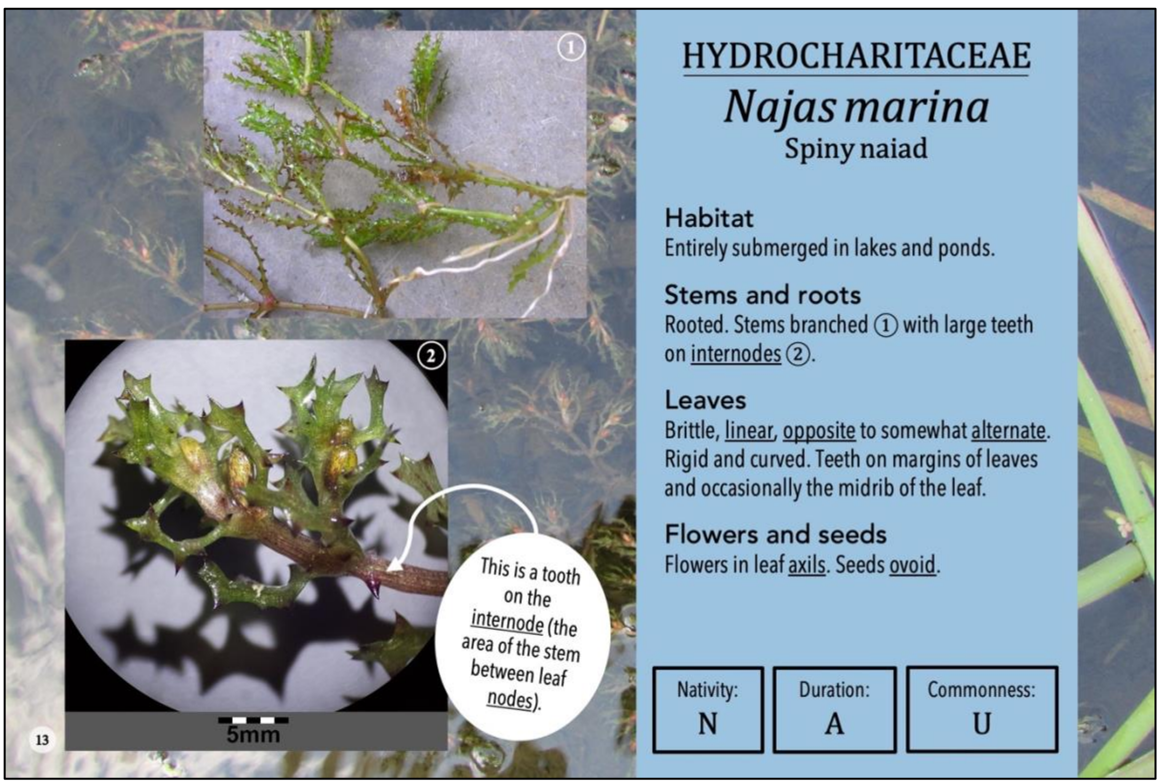
Forms winter buds (turions) that look like sections of the plant with very condensed leaves.

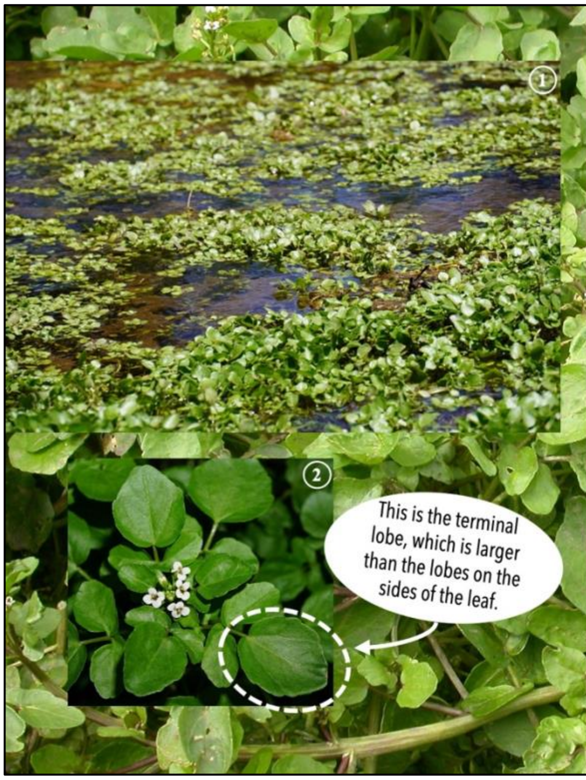
Can hybridize with the invasive *M. spicatum* (pg. 12), so genetic testing may be necessary for identification.

Nativity:	Duration:	Commonness:
N	P	C

11


HALORAGACEAE
Myriophyllum spicatum
Eurasian watermilfoil
Habitat
Submerged except flowers in lakes, ponds, slow-moving streams ①.
Stems and roots
Rhizomatous with branching leafy shoots. Up to 2.5 m long. Stems reddish brown to pinkish.
Leaves
In whorls of 3 to 5. Simply pinnate with 12 or more segments on each side of the central leaf axis ②.
Flowers and seeds
Flowers and seeds on spike above the surface of the water. Small, inconspicuous, white to pink.
Additional facts
Can hybridize with the native M. sibiricum (pg. 11), so genetic testing may be necessary for identification.
Nativity: AIS
Duration: P
Commonness: C
Plants in the genus Myriophyllum have whorled leaves, meaning they emerge from a single node in a ring around the stem.
This species has more leaflet pairs than M. sibiricum.
①
②
12


HYDROCHARITACEAE
Najas marina
Spiny naiad
Habitat
Entirely submerged in lakes and ponds.
Stems and roots
Rooted. Stems branched ① with large teeth on internodes ②.
Leaves
Brittle, linear, opposite to somewhat alternate. Rigid and curved. Teeth on margins of leaves and occasionally the midrib of the leaf.
Flowers and seeds
Flowers in leaf axils. Seeds ovoid.
Nativity: N
Duration: A
Commonness: U
This is a tooth on the internode (the area of the stem between leaf nodes).
5mm
①
②
13



BRASSICACEAE

Nasturtium officinale

Watercress

Habitat

Can be submerged, emerged, or floating in clear waters of slow-running streams and in or near cold springs ①.

Stems and roots

Rooted. Stems glabrous, sometimes rooting at the nodes.

Leaves

Pinnately compound with 3–9 segments. Ovate to oval. Terminal lobe is larger than the lobes on sides ②. Somewhat fleshy.

Flowers and seeds

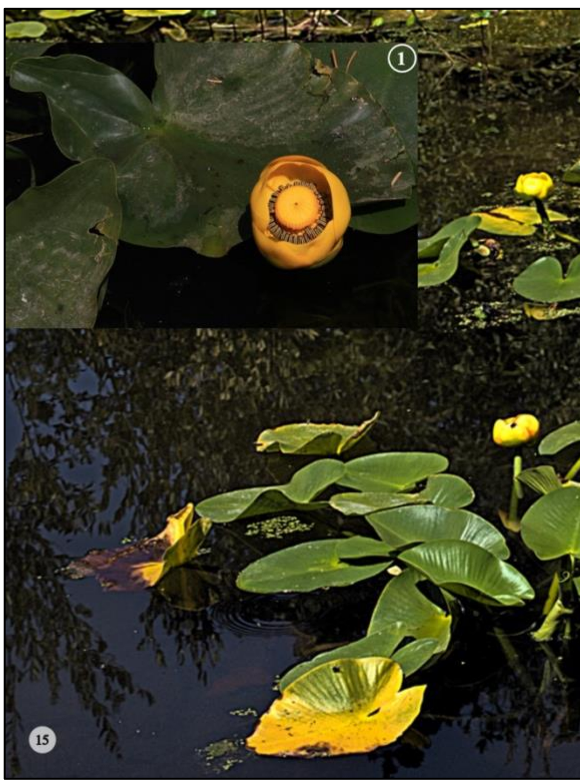
White, four-petaled flowers. Fruit is a pod that curves upward.

Additional facts

Edible. Synonym: *Rorippa nasturtium-aquaticum*

Nativity:	Duration:	Commonness:
I	P	C

14



NYMPHAEACEAE

Nuphar polysepala

Great yellow waterlily

Habitat

Floating, emergent, or rarely submerged in mountain ponds and lakes, especially where scoured by glacial activity.

Roots

Rhizomatous. Leaves arise directly from rhizomes.

Leaves

Ovate and sagittately lobed on the base. 8–25 cm long. Leathery.

Flowers and seeds

Stigma broad, forming a circular disk. Sepals 5–12, yellow or tinged with green or red. Petals yellow to purple ①. Fruit is ovoid and 4–6 cm long.

Nativity:	Duration:	Commonness:
N	P	U

15

NYMPHAEACEAE
Nymphaea odorata
American white waterlily

Habitat
Floating in ponds and springs.

Roots
Rhizomatous. Leaves arise directly from rhizomes.

Leaves
Round, basally sagittately lobed, leathery ①.

Flowers and seeds
Stigma broad, forming a circular disk. Many petals, pink to white ②-③.

Additional facts
Introduced in Utah but native in other parts of the United States.

Nativity:	Duration:	Commonness:
I	P	O

16

POLYGONACEAE
Polygonum amphibium
Water smartweed

Habitat
Floating in springs, streams, ponds, lakes, reservoirs, and irrigation canals.

Stems and roots
Rhizomes or stolons. Stems floating or erect.

Leaves
Length of 3–18 cm, lanceolate to oblong, obtuse to square basally, acute to round tip.

Flowers and seeds
Flowers bright pink on spike-like panicles. Fruit brown and lenticular ①.

Additional facts
Synonym: *Persicaria amphibia*. Floating leaves can be distinguished from *Potamogeton nodosus* (pg. 23) by the pinnate leaf venation ②.

Nativity:	Duration:	Commonness:
N	P	C

POTAMOGETONACEAE
Potamogeton alpinus
Alpine pondweed

Habitat
Submerged except flowers in streams, ponds, and lakes.

Stems and roots
Rooted. Stems reddish brown, simple or rarely branched ①.

Leaves
Submerged leaves 0.5–2 cm wide, 4–18 cm long, translucent, obtuse. Floating leaves oblanceolate, translucent, and tapering ②. Leaves may have red tint.

Flowers and seeds
Spikes dense and compact, 5 to 9 whorls. Flowers greenish to red.

Additional facts
Floating leaves thinner (more membranous) than *P. gramineus, P. natans,* and *P. nodosus*. Can be distinguished from *P. praelongus* by absence of whitish zigzag stems.

Nativity:	Duration:	Commonness:
N	P	U

POTAMOGETONACEAE
Potamogeton crispus
Curly–leaf pondweed

Habitat
Submerged except flowers in ponds and streams, often abundant in quiet calcareous water.

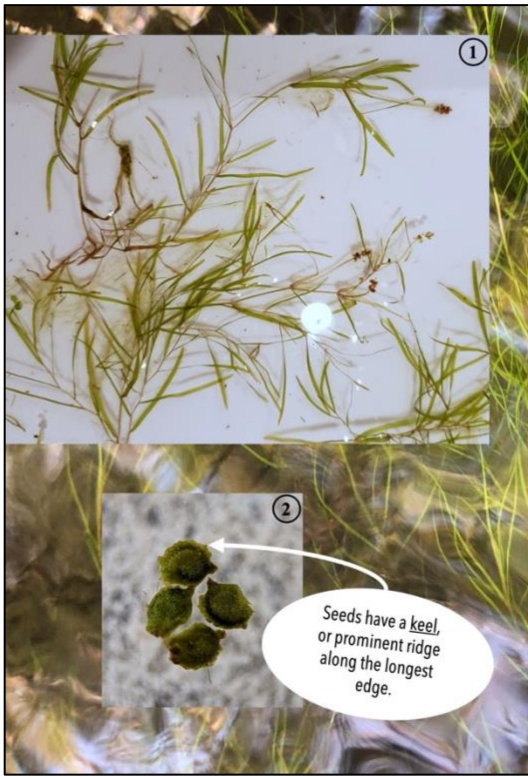
Stems and roots
Stem simple or branched. Rhizome reddish, about the same thickness as the stem.

Leaves
Bright green to dark green or reddish. Very characteristic wavy leaf margins ①.

Flowers and seeds
Flowers on spikes above water's surface. Fruits are achenes with a beak and keel.

Additional facts
Seldom found fruiting. Often reproduces by fragments or turions ②. Aboveground biomass dies off in summer.

Nativity:	Duration:	Commonness:
AIS	P	C



POTAMOGETONACEAE

Potamogeton foliosus

Leafy pondweed

Habitat

Entirely submerged in fresh (mostly calcareous) or brackish water of ponds, irrigation ditches, and streams.

Stems and roots

Rhizome freely branching, rooting at nodes. Stem simple below, branched above.

Leaves

Grass-like leaves, green to bronze, up to 10 cm long. Entire margins. Acute or subacute tip. Leaves are very flat ①.

Flowers and seeds

Flowers/fruits on spikes. Fruits suborbicular with dorsal keel.

Additional facts

Can be distinguished from *P. pusillus* (pg. 25) by presence of obvious keel on the fruit ②.

Nativity:	Duration:	Commonness:
N	P	C

20

POTAMOGETONACEAE

Potamogeton gramineus

Variable-leaf pondweed

Habitat

Submerged and floating in ponds, lakes, and slow streams.

Stems and roots

Rhizomatous. Stems slender.

Leaves

Floating leaves on petioles, leaves are usually shorter than petioles ①. Submerged leaves abundant, sessile, linear to lanceolate ②.

Flowers and seeds

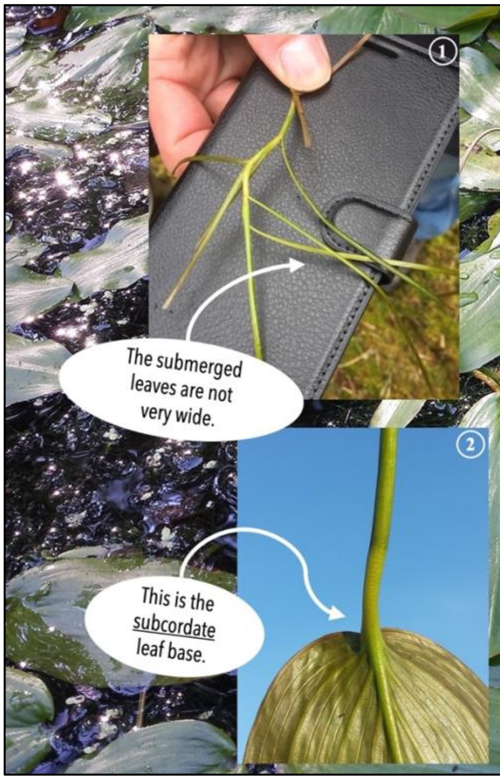
Flowers and fruits on compact spikes. Fruits keeled.

Additional facts

Leaves are variable (hence the name!). Can resemble other *Potamogeton* species.

Nativity:	Duration:	Commonness:
N	P	C

21



POTAMOGETONACEAE

Potamogeton natans

Floating pondweed

Habitat
Submerged and floating in marshy ponds and lakes, often brackish.

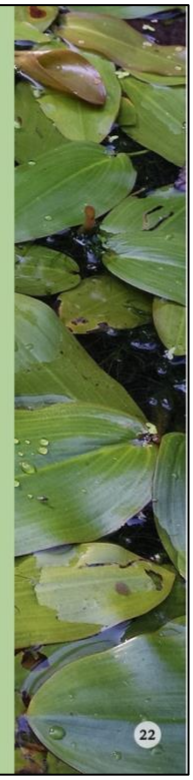
Stems and roots
Stems branch from rhizome. Stems usually simple.

Leaves
Submerged leaves very thin, up to 2 mm wide ①. Floating leaves often subcordate at base ②.

Flowers and seeds
Flowers and fruits on spikes. Peduncles are 1.5 to 3 times as long as the spike. Fruit are strongly keeled.

Additional facts
Submerged leaves are less wide than *P. gramineus* (pg. 21) and *P. nodosus* (pg. 23), and floating leaf bases are subcordate.

Nativity:	Duration:	Commonness:
N	P	U



POTAMOGETONACEAE

Potamogeton nodosus

Longleaf pondweed

Habitat
Submerged and floating in streams and lakes.

Stems and roots
Rhizome flat, covered or spotted with rusty red. Stem simple, often pressing very flat.

Leaves
Has both floating and submerged leaves ①. Submerged leaves thin, up to 20 cm long with white veins. Floating leaves with long petioles, lenticular to elliptical ③.

Flowers and seeds
Green to brown flowers on spike ②. Seed keels prominent.

Additional facts
Floating leaves can be distinguished from *P. amphibium* (pg. 17) by parallel venation and from other floating-leaf *Potamogeton* species by its long petioles.

Nativity:	Duration:	Commonness:
N	P	C

POTAMOGETONACEAE

Potamogeton praelongus

Whitestem pondweed

Habitat
Entirely submerged in deep cold water lakes and slow-moving streams.

Stems and roots
Rooted. Stems whitish to olive green, zigzag ①, simple or occasionally branched.

Leaves
Leaves all submerged, oblong-lanceolate, cordate or clasping at the stem, translucent stipule ②.

Flowers and seeds
Spikes compact with 6 to 12 whorls of greenish flowers. Fruit has acute dorsal keel.

Additional facts
The boat-shaped leaf tip ③ and zigzag stem can distinguish this species from other *Potamogeton* spp.

Nativity:	Duration:	Commonness:
N	P	C

24

POTAMOGETONACEAE

Potamogeton pusillus

Small pondweed

Habitat
Entirely submerged in neutral or slightly brackish or alkaline ponds and rivers.

Stems and roots
Rooted, but no rhizome. Stem highly branched ①. Usually a pair of translucent glands at nodes. Late in the season, branches often have winter buds.

Leaves
Linear, entire, light green ②. Up to 7 cm long and 3 mm wide.

Flowers and seeds
Spikes with 3 to 5 separate whorls of flowers. Seed keels are indistinct.

Additional facts
Can be distinguished from *P. foliosus* (pg. 20) by lack of obvious keel on the fruit and presence of winter bud.

Nativity:	Duration:	Commonness:
N	P	U

25

POTAMOGETONACEAE

Potamogeton richardsonii

Richardson's pondweed

Habitat

Entirely submerged in shallow ponds, lakes, and slow-moving streams ①.

Stems and roots

Rooted. Stems round and sparingly branched.

Leaves

Ovate-lanceolate, 3–10 cm long and 1–2 cm wide. Clasping at the base ②. Margins a little wavy. Acute tip.

Flowers and seeds

Spikes crowded. Flowers large and greenish. Dorsal keel low and rounded.

Additional facts

Synonym: *Potamogeton perfoliatus* ssp. *richardsonii*. Distinguishable by clasping leaf bases and pointed leaf tip.

Nativity:	Duration:	Commonness:
N	P	U

26

RANUNCULACEAE

Ranunculus aquatilis

White water crowfoot

Habitat

Floating and submerged in ponds, streams, pools, and springs, often in swift-flowing water ①.

Stems and roots

Stems submerged, rooting at the lowest nodes.

Leaves

Submerged leaves finely dissected in sets of three that look like crows' feet ②. Alternate.

Flowers and seeds

Five petals, white, sometimes with yellow bases. Sepals light green. Fruit an achene.

Additional facts

Synonym: *Ranunculus trichophyllus*

Nativity:	Duration:	Commonness:
N	P	C

RUPPIACEAE

Ruppia cirrhosa

Spiral ditchgrass

Habitat
Entirely submerged in shallow, brackish water.

Stems and roots
Stems grow from rhizomes. Stems up to 80 cm high.

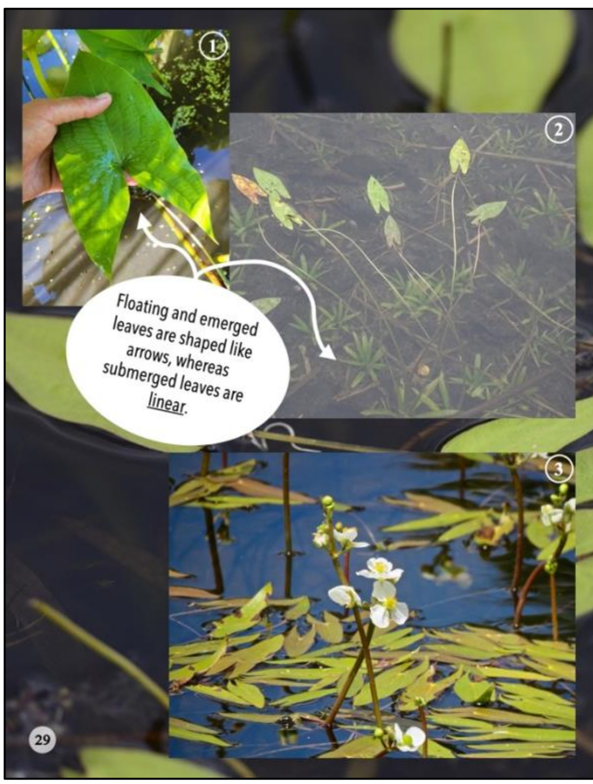
Leaves
Thread-like leaves, not numerous ①. An expanded sheath is present at the base of most leaves.

Flowers and seeds
Flowers and seeds are on a long, spiraling stalk (peduncle) ②-③.

Additional facts
Holds its shape out of water more than the grass-like species in Potamogetonaceae.

Nativity:	Duration:	Commonness:
N	P	U

28



ALISMATACEAE

Sagittaria cuneata

Arumleaf arrowhead

Habitat
Submerged to emergent in shallow ponds, lakes, and streams.

Stems and roots
Leaves arise directly from tubers.

Leaves
Submerged leaves are flat and linear with prominent midvein. Floating/emerged leaves are on long petioles and are sagittately lobed ①-②.

Flowers and seeds
Flowers on long stalk in whorls of three. Each flower has three round, white petals ③.

Additional facts
Tubers are edible and have a potato-like texture.

Nativity:	Duration:	Commonness:
N	P	C

29

POTAMOGETONACEAE

Stuckenia filiformis

Fineleaf pondweed

Habitat
Entirely submerged in brackish waters: ponds, slow streams, and ditches ①.

Stems and roots
Rooted. Stems slender, branchy.

Leaves
Slender, thread-like. Up to 12 cm long and 0.5 mm wide, blunt or obtuse ②.

Flowers and seeds
Flowers and fruit on spike ③. Peduncle up to 10 cm long. Fruit beak short, wartlike, nearly central.

Additional facts
Synonym: *Potamogeton filiformis*
Branching is not as fan-like as *S. pectinata* (pg. 31), and leaf tips are blunt.

Nativity:	Duration:	Commonness:
N	P	C

POTAMOGETONACEAE

Stuckenia pectinata

Sago pondweed

Habitat
Entirely submerged in alkaline, brackish, or saline water of ponds, quiet rivers, and marshes.

Stems and roots
Rhizome creeping, with small tubers. Stem round or slightly compressed, abundantly branched near summit (fanlike) ①.

Leaves
Leaves threadlike, entire, up to 15 cm long and 1 mm wide. Leaf tip is an acute point (sometimes obtuse on young seedlings).

Flowers and seeds
Spikes with 2 to 5 whorls of sessile flowers ②. No dorsal keel on seed.

Additional facts
Synonyms: *Potamogeton pectinatus, Coleogeton pectinatus*
Can be distinguished from other species of *Stuckenia* by acute leaf tips and fanlike shape.

Nativity:	Duration:	Commonness:
N	P	C

POTAMOGETONACEAE

Stuckenia striata

Broadleaf pondweed

Habitat

Entirely submerged in quiet or flowing fresh or brackish water ①.

Stems and roots

Rhizome creeping, rooting freely at the nodes. Stem whitish, simple below, repeatedly branched above.

Leaves

Linear, entire, green to bronze, rather opaque, up to 5 mm wide, tip obtuse to rounded ②.

Flowers and seeds

Spikes on peduncles. Fruits ovoid with convex sides.

Additional facts

Leaves much wider than the other species in *Stuckenia*.

Nativity:	Duration:	Commonness:
N	P	U

32

POTAMOGETONACEAE

Stuckenia vaginata

Sheathed pondweed

Habitat

Entirely submerged in ponds, streams, and lakes.

Stems

Rooted. Stems round, greenish, and branching.

Leaves

Threadlike to linear. 1–2 mm wide. Rounded or obtuse at the tip. Stipules joined to the base of the leaf, forming a closed, clasping sheath around the stem ①. This sheath is usually brownish and swollen.

Flowers and seeds

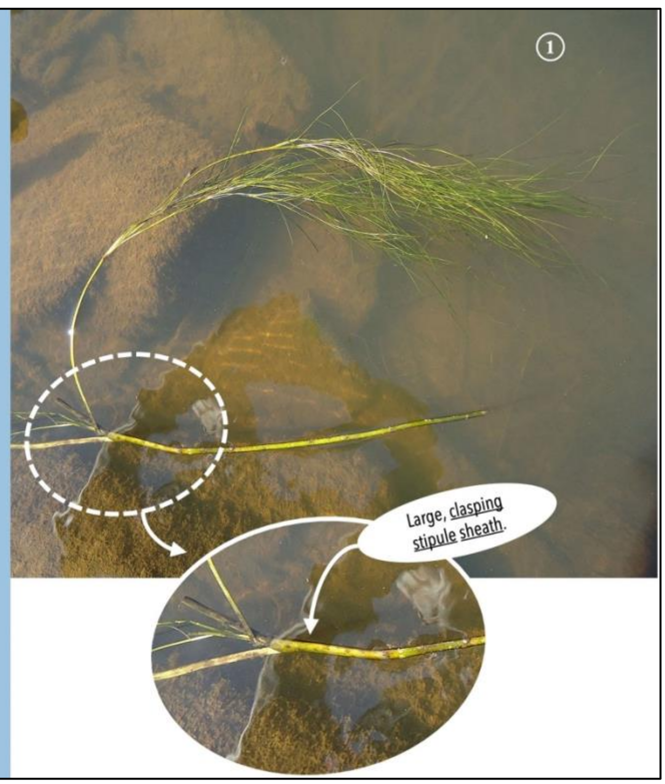
Spike with 4–9 evenly spaced whorls. Flowers small and brownish. Fruit with inconspicuous dorsal keel.

Additional facts

Synonym: *Potamogeton vaginatus*. Distinguishable by leaf sheath.

Nativity:	Duration:	Commonness:
N	P	U

33



LENTIBULARIACEAE
Utricularia macrorhiza
Common bladderwort

Habitat
Submerged except flowers in deep to shallow quiet water.

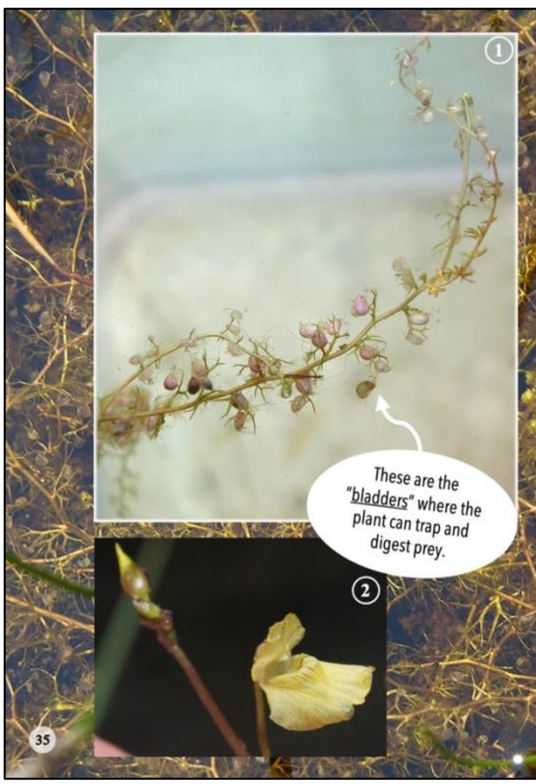
Stems and roots
No roots. Stems up to 2 m long, floating just below the water's surface.

Leaves
Leaves are much-dissected, with numerous large bladders ①. Featherlike branches of foliage ②.

Flowers and seeds
Flowers emerge out of the water ③. Yellow with brown or orange vertical stripe. Seeds brown.

Additional facts
Synonym: *U. vulgaris*
Plants in the genus *Utricularia* are carnivorous.

Nativity:	Duration:	Commonness:
N	P	C



LENTIBULARIACEAE
Utricularia minor
Lesser bladderwort

Habitat
Submerged except flowers in shallow ponds and lakes, growing along the bottom or floating.

Roots
Does not have roots but can affix to the substrate.

Leaves
Alternate, 4–10 mm long and branching. Bladders are found on leaves and are 1–2 mm long ①.

Flowers
Flowers are emergent, yellow ②, and 5–9 mm long. The spur is short or lacking.

Additional facts
Plants in the genus *Utricularia* are carnivorous.

Nativity:	Duration:	Commonness:
N	P	U

POTAMOGETONACEAE

Zannichellia palustris

Horned pondweed

Habitat

Entirely submerged in ponds, lakes, marshes, streams, and irrigation canals.

Stems and roots

Rhizome creeping, stem slender, simple or branching.

Leaves

Mostly opposite. Linear or threadlike ①, entire, up to 10 cm long. Acute at the tip. Leaves flat.

Flowers and seeds

Flowers in axil. Seeds banana-shaped ②.

Additional facts

Easily distinguished from other species in Potamogetonaceae by its banana-shaped seeds. Fruits and foliage eaten by waterfowl and fish.

Nativity:	Duration:	Commonness:
N	P	C

Pondweed Key

Trust me, we hear ya–the pondweeds are tricky! Here's a key for figuring them out. This key includes only the members of the family Potamogetonaceae that are included in this guide.

Select the statement that applies to the plant you are trying to identify, and follow the number in the parentheses until you reach a species name!

In brackets is the number that brought you here.

1. Stipules clasping leaf base (2)
1. Stipules free from the leaf (5)

2 [1]. Leaves less than 2 mm wide (3)
2. Leaves greater than 2 mm wide........ *Stuckenia striata* (pg.32)

3 [2]. Sheathed stipules not inflated (4)
3. Sheathed stipules inflated, 2–3 times as thick as the stem........ *S. vaginata* (pg. 33)

4 [3]. Leaf tips blunt or obtuse........ *S. filiformis* (pg. 30)
4. Leaf tips acute, leaves branch like a fan........ *S. pectinata* (pg. 31)

5 [1]. Floating leaves absent or similar in shape to submerged leaves (6)
5. Floating leaves present and different in shape from submerged leaves (11)

6 [5]. Flowers and seeds on spike (7)
6. Flowers and seeds in axil, seeds banana-shaped........ *Zannichellia palustris* (pg. 36)

7 [6]. Leaves less than 3 mm wide (8)
7. Leaves are greater than 3 mm wide (9)

8 [7]. Dorsal keel on fruit .... *Potamogeton foliosus* (pg. 20)
8. Dorsal keel on fruit absent .... *P. pusillus* (pg. 25)

9 [7]. Leaf margin is slightly wavy, entire (10)
9. Leaf margin is very wavy, serrate .... *P. crispus* (pg. 19)

10 [9]. Leaf tip is boat-shaped .... *P. praelongus* (pg. 24)
10. Leaf tip is sharply pointed .... *P. richardsonii* (pg. 26)

11 [5]. Submerged leaves sessile (12)
11. Submerged leaves on long petiole .... *P. nodosus* (pg. 23)

12 [11]. Submerged leaves greater than 2 mm wide (13)
12. Submerged leaves less than 2 mm wide .... *P. natans* (pg. 22)

13 [12]. Floating leaves tapering to petiole .... *P. alpinus* (pg. 18)
13. Floating leaves typically rounded at base........ *P. gramineus* (pg. 21)

GLOSSARY

achene: a small, dry fruit with a single seed

alternate: a single leaf arises from each node, alternating sides as they go up the stem

axil: angle between the leaf and the stem bearing the leaf

axis: a stem on which parts are arranged

beak: a long, substantial point

bladder: hollow, submerged structure used to trap and digest prey

brackish: water with moderate concentration of dissolved substances, especially salts

calcareous: containing an excess of calcium that is available to be absorbed

clasping: leaf bases wrap around the stem

commonness: a description of the occurrence of species

Note. In this guide, we used BONAP[5] maps to determine commonness. If the species was described as "present and not rare" in >30% of Utah counties, it is noted as "common; in <30% of counties, "uncommon"; and in <10% of counties, "occasional."

cordate: heart-shaped with a notched base

dichotomous: in pairs

dorsal: pertaining to the back, away from the main line/central part

elliptical: shaped like an oval, broadest in the center

entire: leaf margin void of indentations, lobes, or teeth

glabrous: without hair

internode: the part of the stem between two adjacent nodes

invasive species: non-native, spreading prolifically, and disrupting ecosystems

keel: a prominent ridge along the longest edge

lanceolate: a shape that is longer than wide, tapering to a point with petiole at wide end

lenticular: convex on both sides, lentil-shaped

linear: long and narrow shaped, with near-parallel sides

node: section of stem where leaves originate

oblanceolate: a shape that is longer than wide, tapering to a point with petiole at the narrow end

oblong: shape that is longer than wide, sides near parallel

opposite: occurring two at a node on opposite sides of the stem

ovate: egg-shaped, petiole at widest end

ovoid: egg-shaped

40

panicle: a compound inflorescence, in which the axis is branched one or more times

peduncle: the stem of a solitary flower or the main stem of the flower cluster

petiole: stalk of the leaf

pinnate: leaflets arranged on opposite sides of the leaf axis

rhizomatous: proliferating by means of underground, horizontal stems

rhizome: thick, horizontal underground stems

sagittate: shaped like an arrow

sepal: a single part of the outermost whorl of flower organs

serrate: having marginal teeth pointing forward

sessile: joined directly to the base without a stalk or petiole

sheath: a tubular tissue enclosing another tissue, usually referring to the area where a leaf base encloses the stem

simple: neither branched nor otherwise compound

spike: an inflorescence consisting of a long axis with unstalked flowers

sporangia: an enclosure in which spores are formed

spur: a hollow, elongate, pointed, or blunt outgrowth on the flower

41

stigma: the part of the flower that receives the pollen

stipule: an appendage frequently occurring at the base of a leaf

stolon: long, horizontal, creeping stem, rooting at nodes

subacute: between acute and obtuse

subcordate: somewhat cordate

suborbicular: roughly spherical

substrate: the surface or material on or from which the plant lives, grows, or obtains its nourishment

thalli: plants that are not clearly divided into stem and leaf (singular: thallus)

tuber: thickened portion of rhizome bearing nodes and buds

turion: small, overwintering shoot

vascular: plant tissues have a system of vessels that transports water and nutrients

venation: the pattern of veins

whorl: a ring of leaves, flower parts, or flowers occurring at a single node

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COVER AND INTRO PAGES
Photos by Kate Sinnott
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CHAPTER III

RESTORATION TECHNIQUES TO ENHANCE PLANT ESTABLISHMENT AND PROJECT FEASIBILITY IN AQUATIC ECOSYSTEMS

ABSTRACT

Aquatic plant restoration is a priority in inland aquatic systems, where critical habitat is threatened by species introductions, pollution, declining water availability, and climate change. Effective revegetation techniques are essential to restoring degraded aquatic systems and reestablishing desired ecosystem services, yet best practices for revegetating aquatic species are poorly developed. Thus, in two field experiments, I sought to identify successful aquatic planting techniques for two plant material types (plugs and stem fragments) by assessing the relative performance of several planting methods (plugs: burlap wraps, coir pellets, and hand planting; stem fragments: mesh bags and loose fragments) and designs (clumped and dispersed) across three species (*Potamogeton nodosus*, *Ruppia cirrhosa*, and *Stuckenia pectinata*). Two of the plug planting methods were selected for scalability potential (i.e., ability to be planted by being dropped from the surface of the water). These methods were examined in contrast with hand planting. For the species *P. nodosus* and *S. pectinata*, I found that the performance of the scalable planting methods did not significantly differ from hand planting for plugs and that added preparation of stem fragments did not improve plant establishment. However, planting methods demonstrated significantly different performance for *R. cirrhosa*. Thus, I suggest that planting methods be paired carefully with species identity to promote plant establishment. I found limited impact of planting

design on the success of restoration efforts, suggesting that logistical considerations, rather than potential ecological differences (such as functional traits that may affect plant establishment), can guide arrangement choices. Based on these findings, I suggest that practitioners integrate species identity and scalable planting methods into their strategies for augmenting aquatic plant cover and achieving project feasibility in shallow aquatic habitat.

INTRODUCTION

Restoration of degraded freshwater systems can help recover critical ecosystem services, including provisioning of drinking water, habitat for wildlife, recreational opportunities, and water supply for irrigation and agriculture (Hilt et al., 2017; Janssen et al., 2021). However, aquatic plant communities (defined here as submerged and floating plants) may take decades to passively recolonize after stressors are removed (Hanson & Butler, 2011; Jeppesen et al., 2005). Active revegetation of aquatic plants is necessary in sites where rapid natural recovery is unlikely due to a lack of adequate sources of aquatic plants in the landscape due to fragmentation and loss or degradation of remaining natural aquatic plant populations (Galatowitsch & van der Valk, 1996; Hilt et al., 2006; Körner, 2002). Despite the need for active revegetation, aquatic planting techniques that improve establishment and overall community recovery are poorly understood (but see Rohal et al., 2021; Smart & Dick, 1999) relative to other types of wetland and upland species (Kettenring & Tarsa, 2020; Török et al., 2011). As urgency for restoration of aquatic systems intensifies (Finlayson et al., 2019), research that addresses uncertainties in plant revegetation is essential (Suding, 2011).

Decision-making plays a crucial role in restoration, with practitioners balancing ecological, practical, and financial factors to make choices about revegetation techniques, including selecting *planting method* (how plants are introduced to a site), *planting design* (the arrangement of plants within a site), and *plant material type* (e.g., seeds, plugs, fragments) (Barak et al., 2022; Rohal et al., 2021). There is a myriad of ways to introduce plants to a site, though hand planting and anchoring of plant material are two fundamental planting methods for aquatic species. Analysis of seagrass restorations has found that techniques that increase plant-soil contact by hand planting plant material into the substrate or anchoring plant material (by adding sediment or weight) significantly improved success (van Katwijk et al., 2016). However, hand planting can be extremely labor and cost intensive and is potentially infeasible in areas where visibility is low or safety is a concern for practitioners (Orth et al., 2006). Anchoring plant material provides an alternative to hand planting—added weight can allow plants to be dropped from the surface of the water while still promoting plant-soil contact (Rohal et al., 2021), making it more feasible to scale up by eliminating the need to individually plant propagules in the substrate. Though scalable planting methods (i.e., anchoring methods that reduce financial and temporal input and can be applied to larger scales) are in the process of development (Reynolds et al., 2020), these approaches are still in the proof-of-concept phase where efficacy needs to be experimentally evaluated (Bayraktarov et al., 2020).

Practitioners are also faced with the decision of how to arrange plants within a site. Planting designs for wetland restorations have been influenced by forestry science, which emphasizes minimization of competition by distancing plants in a *dispersed planting design* (Silliman et al., 2015). However, this practice of dispersing plants does not incorporate a robust body of research showing the importance of positive interactions in ecological communities, particularly in stressful environments, which can be harnessed through *clumped planting designs* (Angelini et al., 2011; Bertness & Callaway, 1994; He et al., 2013). Though clumped planting designs have been shown to improve restoration outcomes in coastal marsh and seagrass communities (Silliman et al., 2015; Valdez et al., 2020), research on use of planting designs in inland aquatic plant communities is lacking. Nonetheless, aquatic plant responses to stressors such as anoxia indicate that a clumped planting design can alleviate negative impacts of those stressors. Limited oxygen availability in the substrate inhibits plant growth in flooded, anoxic environments (Wu et al., 2009), though many aquatic species diffuse excess oxygen into the surrounding soil matrix (Mitsch & Gosselink, 2015), allowing that oxygen to become available to neighboring plants with commingling rhizospheres.

Species-specific modes of reproduction and growth can be harnessed in different ways to introduce a diverse array of plants to restoration sites. Aquatic plants reproduce and spread through multiple means, such as seeds, stem fragments, modified buds (e.g., turions, dormant apices, psuedoviviparous or gemmiparous buds), modified stems (e.g., runners, stolons, rhizomes), modified roots (e.g., tubers), or modified shoot bases (e.g., corms, bulbs) (Cronk & Fennessy, 2016). However, as many aquatic species are known to regenerate primarily vegetatively (Barrat-Segretain & Bornette, 2000), a focus on vegetative reproduction is logical when selecting plant material type for aquatic plant restoration. Plant materials that are produced through vegetative reproduction may include *plugs* (here, stem fragments grown in soil that can then be transplanted into the restoration site) or *stem fragments* (stem cuttings without roots that can be introduced directly into the site), though both of these options have tradeoffs. Specifically, due to added soil around the root ball, using plugs may reduce transplant shock and provide initial fertilization (Rohal et al., 2021). However, plugs also require significant infrastructure and resources for production, transportation, and planting (Orth et al., 2006; Smart & Dick, 1999). Collection and transportation of stem fragments requires much less input. Aquatic plants are uniquely adept at recolonizing disturbed areas via fragments (Barrat-Segretain, 1996; Barrat-Segretain et al., 1998; Barrat-Segretain & Bornette, 2000), but research into application of this ability to a restoration context remains underdeveloped. Factors that may impact restoration outcomes such as survival of fragments and risk of transplant stress are poorly understood.

Here, I assessed planting methods and designs for three aquatic plant species (*Potamogeton nodosus*, *Ruppia cirrhosa*, and *Stuckenia pectinata*) to determine factors that affect restoration success, defined as plant establishment. I asked: What are the best planting methods for plugs and fragments to maximize success? I predicted that planting methods that resulted in increased soil-plant contact would lead to the highest cover, i.e., hand planting for plugs and mesh bags for the fragments. Planting methods for plugs were selected to test scalable methods against hand planting, though I predicted hand planting would result in higher success. I also asked, does manipulating planting design affect restoration success? Here, I predicted that a clumped planting design would promote positive interactions between plants and increase establishment. I addressed these questions in two field experiments that evaluated plug and fragment plant material types independently.

METHODS

Study site

This study was conducted at the Provo River Delta Restoration Project (PRDRP), located on the eastern shore of Utah Lake in Provo, Utah, USA (Figure 3.1A) on land that was historically covered by wetlands associated with the Provo River delta. For several decades, the land was drained and used for grazing. In, 2020, construction began to excavate a series of braided channels and ponds to restore the natural ecosystem of the river delta. The field experiments were placed in a pond (Experiment 1) and channel (Experiment 2) that were excavated in 2021 (Figure 3.1B). As the restoration site was not yet connected to the Provo River or Utah Lake at the time of experimentation, the majority of the water in the site was groundwater, in addition to a small amount of surface inflow from a canal at the northwest border of the restoration project. Experiment 1 was completely unvegetated at the time of planting, whereas Experiment 2 had experienced moderate passive recovery of submerged and emergent plant species, which were not cleared prior to planting. PRDRP was connected to Utah Lake and the Provo River in March 2023, limiting ongoing monitoring due to significant shifts in hydrology resulting from site re-flooding.

Species selection

Due to ongoing negotiations with nearby landowners, the aquatic plants introduced to the PRDRP as part of the experiments were required to be on a list of nine species identified in the original revegetation plan developed by BIO-WEST, Inc. and Allred Restoration (*Final Design Report: Provo River Delta Restoration Project*, 2019). From that list of nine species, I selected three species that are common in the area, root in the substrate, and span a range of growth forms and habitat preferences: *Potamogeton nodosus* (longleaf pondweed), *Ruppia cirrhosa* (spiral ditchgrass), and *Stuckenia pectinata* (sago pondweed; Table S3.1).

Plant sourcing, cleaning, and cultivation

I established foundation populations of submerged and floating aquatic plant species in Millville, Utah. These foundation populations allowed us consistent access to plant materials for experiments. Stem fragments of wild plant populations were collected from wetlands throughout Utah in 2020 and 2021 (Figure S3.1), then cleaned and soaked in a potassium permanganate solution to prevent any non-native invertebrate or algal contamination of the plant collections. The fragments were then cultivated in individual mesocosms constructed of 300-gallon Rubbermaid stock tanks and filled with eight inches of soil from PRDRP for durations of 1 to 10 months prior to the experiment (depending on the population).

Experiment 1: Effects of planting method and arrangement on aquatic plant establishment from plugs

Experimental Design

I installed a field experiment in September 2021 to determine what planting methods and designs promote successful establishment for aquatic plant species using plugs. In July–September of 2021, plugs of *S. pectinata*, *R. cirrhosa,* and *P. nodosus* were propagated from stem fragments of the foundation populations for use in Experiment 1. Plant material from each of the target species was removed from the foundation tanks, divided into stem fragments containing meristematic tissue, and planted into each plug. Plugs were considered ready when roots were protruding out of the bottom of roughly half of the plugs in each tray, which occurred after approximately 4 weeks. Rate of growth was approximately uniform across trays.

The planting methods examined in this experiment were burlap wraps, coir pellets, and hand planting (Figure S3.2; see Table S3.2 for additional details). The burlap wraps and coir pellets were intended to be "scalable" planting methods—methods that are easier to apply to larger scales due to their capacity to be dropped from the surface of the water rather than the hand planted plug treatment. In the burlap wrap treatment, plugs were wrapped in burlap and tied with twine. This treatment may protect the root ball and soil surrounding the plug. Plants in the coir pellet treatment were grown directly in a coir plug (rather than site soil) which was enclosed in mesh, again protecting the roots of the plug. The two scalable planting methods were compared against hand planting, which has the highest-level plant-soil contact but requires significant labor input to plant. Hand planted plugs were planted directly into the sediment with no added material.

Four blocks of experimental plots were established in a $2 \times 3 \times 3 + 1$ factorial design in a pond at the PRDRP that was excavated in 2020 (additional details in Table S3.3 on the nature of the block designs for Experiments 1 and 2). Each block contained 18 1 m^2 single-species plots (*S. pectinata*, *R. cirrhosa*, or *P. nodosus*). On September 10–11, 2021, nine plugs were introduced to each plot. This density (one plant per 0.09 m^2) was chosen to closely follow the density guidelines suggested by BIO-WEST and Allred Restoration's original vegetation plan (*Final Design Report: Provo River Delta Restoration Project*, 2019). Plants were introduced to each plot via one of the three planting methods (burlap wraps, coir pellets, or hand planting) in a clumped (plugs touching) or dispersed design (plugs 50 cm apart; Figure 3.2). Burlap wraps and coir pellets were affixed to 1 m^2 wire frames to implement spacing treatments. Standing water depth was ~50 cm on average at the time of planting. Several plugs of the species *P. nodosus* were damaged during transportation to the site. As a result, this species was planted in three blocks rather than four.

Data collection

Visual estimates of percent cover of planted species were collected to assess establishment success across species and treatments. Percent cover of passively recolonizing species in control plots was also visually estimated. Percent cover was assessed approximately biweekly using a bathyscope (Figure S3.3) or by eye when water quality and light were optimal. Percent cover was broken into the following classes: <1%, 1–5%, >5–25%, >25–50%, >50–75%, >75–95%, and >95% (Daubenmire, 1959). From September 2021 to October 2022, monitoring began in September 2021 and ceased over the winter (beginning in November), recommencing approximately biweekly in May 2022. Three monitoring dates were missed on approximately August 16, August 30, and September 6, 2022 due to the presence of a harmful algal bloom in the water. Monitoring was limited to two seasons due to site re-flooding in March 2023.

To monitor changes in environmental conditions, I measured water depth and temperature in each plot. Temperature was recorded at the block level on the substrate every one hour using a Thermochron iButton data logger (model DS1922L, iButton Link Technology, Whitewater, Wisconsin) encased in a waterproof capsule (model DS9107). Water depth was measured during each site visit within the central 25 cm^2 of each plot using a meter stick.

Experiment 2: Effects of reintroduction method and arrangement on aquatic plant establishment from stem fragments

Experimental Design

In summer 2022, I conducted a field experiment to assess the establishment success of planting methods and designs using aquatic plant stem fragments as propagules. In August 2022, stem fragments were harvested from the foundation population tanks in Millville, Utah. The plant fragments were transported to the lab for preparation then to the restoration site within 36 hours. The planting methods examined in this experiment included mesh bags (stem fragments enclosed within cotton mesh bags) and "loose" (not enclosed in mesh; Table S3.4; Figure S3.4). In addition to possibly protecting plant stem fragments against herbivory, mesh bags add additional weight that can better anchor plants to substrate. Both of these planting methods are considered scalable as they can both be dropped from the surface of the water. In the clumped treatments, all nine stem fragments were grouped together in a cotton mesh bag or with twine. In the dispersed treatments, each stem fragment was introduced individually to the plots, either in a bag or with no additional material.

Four blocks of experimental plots were established in a $2 \times 2 \times 3 + 2$ factorial design (Table S3.3). Each block contained twelve 0.81 m^2 single-species plots of each of the three target species (same species as Experiment 1: *S. pectinata*, *R. cirrhosa*, and *P. nodosus*) with one of the two planting methods (loose stem fragments, mesh bag) in both clumped (stem fragments tied together) and dispersed (stem fragments not tied together) designs. Plots were lined vertically with a permeable High Density Polyethylene mesh (Coolaroo 50% UV Sun Block Shade Fabric; height: 0.9 m) to ensure plant fragments stayed within the plots. Nine stem fragments were introduced to each experimental plot at PRDRP on August 5, 2022. All treatments were dropped into the plot from ~30 cm above the water's surface, and standing water was ~20 cm deep at the time of planting.

Data collection

From August to September 2022, visual estimates of percent cover were collected to provide insight on establishment success across species and treatments. Percent cover (same classes as in Experiment 1) of planted (in treated plots) and unplanted species (in untreated control plots) was collected every other week. Due to shallow water depth and clear water conditions, I was able to visually estimate percent cover by eye without the use of a bathyscope for all observation dates. Monitoring was limited to one season due to site re-flooding in March 2023. Environmental conditions (depth and temperature) were measured using the same instruments and methods as Experiment 1.

Analysis

For each experiment, I plotted changes in plant cover across time by species and treatment to qualitatively assess patterns. In addition, generalized linear mixed effects models were created in each experiment to assess the effects of planting method and planting design on proportion cover at the peak date separately for each species. In Experiment 1, planting method (3 levels: coir pellets, burlap wraps, and hand planting), planting design (2 levels: clumped and dispersed), and their interaction were included as fixed effect factors. In Experiment 2, fixed effect factors included planting method (2 levels: loose and mesh bag), planting design (2 levels: clumped and dispersed), and their interaction. In both experiments, block was included as a random effect.

Peak date for percent cover was determined for each species as the date of its maximum mean percent cover. Data were analyzed in R version 4.2.2 (R Core Team, 2022). I built generalized linear mixed models for each experiment using the 'glmmTMB' package (Brooks et al., 2022). Percent cover categories were converted to midpoint values and then to proportions. For analysis of proportion cover, a beta distribution with a logit link was used (Damgaard & Irvine, 2019; Douma & Weedon, 2019). Model fit was assessed using residual plots produced with the 'DHARMa' package (Hartig & Lohse, 2022). I evaluated treatment effects with Analysis of Deviance tests using the 'car' package (Fox et al., 2022) followed by estimation of means and pairwise comparisons that were Tukey-adjusted for family-wise Type I error using the 'emmeans' package as appropriate (Lenth et al., 2022). Environmental and control plot data were not included as predictors in the models, but were plotted to qualitatively describe site conditions.

RESULTS

Experiment 1: Effects of planting method and arrangement on aquatic plant establishment from plugs

Growth for each native species was gradual in the first year of implementation, but increased considerably in the second growing season by mid-summer (Figure 3.3). Planting method had a significant effect only on *R. cirrhosa* cover (Table 3.1a), with coir pellets and hand planting performing substantially better than burlap wraps (Figure 3.4A; Table S3.5). I found a moderate effect of planting design on *P. nodosus* (p = 0.059; Table 3.1b; Figure 3.4B) with the dispersed design treatment performing slightly better than the clumped design. In contrast, the planting method and planting design treatments did not have observed effects on *S. pectinata* cover (Table 3.1c). Standing water depth differed slightly between blocks, but followed similar trends of depths ranging from 35 to 75 cm (Figure 3.5A). Temperatures were consistent between blocks, peaking in summer 2022 at approximately 25°C on average and dropping to 5°C in the winter (Figure 3.5B). Unplanted species did not recolonize the control plots during the first growing season, but cover increased rapidly in 2022, with large proportions of *Chara* spp. in midsummer joined by growing proportions of *P. nodosu*s and *S. pectinata* later in the season (Figure 3.6). I suspect *P. nodosus* and *S. pectinata* established in control plots from fragments migrating from plots where they were planted, though cover of these species was much higher in the plots where they were planted.

Experiment 2: Effects of reintroduction method and arrangement on aquatic plant establishment from fragments

Planted cover remained minimal (means < 5%) over the monitoring period (Figure 3.7). Nonetheless, I found that planting method had a significant effect on *R. cirrhosa* cover (Table 3.2a), with the loose treatment performing better than mesh bags (Figure 3.8A). In contrast, the planting method and planting design treatments did not have observed effects on *P. nodosus* or *S. pectinata* cover (Tables 3.2b–3.2c; Figure 3.8B). Standing water depth was overall lower than Experiment 1 and notably declined dramatically in September, reaching means below 5 cm across blocks (Figure 3.9A). Temperatures were consistent between blocks, peaking in summer 2022 at approximately 25°C on average and declining to 10°C in October (Figure 3.9B). As Experiment 2 had consistently lower water levels as compared to Experiment 1, the species recolonizing untreated control plots were more commonly emergent species, including *Schoenoplectus acutus* and *Typha* spp., in addition to the submerged *Chara* spp. (Figure 3.10).

DISCUSSION

Restoration of aquatic plants is essential to reestablishing critical ecosystem services associated with freshwater systems. However, best practices for revegetating aquatic species are poorly developed, thus, I sought to identify successful aquatic planting techniques by assessing planting methods and designs across three species for two plant material types (plugs and stem). Results suggest that scalable plug planting methods (i.e., burlap wraps and coir pellets) may be a viable alternative to hand planting for some species (in this case, *P. nodosus* and *S. pectinata*). I also found little evidence for the effects of planting design on restoration success, suggesting that clumped vs. dispersed arrangement choices can be based on logistics rather than potential ecological differences. Based on these results, I propose that practitioners consider both species identity and scalable planting methods as tools to increase aquatic plant cover *and* project feasibility in shallow aquatic habitat.

Scalable planting methods may offer viable alternative to hand planting, but species identity should be considered during planting method selection

Aquatic plant establishment is influenced by a wide variety of biotic and abiotic factors, including nutrients and water quality, competition, light availability, seasonality, hydrology, and herbivory (Bakker et al., 2013; Barrat-Segretain & Bornette, 2000; Bornette & Puijalon, 2011; Hilt et al., 2006; Kuntz et al., 2014; Riis et al., 2012). Appropriate selection of restoration techniques such as planting methods can increase plant establishment across environmental filters (Funk et al., 2008; van Katwijk et al., 2016). I predicted that planting methods that maximize plant-soil contact—i.e., hand planting for plugs and mesh bags for stem fragments—would outperform other planting methods. However, the results from both experiments indicated that tested planting methods did not have a significant impact on plant cover for *P. nodosus* and *S. pectinata*. For Experiment 1, this suggests that the scalable planting methods of coir pellets and burlap wraps—which can be dropped from the surface of the water—could be viable alternatives to hand planting. For Experiment 2, it signals that there may not be significant value added by enclosing stem fragments in mesh bags.

These observations suggest that species identity be considered and carefully paired with planting methods to avoid negative trade-offs and increase diversity in aquatic plant restorations. Although the species were evaluated in separate models due to peak cover occurring at different dates, qualitatively we see that species appear to respond to treatments differently. Whereas planting method did not have a significant effect on *P. nodosus* and *S. pectinata*, it did have a significant effect on *R. cirrhosa* in both Experiments 1 and 2. Rohal et al. (2021) observed that species-specific traits may have interacted with planting methods to result in variable growth patterns in aquatic plants. For example, the authors found that their “burrito” treatment (similar to the burlap wraps used here) produced taller but fewer shoots for *Vallisneria americana* as compared with other treatments. It is possible that the mesh bags and burlap wraps, both of which had significantly lower cover for *R. cirrhosa*, reduced its growth due to decreased light availability or by physically affecting its growth form through the presence of the fabric. Identifying unique restoration requirements of species like *R. cirrhosa* is a critical step in overcoming a bias against species that are difficult to produce or plant and the subsequent widening of the pool of species available for restoration (Ladouceur et al., 2018).

Lack of observed effects of planting design may be attributed to low stress levels at experimental site, though qualitative observations offer bet-hedging strategy

Selection of planting design can be incorporated into restoration planning to address specific challenges and augment plant establishment through managing for positive or negative interactions between introduced individuals (Halpern et al., 2007). I predicted that a "clumped" planting design would perform better across species and planting methods by promoting positive interactions. However, I did not find strong evidence for the impact of planting design for plugs nor stem fragments, with the exception of moderate evidence for *P. nodosus* plugs. Effects of positive interactions have been observed in coastal aquatic plant restorations where wave action is a constant stress to introduced plants (Silliman et al., 2015), as well as terrestrial plant communities in relation to significant biotic and abiotic stress (Brooker et al., 2008). Prior to installing the experiment, I identified anoxia to be a potential stressor at the site, which has been shown to be mitigated by the presence of neighboring plants (Smith et al., 1984). Though I did not measure oxygen, I observed higher flow through the site than initially expected (presumably resulting in higher oxygen levels). This lack of stress in the experiment site may have contributed to the observed absence of conspecific facilitation.

Despite the absence of model support for either planting design, qualitative observations indicated selecting for dispersed planting designs could be a bet-hedging strategy in sites with dynamic water conditions. Experiment 2 results did not show evidence of impact of planting design, but site conditions make these data difficult to conclusively parse. Mid-season, standing water in the experimental area dropped dramatically, resulting in plot heterogeneity derived from parts of the plots remaining submerged while others had no standing water (Figure 3.8A). Whereas the fates of clumped treatments were directly connected to the standing water status in a single location in each plot, stem fragments in dispersed treatments had a greater probability of encountering sufficient water depth due to their spread throughout the plots. As climate-induced wetland alterations in arid landscapes become increasingly prevalent (Döll et al., 2020; Haig et al., 2019), bet-hedging strategies that accommodate substantial water fluctuations can have wide-ranging implications.

Future research directions and recommendations for practitioners

The United Nations declared 2021–2030 the Decade on Ecosystem Restoration, with an aim to "massively scale up the restoration of degraded and destroyed ecosystems" (Eisele & Hwang, 2019). However, this demand for scale, though timely, is hampered by a deficit of critical knowledge on how to rebuild aquatic plant communities (Waltham et al., 2020). Furthermore, the need to scale up restoration is mirrored by the foundational step of scaling up research on restoration across spatial, temporal, and environmental scales (Brudvig, 2011). Small scale experimentation—as conducted in this study—is an essential step in identifying methods that can then be scaled up (Hilt et al., 2006), and the next step is to execute similar experimentation at larger spatial scales to assess on-the-ground efficacy and enact restoration goals (Bayraktarov et al., 2019). To temporally scale up this research, long-term monitoring is needed to understand how planting methods and designs affect restoration success beyond initial establishment, especially as recovering communities experience disturbances and plant invasions.

Lastly, scaling up experimentation across environmental gradients is particularly important for aquatic species, which have been shown to respond to restoration variably across site conditions (van Katwijk et al., 2016).

This study informs aquatic plant restoration by assessing efficacy of scalable planting methods and identifying optimal planting designs. I suggest that carefully pairing species identity and scalable planting methods can increase feasibility and success of restoration projects. Species that perform well across planting methods offer more options for restoration practitioners. Furthermore, species that perform well with only select planting methods should be identified and paired accordingly. With the urgent need to restore the ecosystem functions and services of aquatic plant communities, these findings are timely and imperative to improve restoration of a diversity of critical species into our waterways.

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TABLES AND FIGURES

Table 3.1. ANODEV table (Type II Wald chi-square tests) for Experiment 1 mixed effects model of cover for (a) *R. cirrhosa* on peak date (08/02/22), (b) *P. nodosus* on peak date (09/14/22), and (c) *S. pectinata* on peak date (09/27/22). Statistically significant results at $p \leq 0.05$ are in bold, and marginally significant results at $0.05 < p \leq 0.10$ are italicized.

a. *R. cirrhosa*	χ^2	**Df**	**Pr(>χ^2)**
Planting method	11.198	2	**0.004**
Planting design	0.145	1	0.703
Planting method × design	1.355	2	0.508

b. *P. nodosus*	χ^2	**Df**	**Pr(>χ^2)**
Planting method	0.142	2	0.932
Planting design	3.550	1	*0.059*
Planting method × design	1.945	2	0.378

c. *S. pectinata*	χ^2	**Df**	**Pr(>χ^2)**
Planting method	1.487	2	0.475
Planting design	0.791	1	0.374
Planting method × design	0.877	2	0.645

Table 3.2. ANODEV table (Type II Wald chi-square tests) for Experiment 2 mixed effects models of cover for (a) *R. cirrhosa* on peak date (08/29/22), (b) *P. nodosus* on peak date (08/18/22), and (c) *S. pectinata* on peak date (10/14/22). Statistically significant results at $p \leq 0.05$ are in bold.

a. *R. cirrhosa*	χ^2	**Df**	**Pr($>\chi^2$)**
Planting method	6.966	1	**0.008**
Planting design	1.925	1	0.165
Planting method × design	0.009	1	0.926

b. *P. nodosus*	χ^2	**Df**	**Pr($>\chi^2$)**
Planting method	1.914	1	0.166
Planting design	0.068	1	0.794
Planting method × design	2.046	1	0.153

c. *S. pectinata*	χ^2	**Df**	**Pr($>\chi^2$)**
Planting method	0.417	1	0.519
Planting design	0.400	1	0.527
Planting method × design	0.002	1	0.962

A

B

Figure 3.1. Field experiment locations. (A) shows the location of the Provo River Delta Restoration project (yellow circle) where field experiments were conducted. (B) shows the locations of experiments within the restoration site. Experiment 1 was conducted in a constructed pond (purple triangle), and Experiment 2 was conducted in a constructed channel (orange triangle). Darker blue lines represent excavated channels, and lighter blue amorphous shapes are excavated ponds.

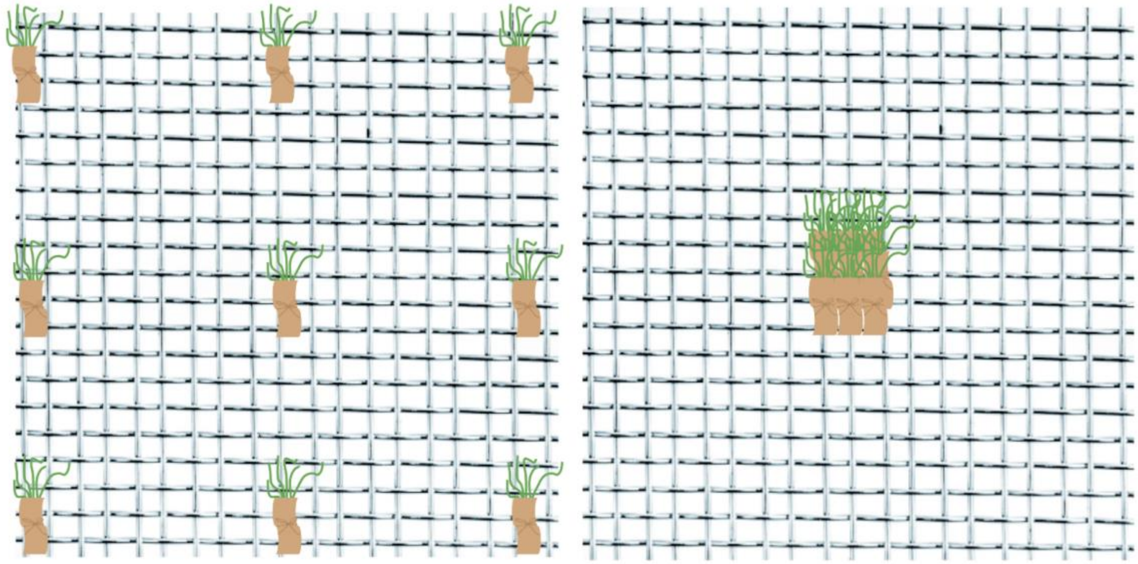

Figure 3.2. Experiment 1 planting design diagram using burlap wraps as the example planting method. Left: dispersed planting design (burlap wraps 50 cm apart), right: clumped planting design (burlap wraps in contact).

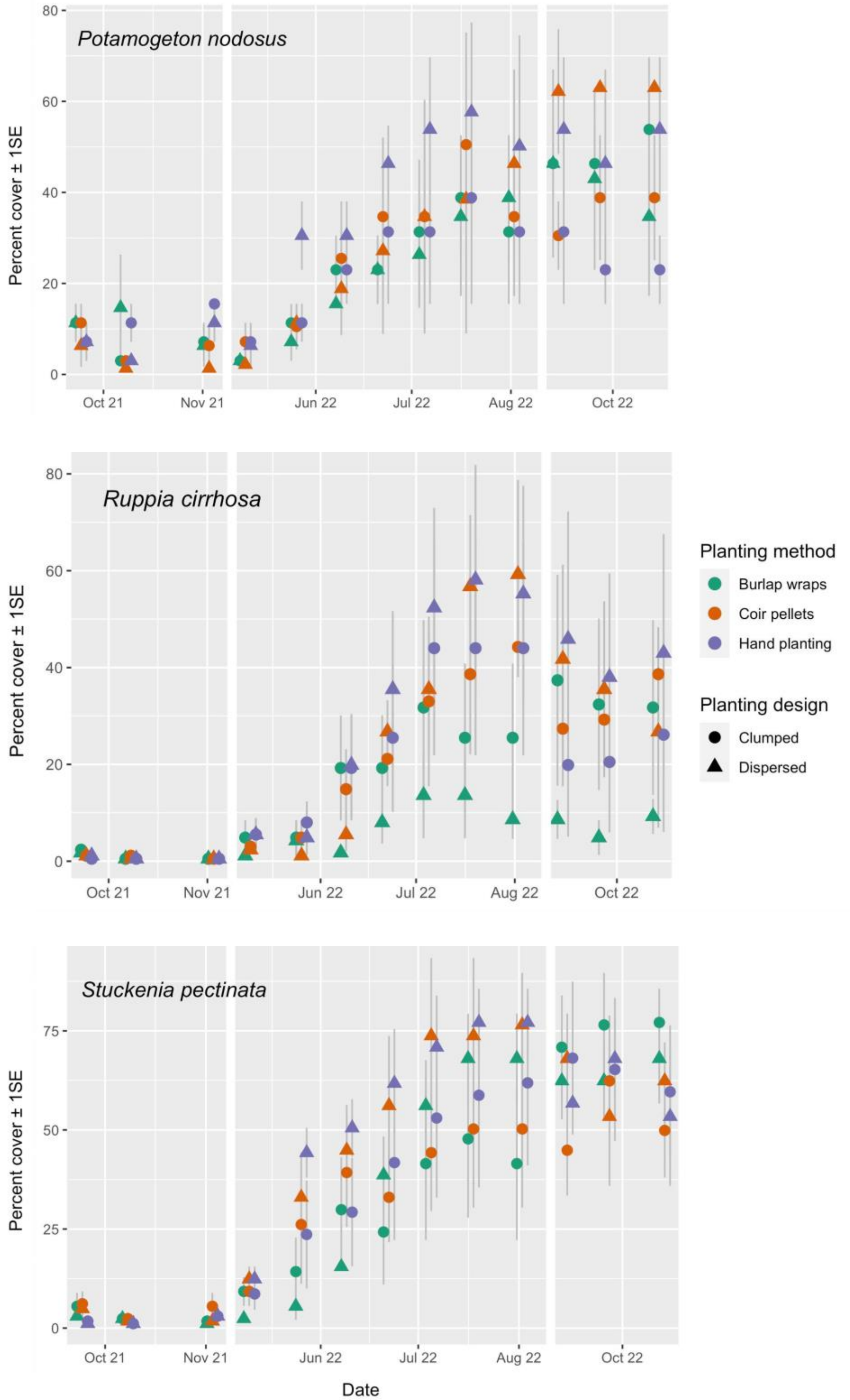

Figure 3.3. Experiment 1 mean percent cover (raw data) by species over the monitoring period.

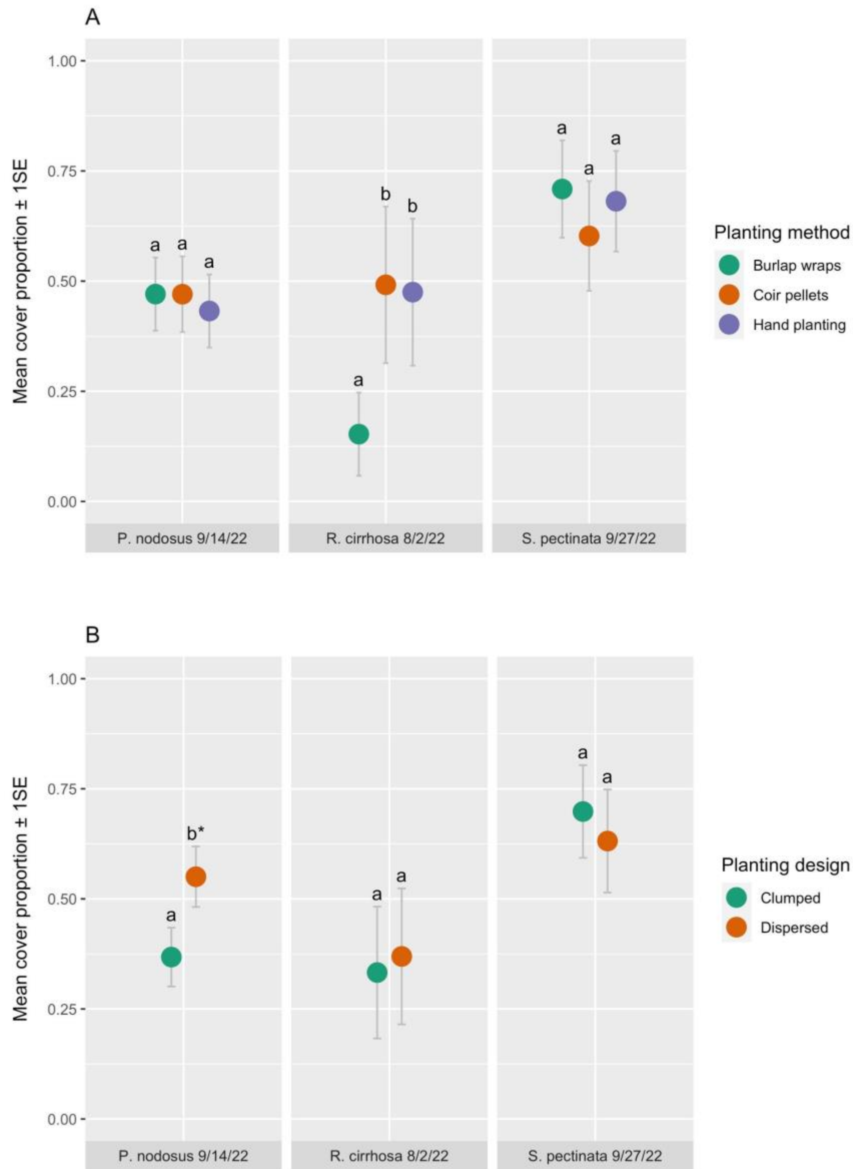

Figure 3.4. Experiment 1 mean cover proportion (model predicted means) on the peak date of each species for the planting method treatment (A) and planting design treatment (B). In plot A, different lowercase letters indicate statistically significant ($p \leq 0.05$) differences among treatments (Table S3.3). In plot B, the letter denoted with an asterisk indicates a moderately significant difference from the other model means ($p \leq 0.10$; Table 3.1b).

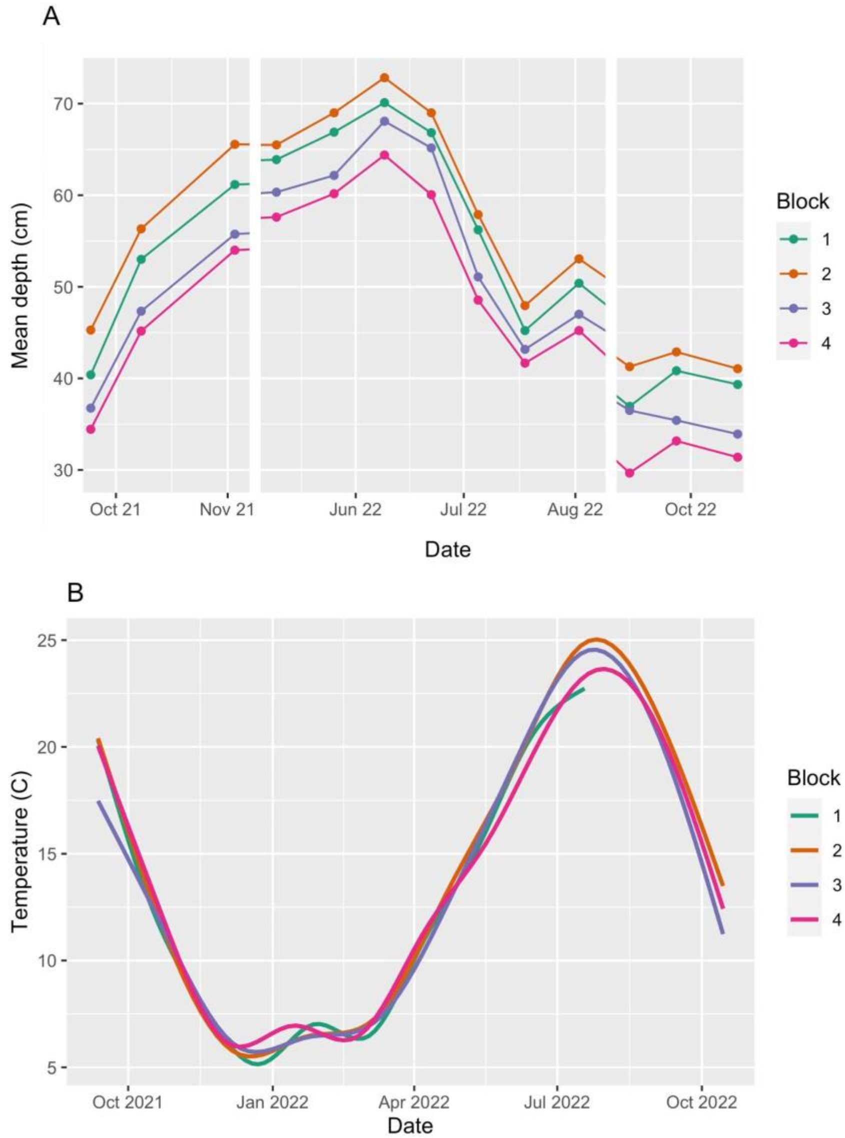

Figure 3.5. Experiment 1 standing water depth (A) and temperature (B) over the monitoring period. The Block 1 temperature logger was corrupted in summer 2022, leading to loss of temperature data.

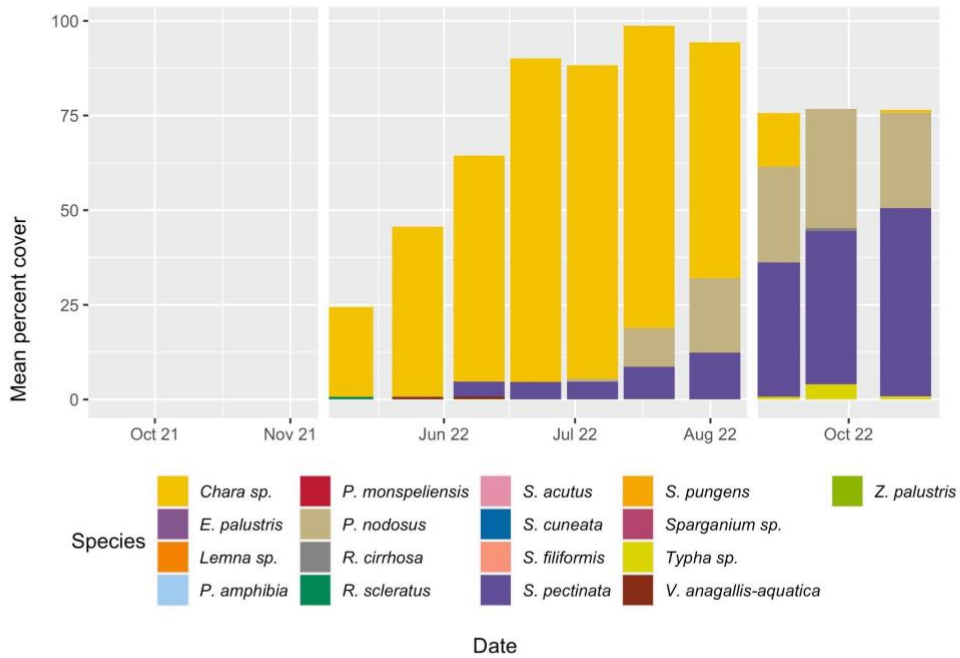

Figure 3.6. Experiment 1 mean percent cover of species in untreated control plots.

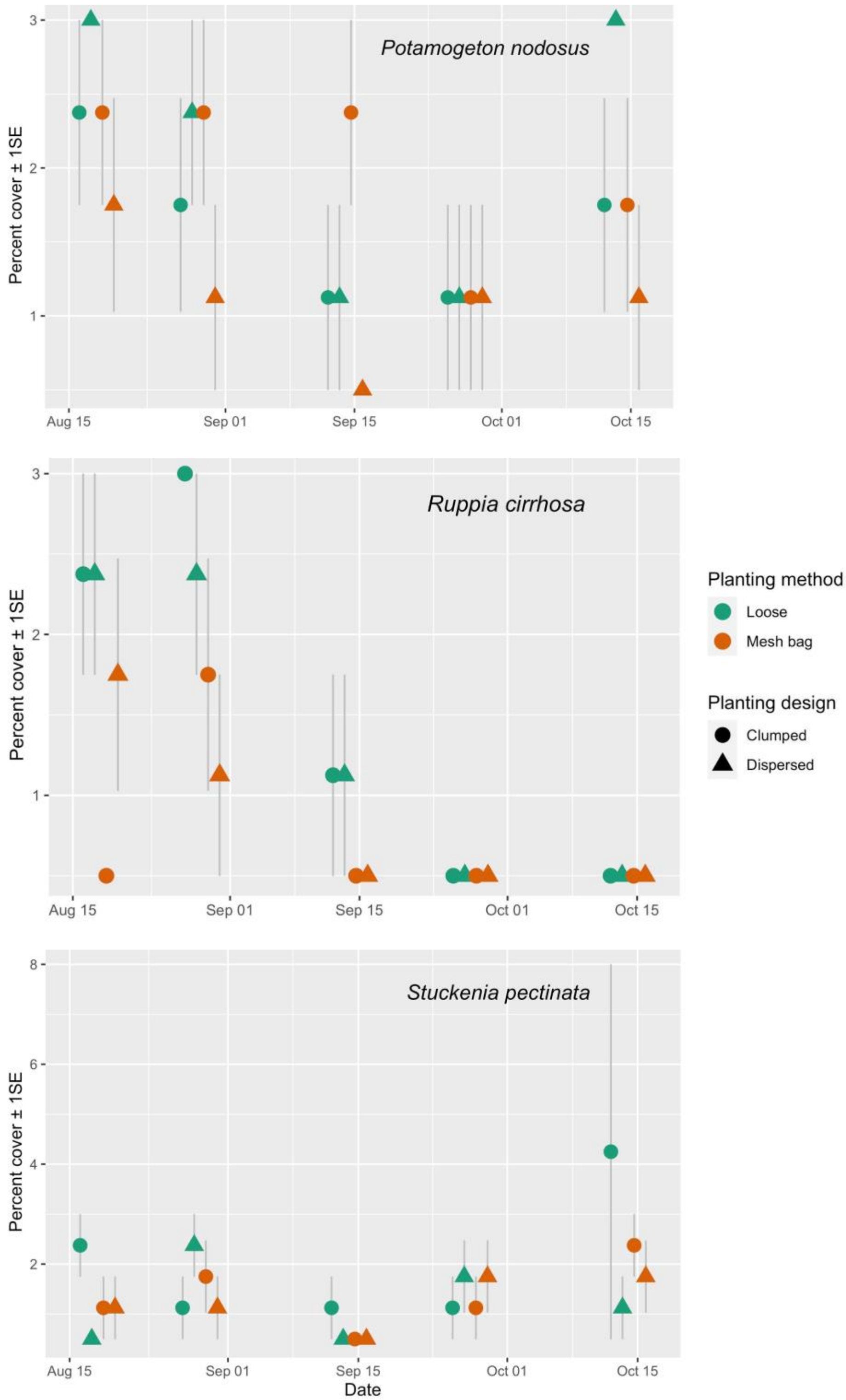

Figure 3.7. Experiment 2 mean percent cover (raw data) by species over the monitoring period.

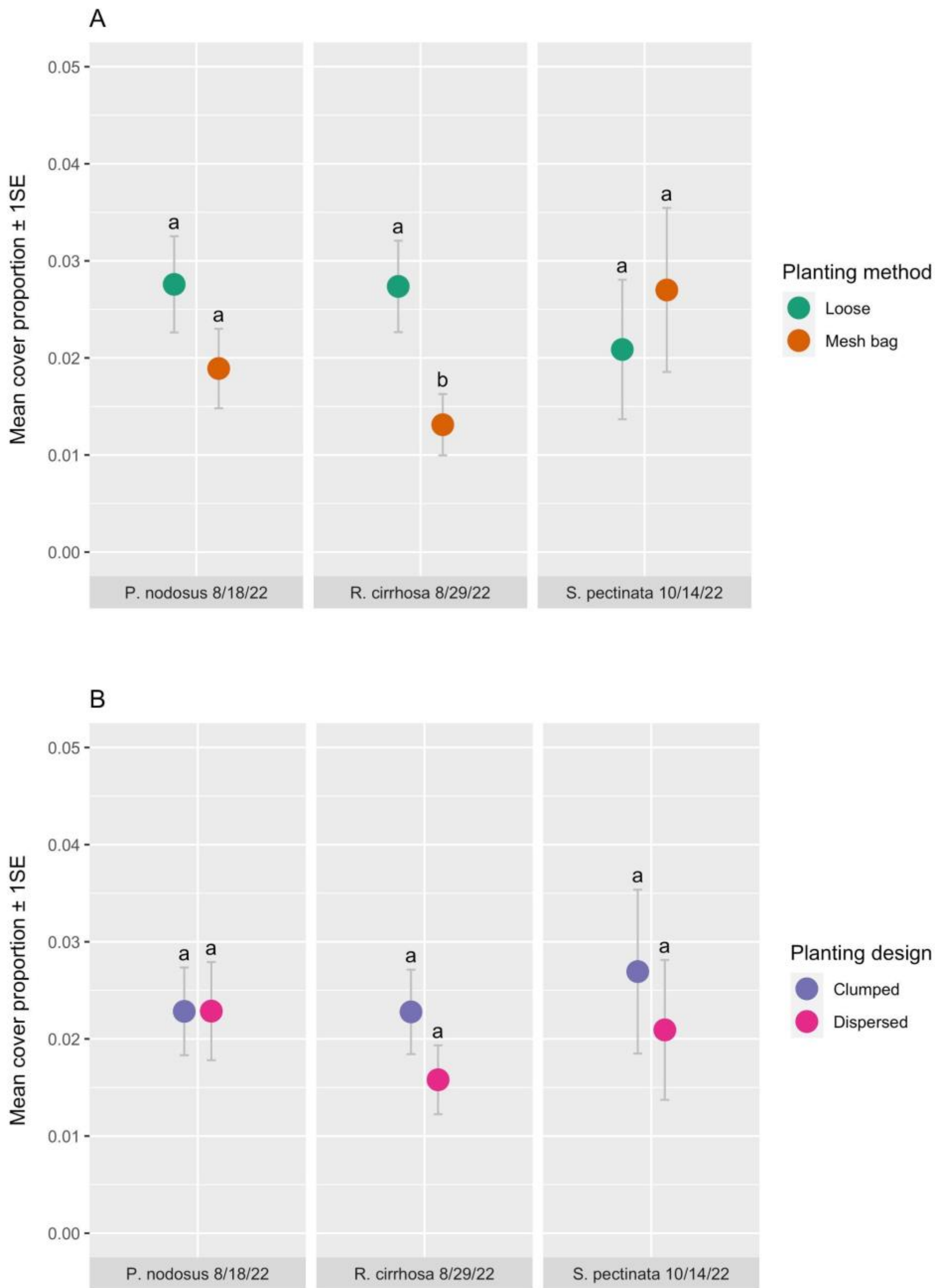

Figure 3.8. Experiment 2 mean cover proportion (model predicted means) on the peak date of each species for the planting method treatment (A) and planting design treatment (B). Different lowercase letters indicate statistically significant ($p \leq 0.05$) differences among treatments (Table 3.2).

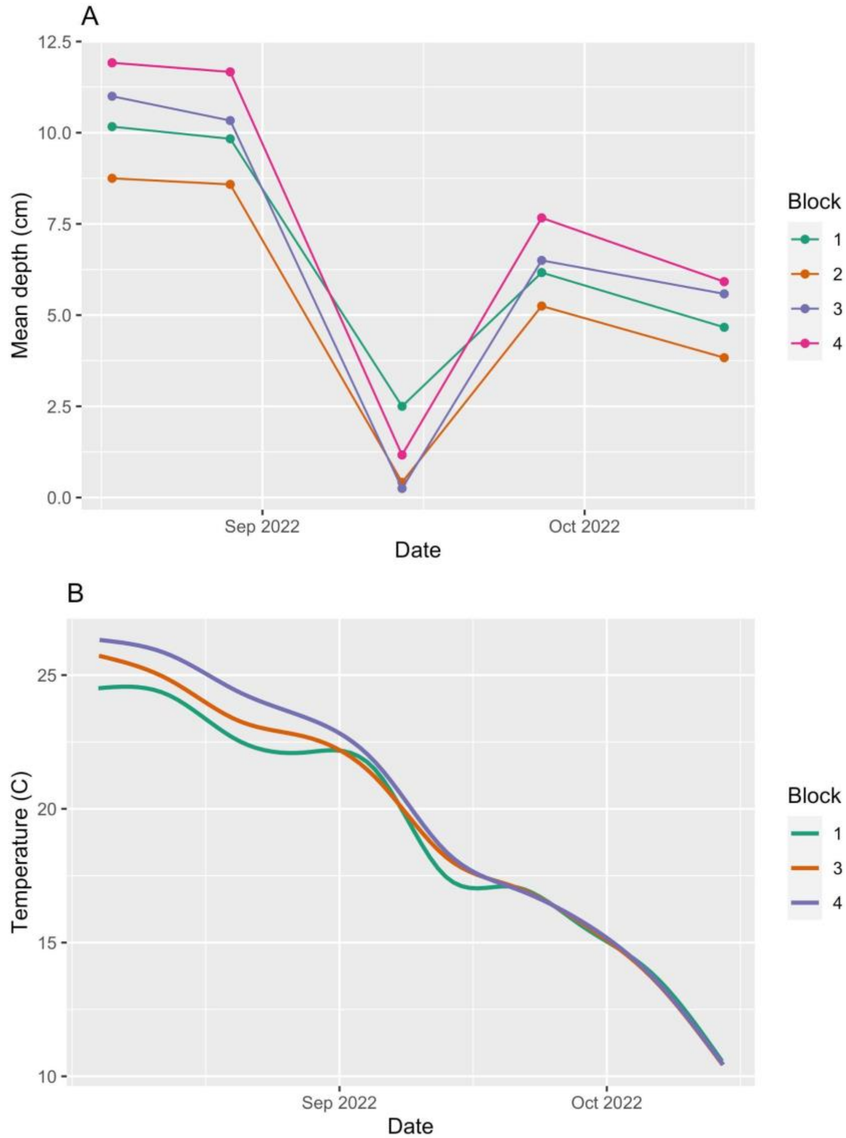

Figure 3.9. Experiment 2 standing water depth (A) and temperature (B) over the monitoring period. Temperature was monitored at the substrate level. The Block 2 temperature logger was corrupted in summer 2022, leading to loss of temperature data.

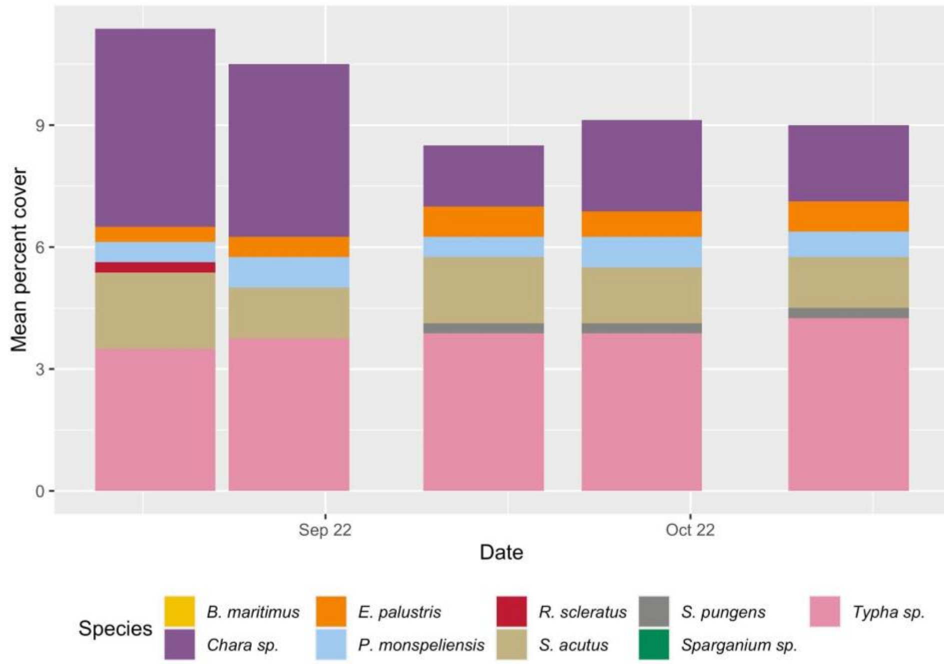

Figure 3.10. Experiment 2 mean percent cover of species in untreated control plots.

CHAPTER IV

SUMMARY AND CONCLUSIONS

I identified practical barriers that limit restoration of aquatic species in the Intermountain West. The two major limitations identified were 1) a lack of confidence in aquatic species identification among wetland managers and restoration practitioners, and 2) underdevelopment of planting techniques that are scalable and result in successful plant establishment. To overcome these barriers, I created the "Floating and Submerged Plants of Utah: Pocket Field Guide," designed for use in the field for those who work in, restore, or care about wetlands. I also investigated the relative performance of planting techniques in two field experiments to identify planting methods and designs that increase establishment across two plant material types.

In informal discussions with wetland managers, restoration practitioners, and researchers in the Intermountain West, I identified species recognition as a significant barrier to aquatic plant research and restoration. Species recognition is an integral requirement of studying, managing, and restoring plants. Although resources exist to identify and distinguish species, traditional species guides are frequently inaccessible in terms of price or portability (Farnsworth et al., 2013). To address this knowledge gap, I created a list of aquatic plant species that may be found throughout Utah and compiled and consolidated information from plant keys (Correll & Correll, 1972; Godfrey, 1981; Welsh et al., 2015), field guides from other regions or larger systems (Downard et al., 2017; Skawinski, 2014), online databases (*AquaPlant*, 2022; Kartesz, 2015; USDA, NRCS, 2023), and personal observations to create a field guide that would be both accessible and informative. The resulting "Floating and Submerged Plants of Utah: Pocket Field Guide" contains identification information, images, and interesting facts about 36 aquatic species, as well as a key specific to the labyrinthine Pondweed family. It is 4" × 6" and constructed of waterproof, tear-proof pages—perfect for users to tuck in the pocket of their waders or toss in their kayak. It will be published through Utah State University Extension, ensuring public accessibility. The intended audience is a wide group of wetland managers, researchers, and restoration practitioners, but the guide can be used by anyone who wants to learn more about the beautiful and enigmatic aquatic species in our waterways.

The field experiment findings will provide critical information to practitioners who make decisions that impact restoration outcomes under ecological, practical, and financial constraints. When using plugs in restoration, I suggest that planting methods such as burlap wraps and coir pellets can be employed to expedite the planting process (by allowing the plugs to be dropped from the surface of the water) while still maintaining establishment levels comparable to hand planting for *Potamogeton nodosus* and *Stuckenia pectinata*. However, due to species responding differently, I urge practitioners to consider species identity when selecting planting methods: I observed that *Ruppia cirrhosa* cover was significantly lower for the burlap wrap treatment. I did not find significant differences between planting methods for stem fragments or between planting designs (clumped vs. dispersed arrangements) for either plugs or stem fragments, suggesting that practitioners can base decisions of these factors based on logistic and financial circumstances rather than ecological concerns. These findings specify where decisions need to be carefully weighed (i.e., when pairing planting method and species identity) and where there is flexibility (i.e., when selecting planting designs). This elucidation of the decision-making process will assist practitioners in making informed choices based on project-specific conditions.

Wetland restoration is a priority in arid landscapes, where critical aquatic habitat is threatened by declining water availability, climate change, pollution, and invasive species. Effective revegetation techniques can help restore degraded wetland habitat, however, practical barriers to aquatic plant restoration continue to impede its widespread practice. In this thesis, I take steps toward overcoming the barriers associated with planting techniques and species recognition. Successful establishment and improved recognition of native aquatic plant species are fundamental to building capacity for restoration of aquatic plant communities and subsequently supporting the health and functioning of inland waterways.

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APPENDIX:

SUPPLEMENTAL INFORMATION FOR CHAPTER III

Table S3.1. Aquatic plant species investigated in field experiments.

Scientific name	Common names	Description	Habitat	Restoration potential
Potamogeton nodosus	Longleaf pondweed	Perennial monocot, submerged and floating leaves, emerged flowers. Fibrous and rhizomatous root system with tubers.	Requires nutrient-rich soil conditions (Coops et al., 1994). Moderate flow conditions.	Positively correlated with invertebrate abundance (Beckett et al., 2011). Successful in restorations and tolerant to fluctuations in water levels (Fleming et al., 2011)
Ruppia cirrhosa	Spiral ditchgrass	Perennial monocot, submerged leaves, slender roots.	Shallow systems with a variety of environmental conditions, including salinity, turbidity, light availability (Mannino & Sarà, 2006)	Regulates suspended matter (Mannino & Sarà, 2006). High resiliency to changes in environmental conditions (Dhib et al., 2013)
Stuckenia pectinata	Sago pondweed	Perennial monocot, submerged leaves, rhizomatous with tubers.	Low water velocity, silt or sand substrate, water depth < 3 m (French & Chambers, 1996)	Often the first species to expand in restorations, after which dominance shifts to other species (Hilt et al., 2006). Can tolerate low light conditions. Good competitor for *Potamogeton crispus* due to similar phenology (Santos et al., 2011).

Table S3.2. Experiment 1 planting method and design information. Plugs were considered ready for all methods when roots were protruding out of the bottom of roughly half of the plugs in each tray, which occurred after approximately four weeks. Soil and pellets were soaked for 24 hours prior to use. Advantages and disadvantages were adapted from Reynolds et al. (2021).

Method	Design	Plug production[1] and preparation	Description	Advantages	Disadvantages
Hand planted	Dispersed	Stem fragments were grown in PRDRP site soil in plug trays[2].	Plugs were planted manually by hand and spaced 50 cm apart from each other in all directions.	Requires little infrastructure and no additional material cost.	Difficult to scale up. May be dangerous in deeper water. Time consuming.
	Clumped		Plugs were planted by hand in contact with one another.		
Burlap wraps	Dispersed	Stem fragments were grown in PRDRP site soil in plug trays[1]. Plugs were wrapped in 30 cm × 30 cm squares of burlap[3] and tied with	Plugs were wrapped in burlap and tied with twine. Wraps were tied[3] to a 1 m × 1 m wire frame[5] at least 37 cm apart (Figure 3.2) to ensure spacing was maintained. Frame was affixed to the	Reduces transplant stress by protecting roots and incorporating site soil. Easily transported. Can be	Requires moderate preparation time and additional material cost.

[1] Soil and coir pellets were soaked for 24 hours then filled into or placed in plug trays, respectively. Stem fragments with meristematic tissue were harvested from foundation population tanks and inserted into each plug by pushing the stem into the soil and pinching the soil around the fragment. Throughout this process, plants and plugs were showered with water approximately every three minutes to prevent drying. Trays were then gently set in large tanks and the tanks were filled with water until it was approximately 30 cm above the surface of the plugs. Every three days, roughly one third of the water in each tank was removed (via scooping with a bucket) and refilled with fresh water.

[2] TO Plastics brand 50 plug trays; plug dimensions: 4.8 cm × 4.8 cm × 5.8 cm

[3] Easy Gardener brand Natural Burlap Weed Barrier Fabric

[5] YARDGARD brand chicken wire, mesh size 2.5 cm

		twine[4].	substrate using landscape staples[6].	dropped from the surface. Materials are decomposable. Requires little infrastructure.	
	Clumped		Plugs were wrapped in burlap and tied with twine. Wraps were tied[3] to a wire frame[4] with wraps in contact with one another (Figure 3.2) to ensure clumping was maintained. Frame was affixed to the substrate using landscape staples.		
Coir pellets	Dispersed	Stem fragments were grown into coir pellets[7] instead of site soil.	Pellets were tied[3] to a wire frame[4] at least 37 cm apart (similar to Figure 3.2) to ensure spacing was maintained. Frame was affixed to the substrate using landscape staples[5].	Protects roots and sediment during the planting process. Easily transported. Can be dropped from the surface. Materials are decomposable. Requires little infrastructure and does not require preparation time.	Does not use site soil— increases risk of transplant shock. Requires additional material cost.
	Clumped		Fragments were planted into netted coir pellets instead of plugs. Pellets were tied[3] to a wire frame[4] with pellets in contact with one another (similar to Figure 3.2) to ensure clumping was maintained. Frame was affixed to the substrate using landscape staples[5].		

[4] Gardener's Blue Ribbon Jute Twine

[6] Colmet 10-in Silver Galvanized Steel Edging Pin and Sta-Green 4-in Metal Landscape Stake

[7] Jiffy brand Extra Deep Pellets; dimensions 4.3 cm diameter × 6.5 cm tall when soaked

Table S3.3. Block design descriptions.

Experiment	Attribute	Description
Experiment 1	Plot arrangement	Plots were arranged within blocks in a 3 $\times$ 7 formation. Two unmonitored plots were added to allow for rectangular design.
	Control plots	One control plot was established in each block to assess passive recovery.
	Distances	Plots were 1 m apart and blocks were greater than 5 m apart.
Experiment 2	Plot arrangement	Plots were arranged within blocks in a 3 $\times$ 5 formation. One unmonitored plot was added to allow for rectangular design.
	Control plots	Two control plots were included in each block to assess passive recovery.
	Distances	Plots were 1 m apart and blocks were greater than 5 m apart.

Table S3.4. Experiment 2 planting method and design information. Advantages and disadvantages were adapted from Reynolds et al. (2021).

Method	Design	Description	Advantages	Disadvantages
Loose	Dispersed	9 12–15 cm stem fragments were placed in water at the restoration site.	Little additional time or material cost.	More susceptible to herbivory.
	Clumped	9 12–15 cm stem fragments were bundled and tied together with twine and placed in water at the restoration site.		
Mesh bag	Dispersed	9 individual bags[8] were filled with single 12–15 cm stem fragments. Bags were placed in water at the restoration site.	Protection against herbivory. Weight anchors plants.	Minimal additional time and material cost relative to plugs.
	Clumped	Bags were filled with 9 12–15 cm stem fragments. Bags were placed in water at the restoration site.		

[8] Farberware brand Cotton Canning Cheese Cloth tied with Peaches & Creme Cotton Yarn

Table S3.5. Pairwise comparisons among planting method means for the *R. cirrhosa* cover proportions in Experiment 1. Estimates are on the logit (model) scale. Codes for planting methods: BW = burlap wrap, CP = coir pellet, HP = hand planted.

Contrast	Estimate	SE	Df	*P*-value
BW - CP	-1.679	0.546	16	0.019
BW - HP	-1.613	0.510	16	0.016
CP - HP	0.067	0.477	16	0.989

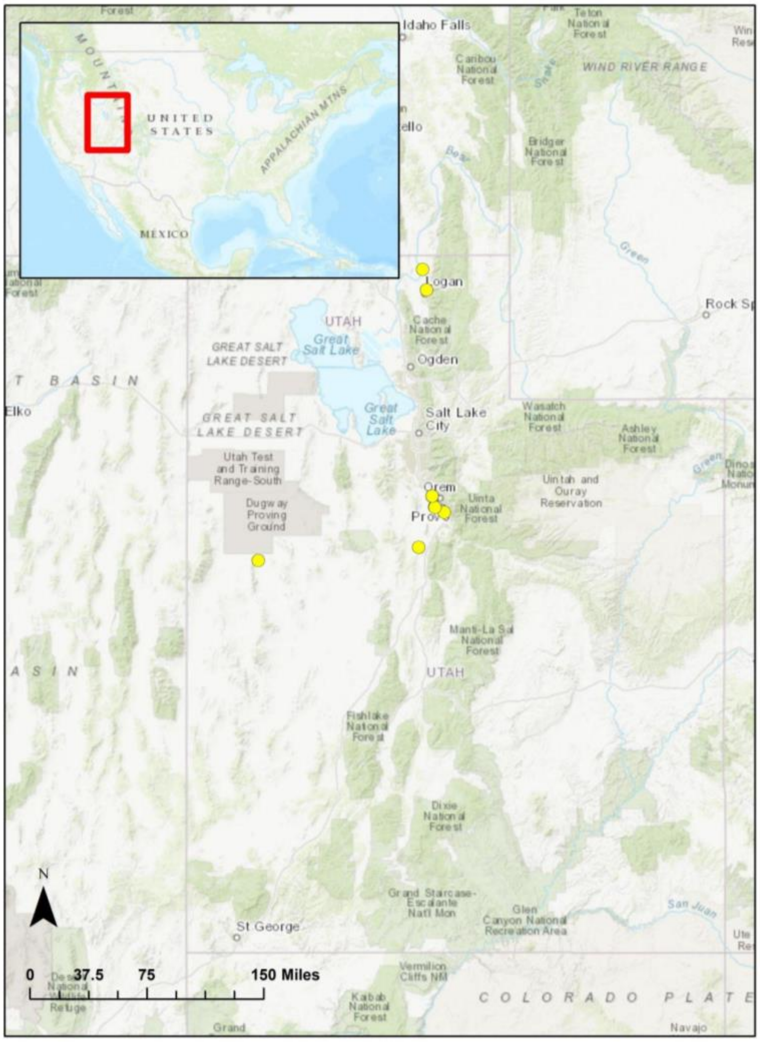

Figure S3.1. Map of plant population collection sites (yellow points) in the state of Utah.

Figure S3.2. Experiment 1 planting methods. From left to right: burlap wrap, coir pellet, and hand planting (burlap in hand planting image is to provide a background, only the plug was planted without additional materials).

Figure S3.3. Bathyscope used to improve visibility to visually assess percent cover.

Figure S3.4. Experiment 2 planting treatments demonstrated with *P. nodosus*. From left to right: loose dispersed, loose clumped, mesh dispersed, and mesh clumped.

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