Chapter 13
Invasive Plants of Great Salt Lake Wetlands: What, Where, When, How, and Why?

Karin M. Kettenring, Chad R. Cranney, Rebekah Downard, Keith R. Hambrecht, Emily E. Tarsa, Diane R. Menuz, and Christine B. Rohal

Abstract Great Salt Lake (GSL) and its wetlands are recognized around the world for the valuable habitat they provide for millions of migratory birds. GSL wetlands are threatened by a number of invasive plants, the most problematic of which is non-native phragmites (*Phragmites australis*) although there are a number of other species that are concerning and also a target of management. In this chapter, we describe the major invasive plants of and their distributions across GSL wetlands, detail the mechanisms driving these plant invasions and their historical context, discuss why different invasive species present unwanted impacts, and synthesize best practices for invasive plant control for these species in GSL wetlands. Managers of GSL wetlands face a daunting task to control these plants, particularly in the case of phragmites, where hundreds of hectares of infestations must be treated and retreated annually. Eradication of phragmites will not be possible given its intense propagule pressure and dense seed banks, thus strategic and prioritized management

K. M. Kettenring (✉) · E. E. Tarsa
Ecology Center and Department of Watershed Sciences, Utah State University, Logan, UT, USA
e-mail: karin.kettenring@usu.edu

C. R. Cranney
Utah Division of Wildlife Resources, Utah Department of Natural Resources, Salt Lake City, UT, USA

R. Downard
Utah Division of Water Quality, Utah Department of Environmental Quality, Salt Lake City, UT, USA

K. R. Hambrecht
Utah Division of Forestry, Fire & State Lands, Utah Department of Natural Resources, Salt Lake City, UT, USA

D. R. Menuz
Utah Geological Survey, Utah Department of Natural Resources, Salt Lake City, UT, USA

C. B. Rohal
Department of Environmental Horticulture, University of Florida, Gainesville, FL, USA

B. K. Baxter, J. K. Butler (eds.), *Great Salt Lake Biology*,
https://doi.org/10.1007/978-3-030-40352-2_13

approaches are critical. Future success for all invaders will be contingent upon continued cooperation between scientists and managers to develop robust treatment techniques and between managers to coordinate their management to reduce invader cover and impacts. Furthermore, future research and management priorities should include (1) limiting invader propagule pressure and seed bank densities, (2) optimizing native plant revegetation following invader removal, (3) early detection and control of new invaders that are likely to increase with climate change, (4) more refined hydrologic management to promote invader control, and (5) quantitative documentation of avian impacts from invaders, especially given the continental importance of this habitat to migratory birds. Despite the threats GSL and its wetlands face with anthropogenic development, water diversions, and climate change, we are optimistic that at least in the case of invasive species, collaborative and science-backed management can continue to be effective given current partnerships and practices.

Keywords Great Salt Lake · *Cardaria draba* · Alien species · Non-indigenous species · Disturbance · *Frankenia pulverulenta* · Invasion mechanisms · Invasive plant management · Invasive species · *Lepidium latifolium* · *Lythrum salicaria* · Non-native species · Nutrients · *Phragmites australis* · *Potamogeton crispus* · Revegetation · Seed sowing · Seed-based restoration · Seeding density · *Typha domingensis* · *Typha latifolia* · Wetland restoration

13.1 Introduction

Wetland plant communities are the food web foundation of Great Salt Lake (GSL) wetlands (Downard et al. 2017). However, native-dominated plant communities in these wetlands—like in many wetlands around the world—are being heavily impacted by invasive plants (Downard et al. 2017; Kettenring et al. 2012; Zedler and Kercher 2004). Invasive plants are usually non-native species (some notable native but undesirable species exist), likely introduced due to human activity, that have substantial negative ecological or economic impacts or cause harm to human health (Executive Presidential Order 1999). Invasive plants are considered particularly problematic in GSL wetlands because they reduce habitat quality for many wildlife species, including continentally important migratory birds, by converting native plant assemblages to monotypic plant stands often with little habitat value (Downard et al. 2017; Intermountain West Joint Venture 2013; Kettenring et al. 2012; Rohal et al. 2018; SWCA 2012). Understanding the mechanisms driving these plant invasions is critical for improving management and recovering the critical habitat of GSL wetlands. In this chapter, we describe the major invasive plants of and their distributions across GSL wetlands, detail the mechanisms driving these plant invasions and their historical context, discuss why different invasive species are undesirable in terms of their impacts, and synthesize best practices for control of these species in GSL wetlands. We conclude with our assessment of next steps for further enhancing our understanding of the mechanisms, impacts, and management of common plant invaders.

13.2 Overview

13.2.1 Significance of Great Salt Lake and Its Wetlands

Understanding the significance of GSL and its wetlands is important to grasp what is currently present and can be lost with widespread plant invasions (Fig. 13.1). The GSL ecosystem is a desert oasis for millions of birds that breed in and migrate through the Great Basin region (Weller 1999; Oring et al. 2000; Olson et al. 2004; Intermountain West Joint Venture 2013). GSL is recognized regionally, nationally, and hemispherically for its importance to more than 130 waterbird species that rely on the lake and its wetlands during certain stages of their life history (Neill and Sorensen, unpublished list 2020). For some of these bird species, a major proportion of their population can be found on GSL during certain times of the year. For example, the largest staging concentration of Wilson's phalarope (*Phalaropus tricolor*), a small wading bird, is found on GSL, numbering over 500,000 (Fig. 13.2) (Paul and Manning 2002). Some of the highest counts within the Pacific Flyway of American avocets (*Recurvirostra americana*) and black-necked stilts (*Himantopus mexicanus*), two iconic shorebirds of GSL wetlands, have been recorded on GSL—250,000 and 65,000, respectively (Fig. 13.2) (Barber and Cavitt 2012; Shuford et al. 1995). GSL wetlands are the only interior staging area in western North America for thousands of marbled godwits (*Limosa fedoa*), another shorebird, with peak counts of 43,000 birds (Fig. 13.2) (Paul and Manning 2002; Shuford et al. 1995). Over 60,000 tundra swans (75% of its western population; *Cygnus columbianus*) rely on GSL wetlands for staging and refueling during their fall migration (Fig. 13.2) (Aldrich and Paul 2002). In addition, an extensive 5-year survey estimated 86,752,258 mean bird use days (1 bird spending 24 h in the study area) for GSL (Paul and Manning 2002). The diversity and vast numbers of aquatic birds that use GSL and its associated wetlands are due to the diversity of habitats and abundance of resources within these habitats that ultimately fuel these birds through critical stages within their life cycle (Downard et al. 2017; Intermountain West Joint Venture 2013; Paul and Manning 2002).

The modern economic and cultural significance of these avian populations is also worth noting. Non-hunting resource users, namely birdwatchers and others who visit the lake and its wetlands for aesthetic, spiritual, and intellectual inspiration, likely contribute more than $50 million in direct spending to the Salt Lake City area economy (Bioeconomics, Inc. 2012). Cultural events that celebrate these bird populations including the annual GSL Bird Festival bring together hundreds of birdwatchers, hunters, and interested citizens for workshops, field trips, and family activities (Burr and Scott 2004; Great Salt Lake Bird Festival 2019). Also, a substantial proportion of these migratory bird populations include waterfowl species

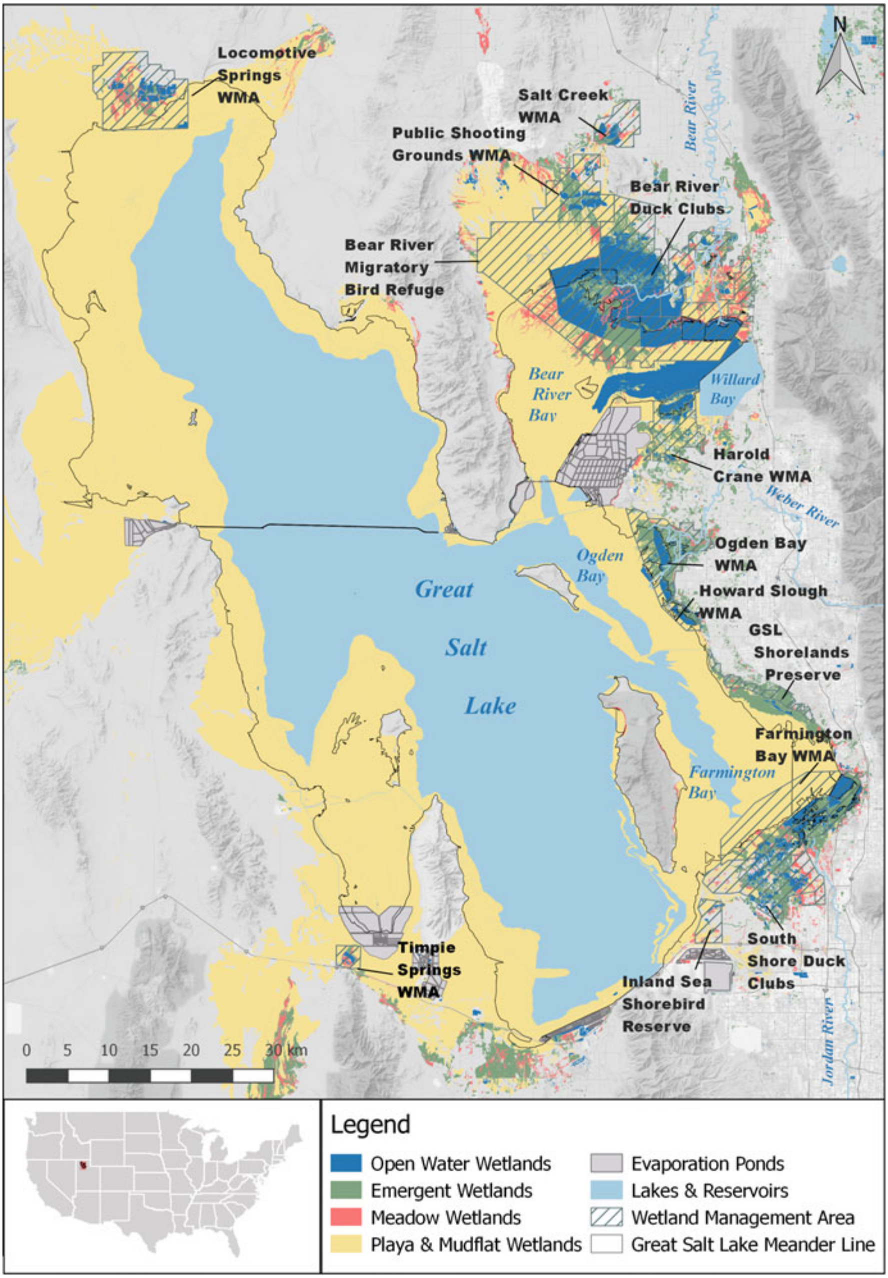

Fig. 13.1 The major federal, state, private, and nonprofit wetland complexes on Great Salt Lake. WMA = Waterfowl Management Area. GSL = Great Salt Lake. Wetland layer: US Fish & Wildlife Service 2017. National Wetlands Inventory website. US Department of the Interior, Fish & Wildlife Service, Washington, DC. http://www.fws.gov/wetlands/. Map tiles by Stamen Design, under CC BY 3.0. Data by OpenStreetMap, under ODbL

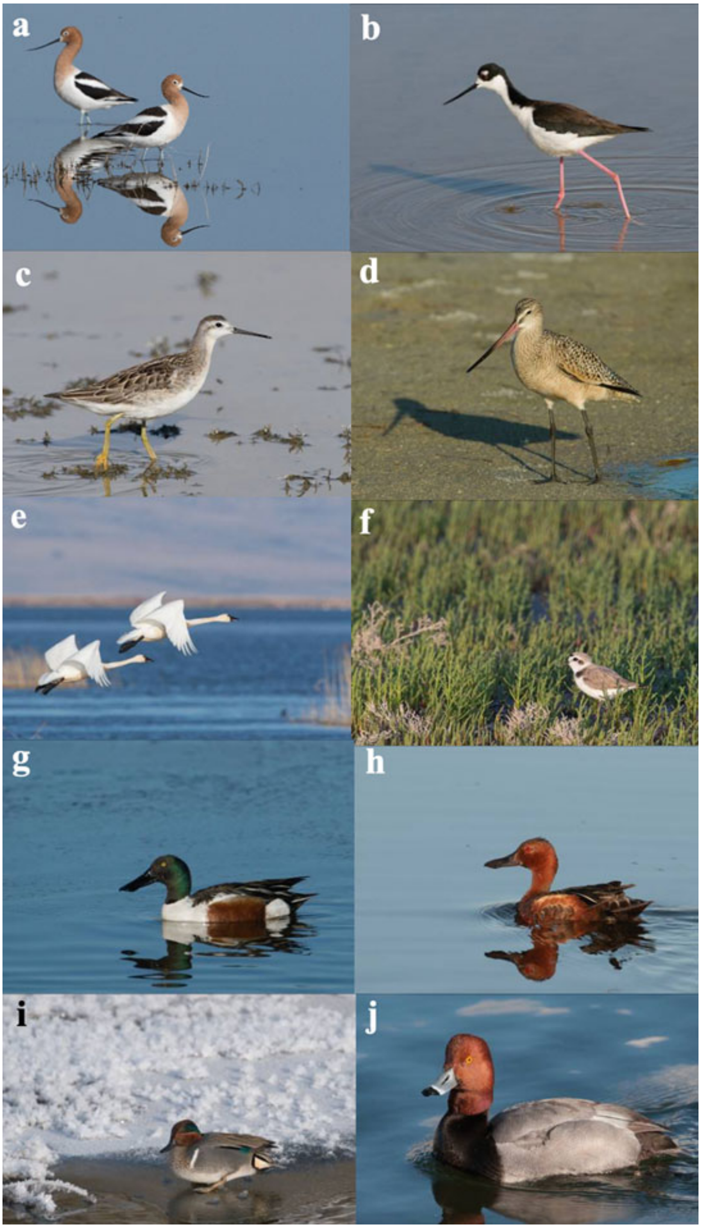

Fig. 13.2 Examples of bird species for whom Great Salt Lake and its wetlands provide significant habitat: (**a**) American avocet (*Recurvirostra americana*), (**b**) black-necked stilt (*Himantopus mexicanus*), (**c**) Wilson's phalarope (*Phalaropus tricolor*), (**d**) marbled godwit (*Limosa fedoa*), (**e**) tundra swans (*Cygnus columbianus*), (**f**) snowy plover (*Charadrius nivosus*), (**g**) northern shoveler (*Anas clypeata*), (**h**) cinnamon teal (*Anas cyanoptera*), (**i**) green-winged teal (*Anas carolinensis*), and (**j**) redhead (*Aythya americana*). All images courtesy of Mia McPherson, On the Wing Photography, with permission

that are popular for hunting. Waterfowl hunting has been a part of the Utah economy for generations (Thursby 2004) and contributes a hundred million dollars annually to the Salt Lake City area economy (Duffield et al. 2011; Bioeconomics, Inc. 2012). Interestingly, a survey of more than 550 GSL hunters in 2011 found that they considered invasive plants the top threat to their hunting hobbies and livelihoods (Duffield et al. 2011). Because of their economic and cultural significance, GSL wetlands are owned and managed for the public by state and federal agencies—US Fish & Wildlife Service, Utah's Division of Wildlife Resources (DWR) and Division of Forestry, Fire & State Lands (DFFSL)—nonprofit conservation groups like The Nature Conservancy and the Audubon Society for habitat conservation, privately managed mitigation wetlands like Inland Sea Shorebird Reserve, and private duck clubs that provide waterfowl hunting privileges to their members (Fig. 13.1).

13.2.2 Great Salt Lake Wetland Habitats Impacted by Invasives

The millions of birds that visit GSL and associated wetlands each year are dependent upon these unique habitats for food, nesting, shelter, loafing, and brood rearing (Aldrich and Paul 2002; Cox and Kadlec 1995; Roberts 2013; Vest and Conover 2011). Habitat types around GSL range from the hypersaline open lake, brackish emergent wetlands (with species like *Bolboschoenus maritimus*, alkali bulrush), mudflat, and playas (with species like *Salicornia rubra*, pickleweed), meadows (with species like *Eleocharis palustris*, common spikerush; *Distichlis spicata*, saltgrass; and *Juncus arcticus* ssp. *littoralis*, mountain rush) to fresh open water impoundments with productive submerged aquatic communities of native pondweeds (*Stuckenia* and *Potamogeton* species) surrounded by emergent wetlands (with species like *Schoenoplectus acutus* and *S. americanus,* hardstem and threesquare bulrush) (Figs. 13.1 and 13.3; Downard et al. 2017). The distribution and extent of each of these habitats are dependent on GSL elevations and the flux between saltwater and freshwater (Downard et al. 2017; SWCA 2013).

Over 70 non-native plant species have been documented in and near GSL wetlands and almost 40% of plant species listed in a recent flora for the region are non-native (Downard et al. 2017). There are numerous reasons why there are so many non-native plants inhabiting GSL wetlands, including high rates of spread from drainages; movement by livestock, birds, and humans; intentional planting by managers and landowners; and a high level of disturbance—such as nutrient enrichment and sedimentation—that lead to opportunities for invasive plants to establish (Long et al. 2017a; Zedler and Kercher 2004). In this chapter, we focus on the most prevalent invasive species in these wetland systems, the most common and impactful of which is *Phragmites australis* (Cav.) Trin. ex Steud. (common reed or phragmites) (Downard et al. 2017; Duffield et al. 2011; Kettenring et al. 2012) (Fig. 13.4). We bring particular attention to phragmites in this chapter because of its dominance in GSL wetlands and its high importance to managers. In addition, we focus on a

Fig. 13.3 Common native wetland plants that are important for wildlife habitat but can be replaced by non-native phragmites: (**a**) hardstem bulrush (*Schoenoplectus acutus* (Muhl. ex Bigelow) Á. Löve & D. Löve; image by Rachel Hager, with permission), (**b**) threesquare bulrush (*Schoenoplectus americanus* (Pers.) Volkart ex Schinz & R. Keller), (**c**) alkali bulrush (*Bolboschoenus maritimus* (L.) Palla), (**d**) saltgrass (*Distichlis spicata* (L.) Greene), (**e**) pickleweed (*Salicornia rubra* A. Nelson), (**f**) sago pondweed (*Stuckenia pectinata* (L.) Börner), (**g**) mountain rush (*Juncus arcticus* Willd. spp. *littoralis* (Engelm.) Hultén), (**h**) common spikerush (*Eleocharis palustris* (L.) Roem. & Schult.), (**i**) nodding beggartick (*Bidens cernua* L.), (**j**) rayless alkali aster (*Symphyotrichum ciliatum* (Ledeb.) G.L. Nesom), and (**k**) fringed willowherb (*Epilobium ciliatum* Raf.)

handful of other problematic species to management—*Lythrum salicaria* (purple loosestrife), *Frankenia pulverulenta* (European seaheath), *Cardaria draba* (whitetop), *Conium maculatum* (poison hemlock), *Lepidium latifolium* (perennial pepperweed), and *Typha latifolia* and *Typha domingensis* (cattails) (Downard et al. 2017). We also mention a number of plants that are non-native and may have a noxious weed classification, but foster differing levels of concern among managers (Table 13.1; Fig. 13.5).

Fig. 13.4 Phragmites phenology, reproduction, and growth: (**a**) phragmites towering above alkali bulrush, (**b**) immature phragmites inflorescences, (**c**) mature phragmites inflorescences, (**d**) phragmites inflorescences on a senesced stand (winter), (**e**) live phragmites towering over wetland researcher and manager, Chad Cranney, and (**f**) drought-stressed phragmites

13.3 Phragmites Distribution, Historical Context, Mechanisms of Invasion, and Impacts

13.3.1 Distribution and Historical Context of Invasion

Phragmites australis subsp. *australis* is a non-native plant (composed of multiple haplotypes; hereafter non-native or invasive phragmites) from Eurasia that is now widespread in coastal and inland wetlands and moist, disturbed habitats across North America (Chambers et al. 1999; Kettenring et al. 2012; Meyerson and Cronin 2013; Saltonstall 2002). Studying and managing the invasion of non-native phragmites is

Table 13.1 Non-native and invasive plant species of Great Salt Lake wetlands. The list includes native species considered to be aggressive (invasive) and non-native species that are the most common, known to be problematic (e.g., noxious weeds), or with high potential to invade wetlands (due to anaerobic tolerance). Species in bold are frequently the focus of management control efforts

Scientific name with author citation Common name	Growth duration and habit[a]	Wetland indicator status[a]	Description
Agrostis stolonifera L. Creeping bentgrass	Perennial grass	FACW	Introduced as a pasture grass, spreading into wetlands. High tolerance to salinity and anaerobic soils (Downard et al. 2017; USDA NRCS 2019)
Atriplex spp. Saltbush	Annual forb	N/A or FACW	*A. micrantha* Ledeb. (twoscale saltbush; non-native), *A. prostrata* Bouchér ex DC. (triangle orache; nativity uncertain), and *A. patula* L. (spear saltbush; non-native) are all found in GSL wetlands and are difficult to distinguish (Downard et al. 2017); the latter two species are FACW (USDA NRCS 2019)
Bassia hyssopifolia (Pall.) Kuntz Fivehorn bassia	Annual forb	FAC	Common along road shoulders, planted to prevent erosion (Downard et al. 2017). Has a high salinity tolerance and medium tolerance of anaerobic soils. Important habitat for wildlife (C. Cranney, *pers. obs.*)
***Cardaria draba* (L.) Desv.** **Whitetop**	**Perennial forb**	**N/A**	**Found in dry to moist, alkaline soil near agriculture and listed as a noxious weed in Utah** (Downard et al. 2017; Lowry et al. 2017)
***Carduus nutans* L.** **Musk thistle**	**Perennial forb**	**FACU**	**Biennial or winter annual that can grow 2 m tall; found in roadsides, pastures, and wetland and stream edges (Lowry et al. 2017)**
Cichorium intybus L. Chicory	Perennial forb	FACU	Considered noxious weed in Colorado (USDA NRCS 2019). No salinity tolerance and low anaerobic tolerance; often occurs on dry fringes (Downard et al. 2017; USDA NRCS 2019)
***Cirsium* spp.** **Thistles**	**Perennial forb**	**FACU**	***C. vulgare* (Savi) Ten. (bull thistle) and *C. arvense* (L.) Scop. (Canada thistle) are nuisance species found in dry margins of GSL wetlands. *C. arvense* is listed as a Class 3 noxious weeds in Utah (Utah Department of Agriculture and Food 2019)**
***Conium maculatum* L.** **Poison hemlock**	**Biennial forb**	**FACW**	**Poisonous to people and livestock, a Class 3 noxious weed in Utah (Utah Department of Agriculture and Food 2019)**

(continued)

Table 13.1 (continued)

Scientific name with author citation Common name	Growth duration and habit[a]	Wetland indicator status[a]	Description
Dipsacus fullonum L. Fuller's teasel	Biennial forb	FAC	A noxious species in Colorado, capable of outcompeting and shading out desirable native species (Downard et al. 2017; USDA NRCS 2019)
Echinochloa crus-galli (L.) P. Beauv. Barnyardgrass	Annual grass	FACW	Native to Asia, this grass is planted as a food source for waterfowl. Able to accumulate a high concentration of nitrogen and phosphorus (Cao et al. 2020)
Elaeagnus angustifolia L. Russian olive	Perennial tree	FAC	A Class 4 noxious weed in Utah with high salinity tolerance and low anaerobic tolerance (Utah Department of Agriculture and Food 2019)
Frankenia pulverulenta L. European seaheath	Annual forb	N/A	Native to Europe, thrives in playa habitat, and very recently documented as widespread (D. Menuz, *pers. obs.*). Impacts unknown
Hordeum marinum Huds. Seaside barley	Annual grass	FAC	A grass that can cover significant wetland area, especially during dry conditions (Downard et al. 2017; USDA NRCS 2019)
Iris pseudacorus L. Pale yellow iris	Perennial forb	OBL	A noxious weed in 3 Western states, dispersed along canals via floating seeds (Downard et al. 2017; USDA NRCS 2019)
Lactuca serriola L. Prickly lettuce	Annual forb	FACU	Common weed in GSL wetlands, opportunistic late-season invader (Downard et al. 2017; USDA NRCS 2019). Important habitat for wildlife (C. Cranney, *pers. obs.*)
***Lepidium latifolium* L.** **Perennial pepperweed**	**Perennial forb**	**FAC**	**Roots are buoyant, can spread long distances by water, can remain dormant in the soil for years, and have been found more than 3 m deep in the soil profile (Fire Effects Information System 2019)**
Lepidium perfoliatum L. Clasping pepperweed	Annual forb	FACU	Found in a wide variety of ecosystems (open desert, alkaline flats, wetlands), though the area it covers is low (Downard et al. 2017)
***Lythrum salicaria* L.** **Purple loosestrife**	**Perennial forb**	**OBL**	**One individual plant can produce up to 2.7 million seeds, which are spread through waterways (DiTomaso et al. 2013)**
***Onopordum acanthium* L.** **Scotch thistle**	**Biennial forb**	**N/A**	**Can grow up to 12 ft tall; found along canals and streams in pastures and rangelands (Lowry et al. 2017)**

Phalaris arundinacea L. Reed canarygrass	Perennial grass	FACW	A cryptic species comprised of native and non-native, invasive genotypes likely introduced to the United States (Kettenring et al. 2019). It has medium salinity tolerance and high tolerance of anaerobic conditions (Downard et al. 2017; USDA NRCS 2019)
Polygonum persicaria L. Spotted ladysthumb	Annual forb	FACW	Moderately common in freshwater wetlands and looks a lot like native *P. lapathifolium* L. (Downard et al. 2017). Important habitat for wildlife (C. Cranney, *pers. obs.*)
Polypogon monspeliensis (L.) Desf. Annual rabbitsfoot grass	Annual grass	FACW	A common wetland-associated grass with low salinity tolerance but high anaerobic tolerance
Potamogeton crispus L. Curly pondweed	Perennial forb	OBL	Submerged aquatic species found in ponded brackish, alkaline, or eutrophic waters (Haynes and Hellquist 2000); not yet a nuisance in GSL wetlands, but listed as a noxious weed in at least six other states (USDA NRCS 2019)
Rumex stenophyllus Ledeb. Narrowleaf dock	Perennial forb	FACW	Very common wetland-associated species, similar to the also non-native *R. crispus* L. (FAC) (Downard et al. 2017). Important habitat for wildlife (C. Cranney, *pers. obs.*)
***Tamarix* L. spp.** **Tamarisk**	**Perennial tree**	**FAC**	**A Class 3 noxious weed in Utah. Deep taproots draw local water tables down while salty leaves make soils saltier (Utah Department of Agriculture and Food 2019)**
Thinopyrum intermedium (Host) Barkworth & D.R. Dewey Intermediate wheatgrass	Perennial grass	N/A	Common near wetlands, planted along road shoulders (Downard et al. 2017). Medium salinity tolerance and low anaerobic tolerance (USDA NRCS 2019). Important habitat for wildlife (C. Cranney, *pers. obs.*)
Trifolium fragiferum L. Strawberry clover	Perennial forb	FACU	High salinity and medium anaerobic tolerances. Likely spreads from pastures to wetlands (Downard et al. 2017; USDA NRCS 2019)
Typha L. spp. Cattail	Perennial forb	OBL	*T. domingensis* Pers. (southern cattail) and *T. latifolia* L. (broadleaf cattail) are native GSL wetland species but undesirable because they are considered poor waterfowl habitat and can push out more desirable wetland species (Downard et al. 2017; Ochterski 2003)

[a]Growth habit, duration, and wetland indicator status, which refers to the percentage of time the species is expected to be found in a wetland (OBL = obligate, >99%; FACW = facultative wetland, 67–99%; FAC = facultative, 34–66%; FACU = facultative upland, 1–33%; N/A = not rated) as determined by USDA NRCS (2019)

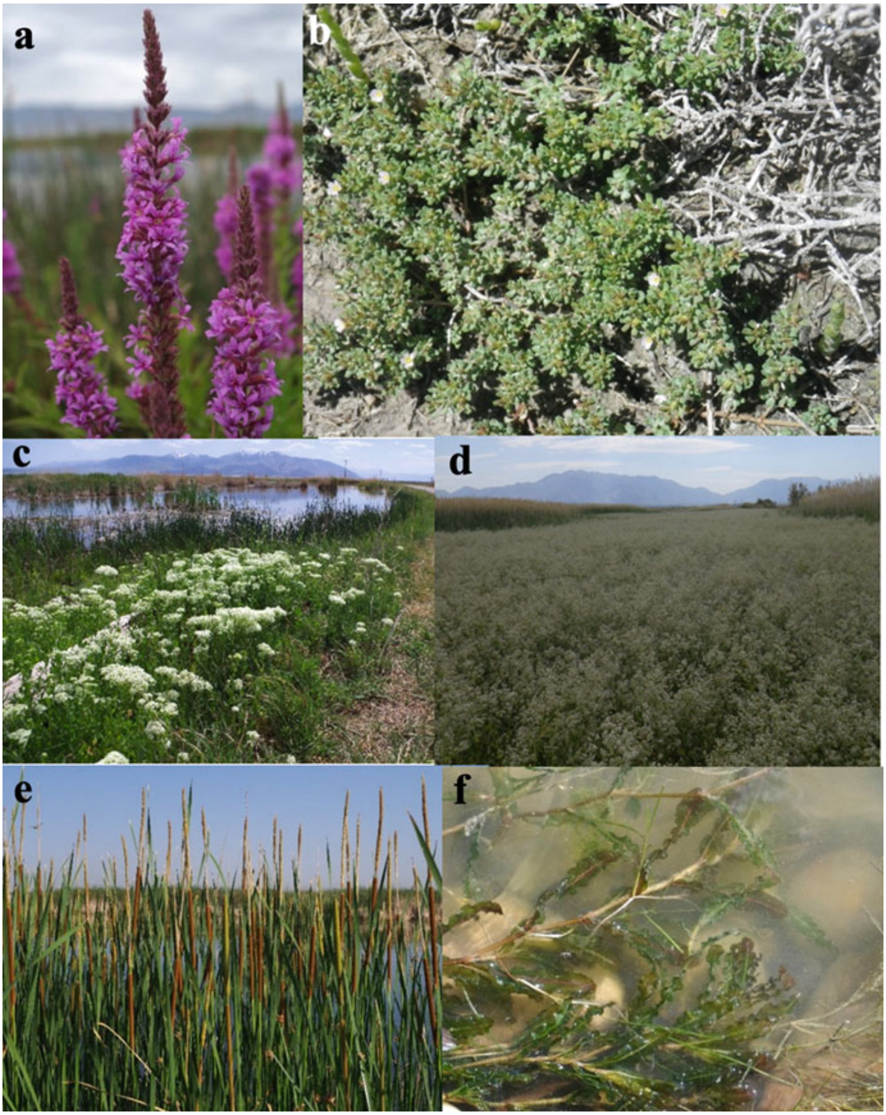

Fig. 13.5 Other common invasive and undesirable plant species in Great Salt Lake wetlands: (**a**) purple loosestrife (*Lythrum salicaria*), (**b**) European seaheath (*Frankenia pulverulenta*), (**c**) whitetop (*Cardaria draba*), (**d**) perennial pepperweed (*Lepidium latifolium*), (**e**) southern cattail (*Typha domingensis*), and (**f**) curly pondweed (*Potamogeton crispus*)

complicated by the fact that it is a cryptic invader, meaning that it is morphologically similar to a native subspecies and the two lineages cannot be easily distinguished without genetic analyses (Saltonstall 2002). Non-native phragmites co-occurs with a native subspecies (*Phragmites australis* subsp. *americanus* Saltonst., P.M. Peterson & Soreng; comprised of numerous haplotypes; hereafter native phragmites) in a number of places in North America including Utah (Kettenring and Mock 2012;

Kulmatiski et al. 2011; Lambert et al. 2016; Meadows and Saltonstall 2007; Meyerson et al. 2010a; Price et al. 2014; Saltonstall 2002, 2011, 2016). Native phragmites has been a part of the flora of North American inland and coastal wetlands for thousands of years (Goman and Wells 2000; Hansen 1978; Kiviat and Hamilton 2001; Niering et al. 1977; Orson 1999). In Utah and other parts of the American Southwest, native phragmites is broadly distributed but rarely abundant, reflecting the distribution of its habitats—isolated springs, riparian areas, and mesohaline and alkaline wetlands (Kettenring and Mock 2012; Kulmatiski et al. 2011; Meyerson et al. 2010a; Saltonstall et al. 2016). Native phragmites is mostly or entirely absent from the flora of GSL wetlands and the negative impacts associated with this species are due to the non-native lineage, the main focus of this chapter. Non-native phragmites has been in Utah for decades—it was first documented in herbarium records in 1993 (confirmed as non-native with genetic analyses) and flourished after the flooding of GSL in the 1980s (Kettenring et al. 2012; Kulmatiski et al. 2011; Smith and Kadlec 1983). In 2004, Kulmatiski et al. (2011) estimated that phragmites covered 86 km^2 of GSL wetlands (using methods based on visual inspection of 30-m resolution NAIP imagery and ground-truthing). Another census in 2011, using 1-m resolution imagery and supervised classification estimated that phragmites occupied 93 km^2 of GSL wetlands (Long et al. 2017a). A recent draft of updated National Wetlands Inventory (NWI) mapping for GSL, developed using visual interpretation of 2014 aerial imagery and ancillary data following NWI standards (Dahl et al. 2015), showed extensive spread of phragmites into previously unvegetated mudflats and 164 km^2 of wetland with $\geq$60% phragmites cover (US Fish & Wildlife Service 2019). Although the methods and exact boundaries of these surveys differ, they each indicate that phragmites is widespread and abundant in GSL wetlands, despite concerted efforts to limit its coverage. To encourage its further control, phragmites was recently placed on the state noxious weed list in Utah as a Class 3 containment species (Utah Department of Agriculture and Food 2019). In addition, the state spends hundreds of thousands of dollars each year on invasive phragmites control.

Replacement of native phragmites with non-native phragmites is a major concern across North America (Kettenring et al. 2012; Price et al. 2014; Taddeo and Blois 2012). However, in Utah it appears that many of the historical native phragmites populations still exist and there were likely few native phragmites populations along GSL due to potentially unsuitable (brackish) environmental conditions (Kettenring and Mock 2012; Kulmatiski et al. 2011). Hybridization between the lineages is also a conservation concern because of the increased competitiveness of native/non-native hybrids for other plants species and potential loss of the somewhat rare native phragmites (Galatowitsch et al. 1999; Meyerson et al. 2010b; Saltonstall 2011). Phragmites hybrids form under controlled pollination in experimental settings, and hybrids have been documented in a few places in North America including Las Vegas in the arid Southwest (Meyerson et al. 2010b, 2012; Paul et al. 2010; Saltonstall et al. 2014, 2016; Wu et al. 2015). However, in Utah and in GSL wetlands, phragmites hybrids have not been found (Kettenring and Mock 2012; Kulmatiski et al. 2011; Lambert et al. 2016).

13.3.2 Mechanisms of Invasion

Numerous factors contribute to the establishment and spread of phragmites. It was long believed that phragmites spreads mostly by asexual means—clonal expansion from established plants through stolons and rhizomes as well as dispersal (mostly by water) of stolon and rhizome fragments (Chambers et al. 1999; Keller 2000; Pellegrin and Hauber 1999; Saltonstall 2002). However, more recent research found that sexual reproduction is the predominant mechanism for phragmites dispersal and establishment (Albert et al. 2015; Belzile et al. 2010; Kettenring et al. 2011; Kettenring and Mock 2012; McCormick et al. 2010a, b). In Utah, comparisons between non-native and native phragmites showed that non-native phragmites relies much more on sexual reproduction and spread than does its native congener (Kettenring and Mock 2012). Seeds are important to the spread of non-native phragmites over moderate distances (up to approximately 100–500 m) but expansion of existing patches is mostly clonal with occasional seedling establishment (Fig. 13.4) (Kettenring et al. 2016; Kettenring and Mock 2012; McCormick et al. 2010a, b, 2016). Given that phragmites seeds require light for germination and seedlings are generally poor competitors, it is not surprising that phragmites thrives under disturbed conditions where vegetative cover is minimal and light and nutrients are abundant (Kettenring et al. 2015; Kettenring and Whigham 2018). Throughout its North American range, the occurrence of phragmites has correlated with increasing agricultural activities, suburban development, and highway networks; the presence of shoreline structures like riprap and docks; declines in water levels; and nutrient enrichment (Brisson et al. 2010; Chambers et al. 2008; Jodoin et al. 2008; King et al. 2007; Sciance et al. 2016; Tulbure and Johnston 2010). Along GSL, phragmites is more common at lower elevations with prolonged flooding and in areas closer to point sources of pollution and freshwater inflows likely to have elevated nutrients and moderate salinities (Long et al. 2017a). And it is likely that the massive disturbance of GSL wetlands in the 1980s—when hypersaline lake water completely inundated all wetlands—created the perfect high resource (exposed soil with high light) environment for phragmites seeds and seedlings to flourish (Kettenring et al. 2012, 2015).

13.3.3 Impacts on Native Plant Communities, Habitat Value, Wildlife, Human Use of Wetlands

The impact on avian habitat of non-native phragmites expansion into GSL wetlands is extremely concerning to wetland managers (Kettenring et al. 2012; Rohal et al. 2018). Native plants are not able to resist the clonal expansion of established phragmites stands. And, as described above, phragmites can initially get established via seeds in small (and large) disturbances due to sedimentation, herbivory, dike construction, and the like (Long et al. 2017a; Kettenring et al. 2015; Kettenring and Whigham 2018). Naturally unvegetated areas, such as mudflats and drawdown areas that are critical shorebird habitat, are also very susceptible to phragmites invasion. The fundamental alteration to wetland plant communities (composition and structure) and the macroinvertebrates they support have been observed with concern by GSL wetland stakeholders (37 individuals from 20 agencies and organizations) who in 2018 ranked phragmites as the #2 threat to these wetlands (Low and Downard 2018). The extent of the phragmites impact is so great that recent efforts to find "reference" (i.e., high quality) wetlands within the GSL wetland complex were unsuccessful and instead scientists had to seek out reference wetlands in the west desert of Utah (Utah Division of Water Quality 2015).

To understand the impact of phragmites on bird populations, we can look at research from other regions of North America where negative impacts of phragmites on avian habitats have been well-documented (Benoit and Askins 1999; Kessler et al. 2011; Kettenring et al. 2012; Meyerson et al. 2000; Robichaud and Rooney 2017; Whyte et al. 2015). There are robust data on bird usage of uninvaded, native plant-dominated wetlands (Fig. 13.1) including the types of habitats birds use, the season of use, and the significance of GSL wetlands to particular bird species (Table 13.2). From these bird-use data, we would expect substantial impacts of phragmites invasion on, for example, snowy plover (Fig. 13.2) summer breeding habitat when phragmites invades mudflat and playa areas replacing halophyte species such as pickleweed and saltgrass as well as open areas (Fig. 13.3). Or, in another example, as phragmites expands into deeper water habitats such as emergent wetlands dominated by bulrushes (hardstem, threesquare, and alkali) and submergent wetlands dominated by sago pondweed (Fig. 13.3), we would expect to see substantial declines in waterfowl species, such as swans, northern shovelers, redheads, green-winged teal, and cinnamon teal (Fig. 13.2), which use these habitats for some combination of breeding, staging, wintering, or migrating. Furthermore, GSL wetland managers who have observed their managed properties for decades, have noted highly productive native plant-dominated wetlands that supported abundant waterfowl and shorebirds become largely devoid of bird activity once phragmites dominates the area (Chad Cranney, Randy Berger, Rich Hansen, Jason Jones, *pers. comm.*). Given the critical importance of these GSL native plant-dominated habitats to North American populations of these birds, habitat loss to phragmites poses an enormous threat (Aldrich and Paul 2002; Intermountain West Joint Venture 2013; Paul and Manning 2002).

13.4 Phragmites Management in Great Salt Lake Wetlands

Widespread concern about phragmites impacts across many interest groups including hunters and hunting clubs, wetland managers, birdwatchers, the scientific community, and concerned citizens has led to significant and large-scale efforts to reduce the spread of phragmites and restore invaded areas to native plant-dominated wetlands. Throughout the relatively short period of the phragmites invasion in GSL wetlands, these interest groups have mobilized to recognize the scale of the problem

Table 13.2 Avian species that likely experience negative impacts associated with phragmites expansion as well as the significance of Great Salt Lake to the avian populations, preferred avian habitats, and season of avian use

Avian species common name Latin name	GSL significance to avian populations	Habitat type	Seasonal use
American avocet *Recurvirostra americana*	250,000 which is several times higher than any other Pacific Flyway wetland (Shuford et al. 1995)	Emergent Mudflat/playa	Spring: Migrating Summer: Breeding Fall: Migrating
Black-necked stilt *Himantopus mexicanus*	65,000 which is several times higher than any other Pacific Flyway wetland (Shuford et al. 1995)	Emergent Mudflat/playa	Spring: Migrating Summer: Breeding Fall: Migrating
Cinnamon teal *Anas cyanoptera*	Up to 60% of the US breeding population (Bellrose 1980)	Emergent Submergent Wet meadow	Spring: Migrating Summer: Breeding Fall: Migrating
Green-winged teal *Anas carolinensis*	600,000 migrating (Great Salt Lake Planning Team 2000)	Open lake Submergent Emergent Wet meadow Mudflat/playa	Fall: Migrating Winter: Wintering Spring: Migrating
Marbled godwit *Limosa fedoa*	30,000; only staging area in the interior of western North America (Shuford et al. 1995; Paul and Manning 2002)	Emergent Wet meadow	Fall: Staging
Northern shoveler *Anas clypeata*	>160,000 migrating and 10,000 breeding (Paul and Manning 2002)	Open lake Submergent Emergent Wet meadow	Spring: Migrating Summer: Breeding Fall: Staging Winter: Wintering
Redhead *Aythya americana*	20,000 breeding pairs and >150,000 migrating (Great Salt Lake Planning Team 2000)	Submergent Emergent	Spring: Migrating Summer: Breading Fall: Migrating
Snowy plover *Charadrius alexandrinus*	>5000 which is the world's largest assemblage representing 23% of breeding population (Thomas et al. 2012)	Mudflat/Playa	Summer: Breeding
White-faced ibis *Plegadis chihi*	>27,000 breeding adults that are 20% of western North American breeding population (Cavitt et al. 2014)	Emergent Wet meadow	Spring: Migrating Summer: Breeding Fall: Migrating

and coordinate across disciplines and management boundaries to address this challenge (Rohal et al. 2018). Managers and scientists have collaborated to evaluate the tools for phragmites control and containment and to continue to refine management practices to reduce the reproduction and spread of this species (Rohal et al. 2017, 2018, 2019a, b).

13.4.1 Great Salt Lake Phragmites Management History, Collective Problem Solving, and Science-Management Partnerships

The early establishment of phragmites throughout the GSL basin was met with mixed reactions among wetland managers and visitors. Before the invasion was officially documented in 1993 (or fully understood), some welcomed the new plant because of the greater structure it provided and the increase in cover for duck blinds. Others saw the new plant as an unwanted intruder, and they quickly acted to remove it. In many cases, early action was implemented by duck clubs with greater management resources and a long history of intensive wetland management (Rohal et al. 2018). Managers observed that methods previously used to encourage plant diversity and to create open wetland areas, such as water drawdowns and fire, were now encouraging the spread of phragmites (Rohal et al. 2018). Through trial and error, they found that maintaining deep water in some areas while drought stressing others could create conditions that could limit the spread of phragmites (Rohal et al. 2018). Nevertheless, despite early efforts to alter management, phragmites continued to spread. Managers realized that the problem was prominent across property lines, and collective action and coordination were necessary to fully address the issue.

Partnerships between agencies and property holders have developed and expanded as phragmites management efforts have increased to meet the scale of the problem. For example, some adjacent duck clubs have developed working groups to more effectively control phragmites that can easily spread seeds and rhizomes across property lines (e.g., the Southshore Wetlands & Wildlife Management, Inc. for the duck clubs on the south shore, near Farmington Bay, and partnerships among the Chesapeake, Bear River, and Ferry Duck Clubs north of GSL; Fig. 13.1). State agencies (DWR and DFFSL) now coordinate management plans at the interface of Waterfowl Management Areas (WMAs; DWR jurisdiction) and the GSL lakebed (i.e., Utah's Sovereign Lands that are under DFFSL jurisdiction). In some cases, agencies like the DWR and the US Fish & Wildlife Service pool resources to conduct aerial herbicide spraying.

The DWR has been one of the leaders in phragmites management efforts across the GSL watershed. Since 2006, the DWR has coordinated a long-term phragmites management plan that treats several thousand hectares in six state-owned WMAs covering $> 24{,}000$ wetland hectares over a month or more each year. To accomplish this management, they utilize the power of six full-time employees, 3–6 part-time technicians, and over 225 hours of volunteer time. Additionally, the DWR and DFFSL uses prviate contractors for aerial herbicide, ground herbicide, and mechanical removal treatments. One of the major goals of the DWR phragmites management plan is to disseminate phragmites education and management information to other agencies, county governments, private properties, and the public. They have facilitated proposal writing efforts for adjacent property holders and county governments to encourage regional phragmites management coordination and upstream phragmites control. The DFFSL has also worked to improve coordination among

GSL property holders, initiate “Phragmites Working Group” meetings, and work with other agencies to prioritize management in high need areas.

Many management agencies and property holders have also coordinated with researchers to facilitate phragmites management research (Cranney 2016; Rohal et al. 2017, 2018, 2019a, b; Rohal 2018; Duncan 2019). Managers have made properties accessible for research projects, provided feedback on relevant experimental questions, and assisted with research treatment implementation. Wildlife agencies and hunting organizations have also provided financial help to promote phragmites management research.

13.4.2 Methods for Phragmites Control

There are many methods that GSL managers use to control phragmites. The most commonly applied methods include herbicide, mowing, burning, and grazing (Figs. 13.6 and 13.7) (Rohal et al. 2018). Often these methods are used in combination with one another to achieve multiple goals (Figs. 13.6 and 13.7).

13.4.2.1 Herbicide

The primary tool for managing phragmites in GSL wetlands is herbicide. A 2011 survey of GSL managers showed 97% of managers used herbicide as their primary tool (Rohal et al. 2018). Glyphosate and imazapyr are the two herbicides approved for aquatic environments that are most frequently used to remove phragmites in North America (Hazelton et al. 2014). Each herbicide type has its own benefits and drawbacks. Glyphosate is a nonselective, broad-spectrum herbicide, which is absorbed into the plant through its leaves. Imazapyr is also a broad-spectrum herbicide, but it can be absorbed by both plant leaves and roots (Tu et al. 2001). Both herbicides have the potential for nontarget impacts, though imazapyr may be more damaging to nontarget plants due to its ability to impact plants through their roots. Imazapyr is used less frequently in GSL wetlands primarily due to its higher cost (Rohal et al. 2018). In GSL wetlands, glyphosate and imazapyr are equally effective at reducing phragmites cover and the resulting native plant recovery is similar (Cranney 2016; Rohal 2018). The timing of herbicide application can also influence phragmites removal success and native plant recovery. Herbicide applications in the fall (August–September) are more effective at reducing phragmites cover (Fig. 13.7; Cranney 2016; Rohal 2018, 2019a, b) because the herbicide is more effectively translocated to the roots and rhizomes where it has the greatest impact (Tu et al. 2001).

13.4.2.2 Mowing

Mowing phragmites without additional interventions is not effective at removing phragmites as it can actually stimulate its growth (Derr 2008). Nevertheless, in GSL,

Fig. 13.6 Phragmites management: (**a**) Loglogic Softrak, marsh-capable equipment driving through a vast expanse of phragmites, (**b**) Marsh Master amphibious equipment used for phragmites herbicide and mowing management, (**c**) Loglogic Softrak being used for herbicide application to phragmites, (**d**) Wilco amphibious equipment used by the US Fish & Wildlife Service for phragmites management at the Bear River Migratory Bird Refuge (see Fig. 13.4), (**e**) Loglogic Softrak dragging a roller/crusher to break down phragmites litter in winter, (**f**) phragmites litter from winter mowing with live phragmites emerging in spring, (**g**) phragmites litter waist to shoulder high on wetland researchers Brittany Duncan and Karin Kettenring, (**h**) phragmites mowed to provide cattle access for grazing research study by Brittany Duncan, (**i**) cattle grazing phragmites-invaded wetland, (**j**) loading hydroseeding tank with native seeds, a tackifier, and mulch prior to seeding by David England, Emily Tarsa, and Keith Hambrecht, (**k**) seeds in paint strainer mesh for cold stratification prior to hydroseeding, and (**l**) hydroseeding by David England and Chad Cranney at Farmington Bay WMA

mowing is frequently used as a tool in phragmites management programs to address the excess biomass that remains after herbicide applications (Figs. 13.4, 13.6, and 13.7). The large amount of dead phragmites biomass is a major impediment to native plant recovery because it shades the wetland surface. Many native wetland plants require high light levels to trigger germination (e.g., Marty and Kettenring 2017). Mowing and mulching this biomass accelerates its decomposition, opening up the light resources needed for native plant species to germinate. Mowing can be conducted in the summer as long as it does not impact bird nesting nor spread

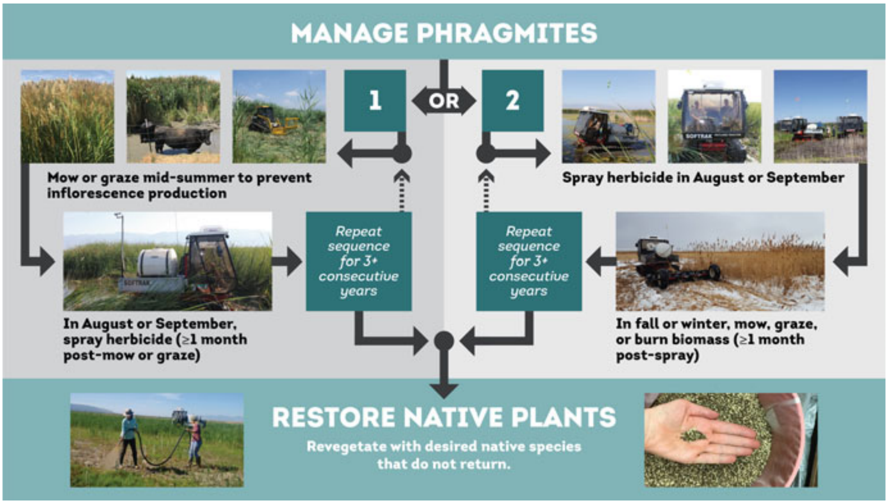

Fig. 13.7 Recommended treatment options for managing phragmites through mowing, grazing, burning, and herbicide application and reestablishing native plants through hydroseeding. Graphic design by Michael Wernert

plant fragments that may further its spread prior to a fall herbicide application. Alternatively, mowing can be done in the winter, following a fall herbicide application (Fig. 13.7). Summer mowing is not always feasible, however, because some mowing equipment can get stuck in the flooded and saturated soil conditions. Mowing in the winter is often more feasible due to the frozen ground conditions.

13.4.2.3 Burning

Burning, like mowing, is ineffective at controlling phragmites when used as a single management tool. However, it is commonly used to reduce phragmites biomass following herbicide applications (Hazelton et al. 2014). Burning is most frequently conducted in the spring in GSL wetlands (Rohal et al. 2018). Burning can be highly effective at biomass removal, and it does not require additional time for the biomass to degrade (unlike mowing), allowing native plant species to quickly germinate on the bare soil that remains. Unfortunately, burning is often infeasible in GSL wetlands due to air quality standards that make it difficult to obtain permission to burn (Rohal et al. 2018).

13.4.2.4 Grazing

Cattle grazing of phragmites is a management tool that is increasingly being used in GSL wetlands. While grazing is unlikely to kill phragmites over repeated grazing seasons, it has many other benefits. High intensity, short-term grazing of phragmites over 1–2 growing seasons can reduce phragmites living biomass, making phragmites-invaded wetlands more accessible, while not degrading water quality (Duncan 2019; Duncan et al. 2019). Over time, cattle also trample large amounts of standing dead phragmites, further opening up the wetland surface for native plant germination and accessibility (Duncan 2019; Duncan et al. 2019).

13.4.3 Managing Phragmites to Limit Seed Production

As mentioned earlier, the ability of phragmites to reproduce via seed is an important mechanism enabling its establishment and spread. Managing phragmites seed production is thus vital to both reduce the incidence of phragmites colonization into new areas and to reduce the chances for reinvasion following phragmites control. Phragmites reinvasion once control ceases is common, in part because the density of its seed in the soil of invaded patches can be very high (Cranney 2016; Rohal 2018). When soil seed densities are high, the propagule pressure of the invader increases the chances for establishment and increased competition with other species (Byun et al. 2015). Phragmites propagule pressure is particularly a concern in GSL wetlands, which have the highest recorded phragmites seed densities in North America (Rohal 2018). For example, a review of phragmites seed banks from other regions found the highest phragmites seed densities at ~700 seeds m^{-2} (Baldwin et al. 2010) whereas seed bank densities in GSL wetlands were as high as ~14,000 seeds m^{-2} (Rohal 2018).

There are a variety of management actions that can reduce the ability of phragmites to produce seed. Impacting the plant in the summer greatly reduces phragmites seed production during the reproductive season in fall (Cranney 2016; Duncan 2019; Rohal 2018; Rohal et al. 2019a, b; Duncan et al. 2019). Summer mowing and high-intensity summer livestock grazing both reduce phragmites seed production (Fig. 13.7; Duncan 2019; Rohal 2018). Summer herbicide applications can also greatly reduce phragmites seed production, but summer herbicide does not reduce phragmites cover as effectively as fall applications, so it is not recommended (Cranney 2016; Rohal 2018; Rohal et al. 2019a, b). In addition, drought-stressed phragmites rarely produces high densities of inflorescences (C. Rohal, *pers. obs.*). Managers with water control can intentionally drought stress phragmites patches that are not the target of other management actions to reduce the production of seeds that can spread into surrounding areas.

13.4.4 Managing Wetlands to Reduce Phragmites Spread

Managers have a number of methods available to reduce the spread of phragmites. One strategy is to minimize the conditions that promote phragmites seed germination. As discussed previously, physical disturbance of existing vegetation can create the high light conditions that are favorable for phragmites germination (Kettenring et al. 2015; Kettenring and Whigham 2018). Thus, minimizing disturbance to existing native vegetation (such as burning "decadent" vegetation) is an important tool for limiting phragmites seed germination and establishment. In addition, phragmites seeds need specific hydrologic conditions to germinate (moist to shallowly flooded mudflat conditions). In areas with water control, manipulating water depth to deeper flooding (>3.5 cm) or drought-stressing impounded areas can greatly minimize phragmites germination.

The outward spread of phragmites patches via rhizomes is another important mechanism for its expansion (Kettenring et al. 2016). Rhizome spread can be reduced by hydrologic manipulations. Flooding impoundments as deep as possible (>0.5 m) can restrict phragmites growth (Hudon et al. 2005), and this flooding is often used in GSL wetlands to prevent phragmites spread and to encourage open water and submerged aquatic vegetation habitat favorable to many waterfowl species. In contrast, shallow flooding with a sheet flow of water through the growing season (e.g., to mimic the historical hydrology of river deltas) creates conditions optimal for phragmites seed germination and seedling establishment, and therefore it should be avoided in areas where phragmites seeds are present. Finally, grazing is a low-cost tool for reducing phragmites biomass and stressing phragmites throughout the growing season, which can thus reduce its potential for outward spread (Duncan 2019).

13.4.5 Environmental Context of Management Areas Influences Management Success

The management of phragmites is not equally effective in all locations (Cranney 2016; Duncan 2019; Rohal 2018; Rohal et al. 2017, 2019b). There are a variety of factors, often outside of management control, that can influence management success, including abiotic conditions like site hydrology and nutrient conditions, biotic conditions like the condition of the native seed bank and site disturbance history, as well as the size of the phragmites patch (Brudvig et al. 2017; Zimmerman et al. 2018; Quirion et al. 2018; Rohal et al. 2019a, b). Hydrology is the predominant factor that can influence both phragmites control and native plant recovery (Rohal et al. 2019a, b). Herbicide is typically ineffective when sprayed on phragmites that has been drought stressed (Rohal 2018; Rohal et al. 2019a, b) because the herbicide is not effectively translocated to the rhizomes where it is needed to permanently kill the plant (Tu et al. 2001). Thus, counterintuitively, phragmites control with herbicide is most successful on the healthiest, greenest stands (Rohal 2018; Rohal et al. 2017, 2019a, b). These are typically in areas that have consistent moisture throughout the summer growing season. These conditions also favor more robust native plant recovery following control. More shallow flooding (<10 cm) allows for greater native plant germination, while deeper flooding (>10 cm) reduces germination opportunities for many desirable native plant species, and tends to favor the recruitment of cattail.

Another factor that can influence management success is the scale of the treated patch. In GSL wetlands, phragmites is present in both large, multi-hectare monocultures, which are often isolated from native plants, and small patches (<0.40 ha) that are still surrounded by a matrix of native plant species. Phragmites is more effectively controlled in small patches and native plant species return at a higher cover in these areas (Rohal et al. 2019b). Small patches tend to have more successful outcomes likely because the matrix of native plant species can provide higher densities of propagules to recolonize (Matthews et al. 2017; Rohal et al. 2019b), while large patches typically lack this source of native propagules. In addition, large patches are often in areas with a history of hydrologic manipulation and frequently have deeper flooding throughout the growing season. These conditions can prevent native plant germination and can favor the expansion of extant phragmites patches via rhizomes (Rohal et al. 2019a, b).

13.4.6 Revegetation Following Phragmites Control

Revegetation is an important tool following phragmites control, particularly in areas where native plant recovery is limited (Rohal et al. 2017, 2019a, b). Active revegetation (e.g., seeding, planting plugs) is often necessary as desirable native species rarely recruit at high densities following phragmites control (Cranney 2016; Rohal 2018). In GSL wetlands, revegetation is essential for restoring native species that provide high-quality food and habitat for waterfowl and shorebirds and deliver valuable ecosystem functions and services that are characteristic of wetland ecosystems (e.g., flood control, carbon sequestration). Furthermore, revegetating areas where phragmites has been treated can be an effective way to prevent phragmites reinvasion because it encourages the quick establishment of native plants, which limits the high light, high nutrient, and bare soil conditions that favor phragmites germination and growth (Byun et al. 2013, 2015; Kettenring et al. 2015; Kettenring and Whigham 2018; Peter and Burdick 2010).

For small sites or projects that have ample budgets, revegetation outcomes can be improved by planting native plugs or installing sod mats as these methods bypass the vulnerable seedling stage (Grubb 1977). When a site for revegetation is large, as are many restorations in GSL wetlands, it is logistically and financially more feasible to sow native seeds as compared to plugs or other forms of active revegetation (Hurd and Shaw 1992; Palmerlee and Young 2010). However, the seedling stage is the most limiting stage of a plant's life cycle and represents a bottleneck in recruitment (Barrett-Lennard et al. 2016; James et al. 2011). As such, several actions should be taken prior to seeding that increase the chance of native plant survival and improve restoration outcomes in GSL wetlands.

13.4.6.1 Preparing the Site for Revegetation

Preparation of the site prior to seeding is essential to create and maintain ideal conditions for native seedling recruitment. Phragmites litter left on the site should be removed so sown seeds have sufficient seed–soil contact and adequate light necessary to trigger germination (Cranney 2016; Lishawa et al. 2015; Rohal 2018). Additionally, maintaining ideal hydrological conditions is critical as many wetland seedlings are unable to survive in water depths greater than 0 cm above the soil surface (Fraser and Karnezis 2005). Therefore, the hydrology should be maintained as follows: (1) during seeding, water levels should be drawn down to the soil surface so that soil is exposed and saturated, thus preventing buoyant wetland seeds from floating away and encouraging seed–soil contact. In areas with unpredictable hydrologic regimes (i.e., flooding), a tackifier can be used while seeding to keep seeds in place through germination (Tilley and John 2013; England 2019); (2) the soil should remain waterlogged through germination and establishment for most species, although there are notable exceptions like saltgrass that performs well against phragmites with lower soil moisture levels (Webb et al. 2012; E.E. Tarsa, *pers. obs.*); and (3) flooding events that are deep or long in duration should be avoided in the first growing season, giving native plants enough time to develop adaptive structures (e.g., aerenchyma) necessary to withstand high water conditions (Cronk and Fennessy 2001). Unfortunately, these conditions are also ideal for phragmites germination and seedling establishment, which underscores the importance of depleting phragmites from the seed bank and removing nearby phragmites propagule sources prior to beginning revegetation while also being vigilant about spraying new phragmites as the native plant community becomes established. Native seedling recruitment can also be improved by creating "safe sites"—or small areas around a seed that have ideal environmental conditions for germination and establishment (Peach and Zedler 2006; Urbanska 1997). This variation in microtopography can be created by hand (e.g., using a shovel to rut the soil) or using large machinery (e.g., tractor rutting) (Moser et al. 2007).

13.4.6.2 Choosing Native Species for Revegetation

Which native species to sow in GSL wetlands is an important consideration that is based on the environmental conditions at a site, target wildlife habitat, and the ability for native species to resist phragmites reinvasion. In GSL wetlands, hardstem, threesquare, and alkali bulrush (Fig. 13.3) provide important habitat for waterfowl in this region and are often included in revegetation seeding mixes. However, sowing these species alone may not be an effective revegetation tool as they are slow-growing perennials and likely do not keep pace with the early emergence of phragmites from the seed bank (Gioria and Pyšek 2017; Downard et al. 2017). Therefore, adding annual (or otherwise fast growing or broadly environmentally tolerant) species to the seed mix that germinate quickly and preempt resources may be particularly effective at resisting phragmites reinvasion (Byun et al. 2013). Such species in GSL wetlands include nodding beggartick (*Bidens cernua*), rayless alkali aster (*Symphyotrichum ciliatum*), and fringed willowherb (Fig. 13.3) as well as (not pictured) Nuttall's alkaligrass (*Puccinellia nuttalliana* (Schult.) Hitchc.), golden dock (*Rumex maritimus* L.), and curlytop knotweed (*Polygonum lapathifolium* L.). Species with varying growth forms, such as mat-forming species (e.g., common spikerush), can also be particularly effective at preventing phragmites reinvasion in the long-term due to their ability to limit light (Fig. 13.3). Ensuring that the native seed mix sown at a restoration site can handle a diversity of environmental conditions (e.g., seeding saltgrass for drier site conditions with hardstem bulrush for wet conditions; Fig. 13.3) is a form of bet-hedging that increases the likelihood that native species will establish given the natural fluctuations and sometimes unpredictable conditions in GSL wetlands (Evans and Dennehy 2005).

13.4.6.3 When to Revegetate Great Salt Lake Wetlands?

Revegetation should occur after phragmites stands have been treated with herbicide and mowed for at least 3 years (Cranney 2016; Rohal 2018; Rohal et al. 2019a, b) (Fig. 13.7). In GSL wetlands, revegetation often occurs in the spring (May–June) when there is adequate moisture and the temperature is within optimal germination requirements of most GSL native species (approximately 28–35 °C) (Downard et al. 2017; Kettenring 2016; Marty and Kettenring 2017). Dormancy, or the ecological adaptation that prevents seeds from germinating during conditions that are sub-optimal for seedling survival (Willis et al. 2014), is present in many wetland species and must be broken prior to seeding in the spring. Breaking dormancy in only half of the seed lot and seeding the remaining seeds dormant can help build the native seed bank, thus ensuring native species are present on the site in future years and varying environmental conditions (Evans and Dennehy 2005). Alternatively, fall seeding of dormant seeds (i.e., a “dormant seeding”) can serve to break dormancy naturally, but increases the likelihood of seed predation and germination of nondormant seeds during harsh winter conditions (Galatowitsch and van der Valk 1994; Kettenring and Galatowitsch 2011).

13.4.6.4 Seeding Density

Given the high phragmites propagule pressure in GSL wetlands (Rohal 2018), native seed mixes should be sown at high enough densities to competitively exclude phragmites reinvasion from the seed bank. The current recommended seeding rates (~1900 seeds m^{-2}), often based on adult plant distributions, are likely not high enough to prevent phragmites return from the seed bank (Tarsa and Kettenring, unpubl. data). Preliminary results suggest that seeding between 5800 and 9700 seeds m^{-2} can significantly reduce phragmites biomass at a site (Tarsa and Kettenring, unpubl. data). However, these results are contingent on phragmites seed density in the seed bank—thus it is important to prioritize restoration sites that have low phragmites seed densities in the seed bank or, as mentioned earlier, focus on depleting phragmites seeds through repeated years of mowing and herbicide (Tarsa and Kettenring, unpubl. data; Rohal 2018). Furthermore, competitive dynamics change across environmental conditions (e.g., water and nutrient availability; Tilman 1994; Wilson and Keddy 1986). For instance, saltgrass can outcompete phragmites under low soil moisture conditions even when saltgrass is sown at a low seeding density (Tarsa and Kettenring unpubl. data).

13.4.6.5 Monitoring and Maintenance

GSL wetlands, as with many wetlands, are highly invasion prone due to high invader propagule pressure and the lake's low position in the landscape that facilitates disturbance and nutrient enrichment (Rohal 2018; Zedler and Kercher 2004). Furthermore, restoration activities themselves create disturbances that result in high light and nutrient conditions, making sites highly prone to secondary invasion (Davis et al. 2000). As such, monitoring and maintaining sites in the years following revegetation is necessary to encourage native species establishment and survival (Rieger et al. 2014). This maintenance is especially critical in the native seedling stage (<1 year of growth) as mature stands have not yet formed to limit light availability for germinating phragmites seeds (Adams and Galatowitsch 2006; Kettenring et al. 2015). Phragmites that is returning from the seed bank or encroaching from nearby sites should be removed as quickly as possible by hand or spot sprayed with glyphosate to prevent expansion into the revegetated wetland (Adams and Galatowitsch 2006; Rohal et al. 2017, 2019a, b). It should be expected that a significant amount of time will be spent to control reinvading phragmites in the revegetation site for at least the first 2 years, with a large reduction in time spent doing these activities over time (Bohnen and Galatowitsch 2005). Revegetation sites should also be coarsely assessed for native species survival rates, which will inform whether seeds should be sown or plugs should be planted the following year.

13.5 Other Common Invasive and Undesirable Species: What Is Known and On-going Management

Little regionally specific research has been conducted on the majority of other invasive species in GSL wetlands, though wetland condition surveys have estimated disturbance and non-native species distribution and abundance around the lake. Data compiled from GSL wetland surveys show 79 non-native or undesirable species, though few of these species are both widely distributed and abundant in wetlands (Downard et al. 2017; Menuz et al. 2014, 2016; Menuz and McCoy-Sulentic 2019; Menuz and Sempler 2018; Utah Division of Water Quality 2016). A species' status as native or non-native is not necessarily a useful indicator of how problematic it is in managed wetlands. In wetlands that are managed for waterfowl habitat, the ability of a species to help meet management goals by providing food and cover is more important to whether it is considered an undesirable weed than where the species originated. Because of this, native species like cattail that grow dense and have little nutritional value are often considered less desirable, while Eurasian species like barnyard grass and sorghum (*Sorghum bicolor* (L.) Moench) are deliberately planted to provide food and shelter for waterfowl and forage kochia (*Bassia* All. spp.) is left untreated (Table 13.1).

A variety of factors determine whether non-native plants become established in GSL wetlands. Species with high anaerobic soil tolerance (e.g., species listed as facultative wetland or obligate species in Table 13.1) are more likely to be able to establish in a wetland than species that cannot grow in waterlogged conditions. Undesirable species like native cattails thrive in artificially stabilized hydroperiods that result from deliberate management or incidental impoundment by roads. On the other hand, drought and altered hydrology can open up habitat that was formerly wetland to a wide variety of upland invaders while annual species such as prickly lettuce (Table 13.1) can move into wetlands that dry out during the late summer (Downard et al. 2017; Zedler and Kercher 2004).

An invader's salinity tolerance will also determine its success (Cronk and Fennessy 2001). Many GSL wetland invaders are primarily found along canals and other sources of freshwater, especially purple loosestrife (Fig. 13.5) and annual rabbitsfoot grass (Table 13.1). Species from the Eurasian steppe, like tamarisk or kochia (forage kochia and related plants) often have high salinity tolerance (Table 13.1). Both those species were purposely introduced to the United States for windbreaks and to prevent erosion, respectively, but their tolerance of harsh environments has facilitated their expansion into wetlands (Downard et al. 2017). Lastly, nutrients also play a role in allowing some species to be successful, particularly species that can take advantage of nutrients to grow quickly, similar to phragmites (Cronk and Fennessy 2001). Barnyard grass is capable of concentrating high nitrogen and phosphorus in its tissues, and fast-growing, floating species like duckweed (*Lemna* L. spp. that are actually native) are indicators of eutrophic conditions (Table 13.1; Esser 1994; Penning et al. 2008).

Non-native species may displace native plant species and in some cases disrupt food webs dependent on those species (Cronk and Fennessy 2001). At least eight species listed as noxious weeds have been documented in the region; many of these are detrimental to grazing, such as Canada thistle, and some are poisonous to livestock and people, like poison hemlock (Table 13.1; Utah Department of Agriculture and Food 2019). Many non-native plant species have the potential to impact hydrology, such as the submerged aquatic plant curly pondweed, which can form dense mats that clog waterways (DiTomaso et al. 2013). Species can also alter biogeochemistry of soils by depleting or enhancing nitrogen in the soil or altering the salinity (e.g., Russian olive or tamarisk; Table 13.1).

While the most intensive invasive species management around GSL is focused on phragmites, some attention is being paid to the impacts and management of other undesirable species. Most control efforts are focused on species listed as noxious weeds in Utah (Table 13.1), including dyer's woad (*Isatis tinctoria* L.), Dalmatian toadflax (*Linaria dalmatica* (L.) Mill.), spotted knapweed (*Centaurea stoebe* L.), Russian knapweed (*Acroptilon repens* (L.) DC.), and yellow star-thistle (*Centaurea solstitialis* L.). Native cattail has also been the focus of management on some of the state-owned WMAs; see below for additional information on the treatment of this species. Most control efforts use chemical application in the spring, except for dyer's woad, which is hand pulled. Focal areas for control efforts in publicly managed areas include property adjacent to private land, highly visible areas, and high bird use areas. Details of some of the species of highest concern within wetlands are described below.

13.5.1 Purple Loosestrife (Lythrum salicaria)

Purple loosestrife is a noxious weed in 33 states, including Utah (USDA NRCS 2019), that was likely first introduced from Europe in shipping ballast, but also spread when it was purposely planted in gardens (Fig. 13.5; Munger 2002). This species grows as a 1.8–3.6 m tall bush with a deep root system and beautiful purple flowers. An individual purple loosestrife plant can produce millions of seeds, which are spread through waterways. Because purple loosestrife is so prolific and puts down such deep roots, controlling new, small patches is the most effective means for managing an invasion (DiTomaso et al. 2013). Young plants can be pulled out by hand or treated with an herbicide that is approved for use in aquatic environments. Two species of beetle native to Europe have also been used to manage large infestations of purple loosestrife (DiTomaso et al. 2013). Once established, purple loosestrife pushes out native plants, crowds out open water refuges, and clogs irrigation systems (Munger 2002).

13.5.2 European Seaheath (Frankenia pulverulenta)

European seaheath is a European plant species that has been introduced to Utah, a few states on the east and west coasts of the United States, and also South America, Australia, and elsewhere (Fig. 13.5; Whalen 2015). The species was first recorded in Utah in 1972 at a privately owned duck club near Salt Lake City International Airport, with two other collections nearby in the late 1970s and early 1980s (Intermountain Region Herbarium Network 2019). The species was then not observed for many years and was even speculated to be eradicated by floods or heavy equipment by the 2000s (Holmgren 2005). However, by 2018 it had been documented across the entire eastern side of the lake and found in 17% and 40% of playa sites in the Bear River and Farmington Bays, respectively, in recent surveys around GSL though always with low ($\leq$2%) cover (Menuz and Sempler 2018; Menuz and McCoy-Sulentic 2019). The species is associated with intermittently flooded and frequently sparsely vegetated areas with high salinity, including playas, mudflats, and greasewood stands. This species is of interest because it is clearly adapted to the harsh conditions of playas around the lake and has become very widespread relatively quickly, though its potential for negative impacts beyond replacing native species is unknown. A 2009 study in Pakistan proposed European seaheath as a newly emerging species of concern in saline areas (Waheed et al. 2009), but a brief literature search failed to find any documented impacts of the species in other areas where it has invaded.

13.5.3 Whitetop (*Cardaria draba*) and Perennial Pepperweed (*Lepidium latifolium*)

Whitetop and perennial pepperweed are both members of the Brassicaceae family and Class 3 noxious weeds in Utah associated with moist agricultural sites and other disturbed areas (Fig. 13.5; Downard et al. 2017; Utah Department of Agriculture and Food 2019). Both species are widespread along the eastern shore of GSL, though neither is particularly abundant within wetlands. Of the two species, perennial pepperweed is more strongly associated with wetlands and riparian areas, though some case studies have suggested the species is intolerant of prolonged inundation and may grow poorly under saturated conditions (Blank et al. 2002), which may explain why it has not become more of a nuisance in GSL wetlands. Asexual reproduction is important to both species, with spread via roots, buds, and rhizomes common, though sexual reproduction is common as well (Fire Effects Information System 2019). The roots of perennial pepperweed are buoyant, can spread long distances by water, can remain dormant in the soil for years, and have been found more than 3 m deep in the soil profile (Fire Effects Information System 2019). Both species have been documented to reduce crop or hay yields, displace native plant species, and reduce wildlife habitat (Fire Effects Information System 2019). More importantly for GSL's ecosystem, perennial pepperweed may negatively affect nesting habitat for waterfowl and other wildlife and displace important food grasses for waterfowl based on observations made in California, though this phenomenon has never been studied in Utah (Fire Effects Information System 2019).

13.5.4 Cattails (*Typha domingensis* and *T. latifolia*)

Cattails are a native GSL wetland species, but undesirable because they make for poor waterfowl habitat and can push out more desirable wetland species (Fig. 13.5; Downard et al. 2017; Ochterski 2003). Cattails are a common problem in wetlands managed for migratory bird habitat where wetland hydroperiods have been lengthened through diversions and dikes. Cattails have large underground rhizomes that transfer oxygen and nutrients between daughter ramets of the same plant (Cronk and Fennessy 2001). They also grow quickly, making them well adapted to consistently deep flooding (Cronk and Fennessy 2001). To control the expansion of cattails, managers must disrupt its robust root system, which requires more than one method of treatment. Small patches of cattail can be hand pulled. Once cattail becomes tall and dense, a combination of growing season mowing, burning, and herbicide use may help control cattail by stressing the plant when carbohydrate reserves in rhizomes are at their lowest (Gleason et al. 2012). Any method of cattail control should be followed by deep flooding (≥0.3 m) to ensure the roots do not survive (DiTomaso et al. 2013). Prior to the expansion of phragmites, cattails were a primary concern of waterfowl managers around GSL and are re-emerging as weed control targets as phragmites cover decreases (C. Cranney, *pers. obs.*).

13.5.5 Curly Pondweed (Potamogeton crispus)

Curly pondweed is an invasive submerged aquatic species native to Eurasia that is found in ponded brackish, alkaline, or eutrophic waters in northern Utah, but has not yet become a major nuisance or focus of management (Fig. 13.5; Haynes and Hellquist 2000; Intermountain Region Herbarium Network 2019). The plant is unusual in that it produces fruit in late spring or early summer and then decays, leaving behind special leaf buds called turions that germinate in late summer or fall; the resulting plants, only a few centimeters tall, overwinter under ice and then resume growth in the spring (Haynes and Hellquist 2000). The species spreads vegetatively via turions along canals and potentially attached to boats, boots, or other equipment. Curly pondweed can deplete nutrients during periods of rapid growth (Brusati and DiTomaso 2005) and cause phosphorus to spike and dissolved oxygen to rapidly decline when it decomposes mid-summer (Haynes and Hellquist 2000; Thayer et al. 2019). Large infestations of curly pondweed can impede water flow and disrupt recreation (Brusati and DiTomaso 2005; Thayer et al. 2019). Despite the negative impacts, the species can provide food and cover for birds, fishes, and macroinvertebrates and may be an important food source in waters too turbid to support other submergent species (Brusati and DiTomaso 2005; Thayer et al. 2019).

13.6 Summary and Concluding Remarks

GSL and its wetlands are recognized around the world for the valuable habitat they provide for millions of migratory birds (Aldrich and Paul 2002; Evans and Martinson 2008; Paul and Manning 2002). The largest threat to these wetlands in terms of invasive plants is phragmites, although there are a number of species that are concerning and a target of management (Table 13.1). Managers of GSL wetlands face a daunting task to control these plants, particularly in the case of phragmites, where hundreds of hectares of infestations must be treated and retreated annually. Eradication will not be possible given the intense propagule pressure and dense seed banks (Rohal 2018; Rohal et al. 2019b), thus strategic and prioritized management approaches are critical (Long et al. 2017b). In addition, there have been exciting advancements in terms of cooperation between scientists and managers, in developing robust treatment techniques, and cooperation between managers, to coordinate their efforts to reduce phragmites cover and impacts (Rohal et al. 2017, 2018). These partnerships are the foundation for any future management programs should current or future invaders prove as formidable as phragmites. Given the threats GSL and its wetlands face with anthropogenic development, water diversions, and climate change (Downard et al. 2014; Downard and Endter-Wada 2013; Li et al. 2019; Wurtsbaugh et al. 2017), we are optimistic that at least in the case of invasive species, collaborative and science-backed management can continue to yield successes.

There are a number of research and management priorities that must be addressed in the near future to foster further invasive management success. First, revegetation following invasive species control, particularly after phragmites removal, is still in the initial stages of development. There are many opportunities for refining techniques to maximize native plant establishment and survival. Second, because phragmites propagule pressure is extraordinarily high in GSL wetlands (Rohal 2018), management efforts need to address this propagule pressure and focus on greatly reducing phragmites seed bank densities through multiple years of summer management prior to seed maturation (Fig. 13.7; Rohal et al. 2017). Third, looking into the future, what will be the next big invader? It is critical to recognize these new invaders—that are likely already problematic in other regions of North America—that may emerge, particularly as environmental conditions shift with climate change. Early detection, rapid response efforts will be essential because once an invader is well established and widespread, the cost of management increases substantially and the likelihood of management success declines markedly. Fourth, hydrologic management can be used to the advantage of managers (and many managers do so effectively already) but there are opportunities to further refine techniques to best prevent invasions and further facilitate successful management (e.g., Alminagorta et al. 2016). Finally, impacts of these invaders and especially phragmites have been documented qualitatively but there are few quantitative data on impacts to avian species from these invasions. These impacts should be a research priority considering the continental importance of this habitat to migratory birds.

Acknowledgments We thank the many agencies and organizations whose funding supported the primary research synthesized in this book chapter including the Community Foundation of Utah; Delta Waterfowl; Ducks Unlimited Canada; FRIENDS of Great Salt Lake; Intermountain West Joint Venture; Kennecott Utah Copper Charitable Foundation; the Salt Institute; Society of Wetland Scientists; Southshore Wetlands and Wildlife Management, Inc.; US Fish & Wildlife Service, Utah Department of Agriculture and Food; Utah Division of Forestry, Fire & State Lands; Utah Division of Water Quality; Utah Division of Wildlife Resources; Utah State University Ecology Center; Utah State University Research and Graduate Studies; U.S. Environmental Protection Agency; Utah Public Lands Initiative; Utah Waterfowl Association; Utah Wetlands Foundation; Wasatch Front Water Quality Council; Western Integrated Pest Management Center; and The Wetland Foundation. We greatly appreciate the many landowners along GSL who have been our partners in wetland research and management. M. Dunphy and N. Berg provided helpful feedback on an earlier version of this book chapter. This research was supported by the Utah Agricultural Experiment Station, Utah State University, and approved as journal paper number 9234.

References

Adams CR, Galatowitsch SM (2006) Increasing the effectiveness of reed canary grass (*Phalaris arundinacea* L.) control in wet meadow restorations. Restor Ecol 14:441–451

Albert A, Brisson J, Belzile F, Turgeon J, Lavoie C (2015) Strategies for a successful plant invasion: the reproduction of *Phragmites australis* in north-eastern North America. J Ecol 103:1529–1537

Aldrich TW, Paul DS (2002) Avian ecology of Great Salt Lake. In: Gwynn JW (ed) Great Salt Lake: an overview of change. Utah Department of Natural Resources and Utah Geological Survey Special Publication, Salt Lake City, pp 343–374

Alminagorta O, Rosenberg DE, Kettenring KM (2016) Systems modeling to improve the hydro-ecological performance of diked wetlands. Water Resour Res 52:7070–7085

Baldwin AH, Kettenring KM, Whigham DF (2010) Seed banks of *Phragmites australis*-dominated brackish wetlands: relationships to seed viability, inundation, and land cover. Aquat Bot 93:163–169

Barber B, Cavitt J (2012) Dietary review for aquatic birds utilizing Willard Spur, Great Salt Lake. Final Report, Utah Division of Water Quality, Salt Lake City, UT

Barrett-Lennard EG, Norman HC, Dixon K (2016) Improving saltland revegetation through understanding the "recruitment niche": potential lessons for ecological restoration in extreme environments. Restor Ecol 24:S91–S97

Bellrose FC (1980) Ducks, geese and swans of North America. Stackpole Books, Harrisburg, PA

Belzile F, Labbé J, LeBlanc MC, Lavoie C (2010) Seeds contribute strongly to the spread of the invasive genotype of the common reed (*Phragmites australis*). Biol Invasions 12:2243–2250

Benoit LK, Askins RA (1999) Impact of the spread of *Phragmites* on the distribution of birds in Connecticut tidal marshes. Wetlands 19:194–208

Bioeconomics, Inc (2012) Economic significance of the Great Salt Lake to the State of Utah. Missoula, MT. https://documents.deq.utah.gov/water-quality/standards-technical-services/great-salt-lake-advisory-council/Activities/DWQ-2012-006864.pdf. Accessed 8 Apr 2019

Blank RR, Qualls RG, Young JA (2002) *Lepidium latifolium*: plant nutrient competition-soil interactions. Biol Fertil Soils 35:458–464

Bohnen JL, Galatowitsch SM (2005) Spring peeper meadow: revegetation practices in a seasonal wetland restoration in Minnesota. Ecol Restor 23:172–181

Brisson J, de Blois S, Lavoie C (2010) Roadside as invasion pathway for common reed (*Phragmites australis*). Invasive Plant Sci Manag 3:506–514

Brudvig LA, Barak RS, Bauer JT, Caughlin TT, Laughlin DC, Larios L, Matthews JW, Stuble KL, Turley NE, Zirbel CR (2017) Interpreting variation to advance predictive restoration science. J Appl Ecol 54:1018–1027

Brusati E, DiTomaso J (2005) *Potamogeton crispus* plant assessment form *Cal-IPC Inventory*. https://www.cal-ipc.org/plants/paf/potamogeton-crispus-plant-assessment-form/

Burr SW, Scott D (2004) Application of the recreational specialization framework to understanding visitors to the Great Salt Lake Bird Festival. Event Manag 9:27–37

Byun C, de Blois S, Brisson J (2013) Plant functional group identity and diversity determine biotic resistance to invasion by an exotic grass. J Ecol 101:128–139

Byun C, de Blois S, Brisson J (2015) Interactions between abiotic constraint, propagule pressure, and biotic resistance regulate plant invasion. Oecologia 178:285–296

Cao L, Berent L, Fusaro A (2020) *Echinochloa crus-galli* (L.) P. Beauv. In: U.S. Geological Survey Nonindigenous Aquatic Species Database, Gainesville, FL, and NOAA Great Lakes Aquatic Nonindigenous Species Information System, Ann Arbor, MI. https://nas.er.usgs.gov/queries/GreatLakes/FactSheet.aspx?SpeciesID=2664

Cavitt JF, Jones SL, Wilson NM, Dieni JS, Zimmerman TS, Doster RH, Howe WH (2014) Atlas of breeding colonial waterbirds in the interior western United States. Final Report, US Department of the Interior, Fish & Wildlife Service, Denver, CO

Chambers RM, Meyerson LA, Saltonstall K (1999) Expansion of *Phragmites australis* into tidal wetlands of North America. Aquat Bot 64:261–273

Chambers RM, Havens KJ, Killeen S, Berman M (2008) Common reed *Phragmites australis* occurrence and adjacent land use along estuarine shoreline in Chesapeake Bay. Wetlands 28:1097

Cox RR, Kadlec JA (1995) Dynamics of potential waterfowl foods in Great Salt Lake marshes during summer. Wetlands 15:1–8

Cranney CR (2016) Control of large stands of *Phragmites australis* in Great Salt Lake, Utah wetlands. Graduate Theses and Dissertations. https://digitalcommons.usu.edu/etd/4988

Cronk JK, Fennessy MS (2001) Wetland plants: biology and ecology. CRC Press, Boca Raton, FL

Dahl TE, Dick J, Swords J, Wilen BO (2015) Data collection requirements and procedures for mapping wetland, deepwater and related habitats of the United States. USFWS Division of Habitat and Resource Conservation, National Standards and Support Team, Madison, WI, 92p

Davis MA, Grime JP, Thompson K (2000) Fluctuating resources in plant communities: a general theory of invasibility. J Ecol 88:528–534

Derr JF (2008) Common reed (*Phragmites australis*) response to mowing and herbicide application. Invasive Plant Sci Manag 1:12–16

DiTomaso JM, Kyser GB, Oneto SR, Wilson RG, Orloff SB, Anderson LW, Wright SD, Roncoroni JA, Miller TL, Prather TS, Ransom C, Beck KG, Duncan C, Wilson KA, Mann JJ (2013) Weed control in natural areas in the western United States. Weed Research and Information Center, University of California

Downard R, Endter-Wada J (2013) Keeping wetlands wet in the western United States: adaptations to drought in agriculture-dominated human-natural systems. J Environ Manag 131:394–406

Downard R, Endter-Wada J, Kettenring KM (2014) Adaptive wetland management in an uncertain and changing arid environment. Ecol Soc 19:23

Downard R, Frank M, Perkins J, Kettenring K, Larese-Casanova M (2017) Wetland plants of Great Salt Lake, a guide to identification, communities, and bird habitat. Current Publications. https://digitalcommons.usu.edu/extension_curall/1761

Duffield J, Neher C, Patterson D (2011) Utah waterfowl hunting: 2011 hunter survey: hunter attitudes and economic benefits. Bioeconomics, Missoula, MT

Duncan BL (2019) Impacts of cattle grazing as a tool to control *Phragmites australis* in wetlands on nitrogen, phosphorus, and carbon. Graduate Theses and Dissertations. https://digitalcommons.usu.edu/etd/7420

Duncan BL, Hansen R, Cranney C, Shah JJF, Veblen KE, Kettenring KM (2019) Cattle grazing for invasive *Phragmites australis* (common reed) management in Northern Utah wetlands. All Current Publications. Paper 2030. https://digitalcommons.usu.edu/extension_curall/2030

England DM (2019) Seeding treatments to enhance seedling performance of the bulrushes *Bolboschoenus maritimus*, *Schoenoplectus acutus* and *S. americanus* in wetland restorations. All Graduate Theses and Dissertations. 7659. https://digitalcommons.usu.edu/etd/7659/

Esser LL (1994) *Echinochloa crus-galli.* In: Fire Effects Information System. https://www.fs.fed.us/database/feis/plants/graminoid/echcru/all.html

Evans MEK, Dennehy JJ (2005) Germ banking: bet-hedging and variable release from egg and seed dormancy. Q R Biol 80:431–451

Evans KE, Martinson W (2008) Utah's featured birds and viewing sites: a conservation platform for IBAs and BHCAs. Sun Litho, Salt Lake City, UT

Executive Presidential Order (1999) Executive Order 13112 of February 3, 1999: invasive species. Fed Regist 64:6183–6186

Fire Effects Information System (2019). https://www.fs.fed.us/database/feis/plants/forb/lytsal/all.html

Fraser LH, Karnezis JP (2005) A comparative assessment of seedling survival and biomass accumulation for fourteen wetland plant species grown under minor water-depth differences. Wetlands 25:520–530

Galatowitsch SM, van der Valk AG (1994) Restoring prairie wetlands: an ecological approach. Iowa State University Press, Ames, IA

Galatowitsch SM, Anderson NO, Ascher PD (1999) Invasiveness in wetland plants in temperate North America. Wetlands 19:733–755

Gioria M, Pyšek P (2017) Early bird catches the worm: germination as a critical step in plant invasion. Biol Invasions 19:1055–1080

Gleason RA, Tangen BA, Laubhan MK, Lor S (2012) A multi-refuge study to evaluate the effectiveness of growing-season and dormant-season burns to control cattail. US Geological Survey, Reston, VA. https://pubs.usgs.gov/sir/2012/5143/sir2012-5143.pdf

Goman M, Wells L (2000) Trends in river flow affecting the northeastern reach of the San Francisco Bay Estuary over the past 7000 years. Quat Res 54:206–217

Great Salt Lake Bird Festival (2019) http://www.daviscountyutah.gov/greatsaltlakebirdfest. Accessed 19 May 2019

Great Salt Lake Planning Team (2000) Great Salt Lake comprehensive management plan and descision document. Utah Department of Natural Resources, Salt Lake City, UT

Grubb PJ (1977) The maintenance of species-richness in plant communities: the importance of the regeneration niche. Biol Rev 52:107–145

Hansen RM (1978) Shasta ground sloth food habits, Rampart Cave, Arizona. Paleobiology 4:302–319

Haynes RR, Hellquist CB (2000) *Potamogeton crispus* in Flora of North America @ eflorasorg. Flora N Am Editor Comm Eds Flora N Am North Mex 20 Vols N Y Oxf Vol 22. http://www.efloras.org/florataxonaspx?flora_id=1&taxon_id=200024690. Accessed 6 Apr 2019

Hazelton ELG, Mozdzer TJ, Burdick DM, Kettenring KM, Whigham DF (2014) *Phragmites australis* management in the United States: 40 years of methods and outcomes. AoB Plants 6. https://doi.org/10.1093/aobpla/plu001

Holmgren NH (2005) In: Holmgren NH, Holmgren PK, Cronquist A (eds) Frankeniaceae, volume two, Part B: Subclass Dilleniidae. Botanical Garden, New York

Hudon C, Gagnon P, Jean M (2005) Hydrological factors controlling the spread of common reed (*Phragmites australis*) in the St Lawrence River (Québec, Canada). Écoscience 12:347–357

Hurd EG, Shaw NL (1992) Seed technology for *Carex* and *Juncus* species of the Intermountain Region. In: Intermountain Nurseryman Association annual meeting. USDA, Forest Service, Rocky Mountain Forest and Range Experiment Station, Park City, UT, pp 74–83

Intermountain Region Herbarium Network (2019) http://intermountainbiota.org/portal/index.php. Accessed 3 Mar 2019

Intermountain West Joint Venture (2013) Implementation plan: strengthening science and partnerships. Missoula, MT

James JJ, Svejcar TJ, Rinella MJ (2011) Demographic processes limiting seedling recruitment in arid grassland restoration. J Appl Ecol 48:961–969

Jodoin Y, Lavoie C, Villeneuve P, Theriault M, Beaulieu J, Belzile F (2008) Highways as corridors and habitats for the invasive common reed *Phragmites australis* in Quebec, Canada. J Appl Ecol 45:459–466

Keller BEM (2000) Genetic variation among and within populations of *Phragmites australis* in the Charles River watershed. Aquat Bot 66:195–208

Kessler AC, Merchant JW, Allen CR, Shultz SD (2011) Impacts of invasive plants on sandhill crane (*Grus canadensis*) roosting habitat. Invasive Plant Sci Manag 4:369–377

Kettenring KM (2016) Viability, dormancy, germination, and intraspecific variation of *Bolboschoenus maritimus* (alkali bulrush) seeds. Aquat Bot 134:26–30

Kettenring KM, Galatowitsch SM (2011) *Carex* seedling emergence in restored and natural prairie wetlands. Wetlands 31:273–281

Kettenring KM, Mock KE (2012) Genetic diversity, reproductive mode, and dispersal differ between the cryptic invader, *Phragmites australis*, and its native conspecific. Biol Invasions 14:2489–2504

Kettenring KM, Whigham DF (2018) The role of propagule type, resource availability, and seed source in *Phragmites* invasion in Chesapeake Bay wetlands. Wetlands 38:1259–1268

Kettenring KM, McCormick MK, Baron HM, Whigham DF (2011) Mechanisms of *Phragmites australis* invasion: feedbacks among genetic diversity, nutrients, and sexual reproduction. J Appl Ecol 48:1305–1313

Kettenring KM, de Blois S, Hauber DP (2012) Moving from a regional to a continental perspective of *Phragmites australis* invasion in North America. AoB Plants 2012. https://doi.org/10.1093/aobpla/pls040

Kettenring KM, Whigham DF, Hazelton ELG, Gallagher SK, Weiner HM (2015) Biotic resistance, disturbance, and mode of colonization impact the invasion of a widespread, introduced wetland grass. Ecol Appl 25:466–480

Kettenring KM, Mock KE, Zaman B, McKee M (2016) Life on the edge: reproductive mode and rate of invasive *Phragmites australis* patch expansion. Biol Invasions 18:2475–2495

Kettenring KM, Menuz DR, Mock KE (2019) The nativity and distribution of the cryptic invader *Phalaris arundinacea* (reed canarygrass) in riparian areas of the Columbia and Missouri River Basins. Wetlands 39:55–66

King RS, Deluca WV, Whigham DF, Marra PP (2007) Threshold effects of coastal urbanization on *Phragmites australis* (common reed) abundance and foliar nitrogen in Chesapeake Bay. Estuar Coasts 30:469–481

Kiviat E, Hamilton E (2001) *Phragmites* use by native North Americans. Aquat Bot 69:341–357

Kulmatiski A, Beard KH, Meyerson LA, Gibson JR, Mock KE (2011) Nonnative *Phragmites australis* invasion into Utah wetlands. West North Am Nat 70:541–552

Lambert AM, Saltonstall K, Long R, Dudley TL (2016) Biogeography of *Phragmites australis* lineages in the southwestern United States. Biol Invasions 18:2597–2617

Li E, Endter-Wada J, Li S (2019) Dynamics of Utah's agricultural landscapes in response to urbanization: a comparison between irrigated and non-irrigated agricultural lands. Appl Geogr 105:58–72

Lishawa SC, Lawrence BA, Albert DA, Tuchman NC (2015) Biomass harvest of invasive *Typha* promotes plant diversity in a Great Lakes coastal wetland. Restor Ecol 23:228–237

Long AL, Kettenring KM, Hawkins CP, Neale CMU (2017a) Distribution and drivers of a widespread, invasive wetland grass, *Phragmites australis*, in wetlands of the Great Salt Lake, Utah, USA. Wetlands 37:45–57

Long AL, Kettenring KM, Toth R (2017b) Prioritizing management of the invasive grass common reed (*Phragmites australis*) in Great Salt Lake wetlands. Invasions Plant Sci Manag 10:155–165

Low G, Downard R (2018) Great Salt Lake Wetlands Water Quality Standards Workshops, 25

Lowry BJ, Ransom C, Whitesides R, Olsen H (2017) Noxious weed field guide for Utah. https://digitalcommons.usu.edu/cgi/viewcontent.cgi?article=2351&context=extension_curall

Marty JE, Kettenring KM (2017) Seed dormancy break and germination for restoration of three globally important wetland bulrushes. Ecol Restor 35:138–147

Matthews JW, Molano-Flores B, Ellis J, Marcum PB, Handel W, Zylka J, Phillippe LR (2017) Impacts of management and antecedent site condition on restoration outcomes in a sand prairie. Restor Ecol 25:972–981

McCormick MK, Kettenring KM, Baron HM, Whigham DF (2010a) Extent and reproductive mechanisms of *Phragmites australis* spread in brackish wetlands in Chesapeake Bay, Maryland (USA). Wetlands 30:67–74

McCormick MK, Kettenring KM, Baron HM, Whigham DF (2010b) Spread of invasive *Phragmites australis* in estuaries with differing degrees of development: genetic patterns, Allee effects and interpretation. J Ecol 98:1369–1378

McCormick MK, Brooks HEA, Whigham DF (2016) Microsatellite analysis to estimate realized dispersal distance in *Phragmites australis*. Biol Invasions 18:2497–2504

Meadows RE, Saltonstall K (2007) Distribution of native and introduced *Phragmites australis* in freshwater and oligohaline tidal marshes of the Delmarva peninsula and southern New Jersey. J Torrey Bot Soc 134:99–107

Menuz D, McCoy-Sulentic M (2019) Bear River watershed wetland assessment and landscape analysis: Salt Lake City, Utah Geological Survey contract deliverable for the US Environmental Protection Agency Wetland Program Development Grant #CD96851201

Menuz D, Sempler R (2018) Jordan River watershed wetland assessment and landscape analysis: Salt Lake City, Utah Geological Survey contract deliverable for the US Environmental Protection Agency Wetland Program Development Grant #CD96804801

Menuz D, Sempler R, Jones J (2014) Great Salt Lake wetland condition assessment: Salt Lake City, Utah Geological Survey contract deliverable for the US Environmental Protection Agency Wetland Program Development Grant #CD96811101

Menuz D, Sempler R, Jones J (2016) Weber River watershed wetland condition assessment: Salt Lake City, Utah Geological Survey contract deliverable for the US Environmental Protection Agency Wetland Program Development Grant #CD96812601-0

Meyerson LA, Cronin JT (2013) Evidence for multiple introductions of *Phragmites australis* to North America: detection of a new non-native haplotype. Biol Invasions 15:2605–2608

Meyerson LA, Saltonstall K, Windham L, Kiviat E, Findlay S (2000) A comparison of *Phragmites australis* in freshwater and brackish marsh environments in North America. Wetl Ecol Manag 8:89–103

Meyerson LA, Lambert AM, Saltonstall K (2010a) A tale of three lineages: expansion of common reed (*Phragmites australis*) in the US Southwest and Gulf Coast. Invasive Plant Sci Manag 3:515–520

Meyerson LA, Viola DV, Brown RN (2010b) Hybridization of invasive *Phragmites australis* with a native subspecies in North America. Biol Invasions 12:103–111

Meyerson LA, Lambertini C, McCormick MK, Whigham DF (2012) Hybridization of common reed in North America? The answer is blowing in the wind. AoB Plants. https://doi.org/10.1093/aobpla/pls022

Moser K, Ahn C, Noe G (2007) Characterization of microtopography and its influence on vegetation patterns in created wetlands. Wetlands 27:1081–1097

Munger GT (2002) *Lythrum salicaria*. In: Fire Effects Information System. https://www.fs.fed.us/database/feis/plants/forb/lytsal/all.html

Niering WA, Warren RS, Weymouth GC (1977) Our dynamic tidal marshes, vegetation changes as revealed by peat analysis [Connecticut]. Bulletin-Connecticut Arboretum (USA)

Ochterski J (2003) Controlling cattails. Cornell Coop Ext. http://albany.cce.cornell.edu/environment/ponds/controlling-cattails

Olson BE, Lindsey K, Hirschboeck V (2004) Habitat management plan: Bear River Migratory Bird Refuge. U.S. Fish & Wildlife Service, Brigham City, UT

Oring LW, Neel L, Oring KE (2000) Intermountain west regional shorebird plan. US Shorebird Conservation Plan

Orson RA (1999) A paleoecological assessment of *Phragmites australis* in New England tidal marshes: changes in plant community structure during the last few millennia. Biol Invasions 1:149–158

Palmerlee AP, Young TP (2010) Direct seeding is more cost effective than container stock across ten woody species in California. Nativ Plants J 11:89–102

Paul DS, Manning AE (2002) Great Salt Lake waterbird survey five-year report (1997–2001). Great Salt Lake Ecosystem Project, Utah Division of Wildlife Resource, Salt Lake City, UT

Paul J, Vachon N, Garroway CJ, Freeland JR (2010) Molecular data provide strong evidence of natural hybridization between native and introduced lineages of *Phragmites australis* in North America. Biol Invasions 12:2967–2973

Peach M, Zedler JB (2006) How tussocks structure sedge meadow vegetation. Wetlands 26:322–335

Pellegrin D, Hauber DP (1999) Isozyme variation among populations of the clonal species, *Phragmites australis* (Cav) Trin ex Steudel. Aquat Bot 63:241–259

Penning WE, Mjelde M, Dudley B, Hellsten S, Hanganu J, Kolada A, van den Berg M, Poikane S, Phillips G, Willby N, Ecke F (2008) Classifying aquatic macrophytes as indicators of eutrophication in European lakes. Aquat Ecol 42:237–251

Peter CR, Burdick DM (2010) Can plant competition and diversity reduce the growth and survival of exotic *Phragmites australis* invading a tidal marsh? Estuar Coasts 33:1225–1236

Price AL, Fant JB, Larkin DJ (2014) Ecology of native vs introduced *Phragmites australis* (common reed) in Chicago-area wetlands. Wetlands 34:369–377

Quirion B, Simek Z, Dávalos A, Blossey B (2018) Management of invasive *Phragmites australis* in the Adirondacks: a cautionary tale about prospects of eradication. Biol Invasions 20:59–73

Rieger JP, Stanley J, Traynor R (2014) Project planning and management for ecological restoration. Springer, New York

Roberts AJ (2013) Avian diets in a saline ecosystem: Great Salt Lake, Utah, USA. Hum Wildl Interact 7:158–168

Robichaud CD, Rooney RC (2017) Long-term effects of a *Phragmites australis* invasion on birds in a Lake Erie coastal marsh. J Gt Lakes Res 43:141–149

Rohal CB (2018) Invasive *Phragmites australis* management in Great Salt Lake wetlands: context dependency and scale effects on vegetation and seed banks. Graduate Theses and Dissertations. https://digitalcommons.usu.edu/etd/7228

Rohal CB, Hambrecht KR, Cranney C, Kettenring KM (2017) How to restore *Phragmites*-invaded wetlands. Utah Agric Exp Stn Res Rep 224:2

Rohal CB, Kettenring KM, Sims K, Hazelton ELG, Ma Z (2018) Surveying managers to inform a regionally relevant invasive *Phragmites australis* control research program. J Environ Manag 206:807–816

Rohal CB, Cranney C, Hazelton ELG, Kettenring KM (2019a) Invasive *Phragmites australis* management outcomes and native plant recovery are context dependent. Ecol Evol 9:13835–13849

Rohal CB, Cranney C, Kettenring KM (2019b) Abiotic and landscape factors constrain restoration outcomes across spatial scales of a widespread invasive plant. Front Plant Sci 10:481

Saltonstall K (2002) Cryptic invasion by a non-native genotype of the common reed, *Phragmites australis*, into North America. Proc Natl Acad Sci 99:2445–2449

Saltonstall K (2011) Remnant native *Phragmites australis* maintains genetic diversity despite multiple threats. Conserv Genet 12:1027–1033

Saltonstall K, Castillo HE, Blossey B (2014) Confirmed field hybridization of native and introduced *Phragmites australis* (Poaceae) in North America. Am J Bot 101:211–215

Saltonstall K, Lambert AM, Rice N (2016) What happens in Vegas, better stay in Vegas: *Phragmites australis* hybrids in the Las Vegas Wash. Biol Invasions 18:2463–2474

Sciance MB, Patrick CJ, Weller DE, Williams MN, McCormick MK, Hazelton ELG (2016) Local and regional disturbances associated with the invasion of Chesapeake Bay marshes by the common reed *Phragmites australis*. Biol Invasions 18:2661–2677

Shuford WD, Roy VL, Page GW, Paul DS (1995) Shorebird surveys in wetlands at Great Salt Lake, Utah. Point Reyes Bird Observatory Report no. 708

Smith LM, Kadlec JA (1983) Seed banks and their role during drawdown of a North American marsh. J Appl Ecol 20:673–684. https://doi.org/10.2307/2403534

SWCA (2012) Definition and assessment of Great Salt Lake health. SWCA Environmental Consultants, Salt Lake City, UT. https://documents.deq.utah.gov/water-quality/standards-technical-services/great-salt-lake-advisory-council/activities/DWQ-2012-006862.pdf. Accessed 8 Apr 2019

SWCA (2013) Final Great Salt Lake comprehensive management plan and record of decision. https://www.scribd.com/document/294220307/Final-Great-Salt-Lake-Comprehensive-Management-Plan-and-Record-of-Decision. Accessed 19 Mar 2019

Taddeo S, de Blois S (2012) Coexistence of introduced and native common reed (*Phragmites australis*) in freshwater wetlands. Écoscience 19:99–105

Thayer DD, Pfingsten IA, Cao L, Berent L (2019) *Potamogeton crispus* L: US Geological Survey, Nonindigenous Aquatic Species Database, Gainesville, FL. https://nas.er.usgs.gov/queries/factsheet.aspx?SpeciesID=1134. Accessed 6 Apr 2019

Thomas SM, Lyons JE, Andres BA, T-Smith EE, Palacios E, Cavitt JF, Royle JA, Fellows SD, Maty K, Howe WH, Mellink E, Melvin S, Zimmerman T (2012) Population size of snowy plovers breeding in North America. Waterbirds 35:1–14

Thursby J (2004) Ritual identity: hunting and feasting in Utah and southeastern Idaho. West Folk 63:101–121

Tilley DJ, St John L (2013) Hydroseeding improves field establishment of Nebraska sedge regardless of seed treatment. Native Plants J 14:89–94

Tilman D (1994) Competition and biodiversity in spatially structured habitats. Ecology 75:2–16

Tu M, Hurd C, Randall JM (2001) Weed control methods handbook: tools & techniques for use in natural areas. The Nature Conservancy

Tulbure MG, Johnston CA (2010) Environmental conditions promoting non-native *Phragmites australis* expansion in Great Lakes coastal wetlands. Wetlands 30:577–587

Urbanska KM (1997) Safe sites—interface of plant population ecology and restoration ecology. Restor Ecol Sustain Dev 81–110

US Fish & Wildlife Service (2019) National Wetlands Inventory website. U.S. Department of the Interior, Fish & Wildlife Service, Washington, DC. http://www.fws.gov/wetlands/

USDA NRCS (2019) PLANTS database. https://plants.sc.egov.usda.gov/java/

Utah Department of Agriculture and Food (2019) State of Utah noxious weed list. https://ag.utah.gov/farmers/plants-industry/noxious-weed-control-resources/state-of-utah-noxious-weed-list/

Utah Division of Water Quality (2015) Ecological characteristics of potential reference standard sites for Great Salt Lake impounded wetlands: 2014 & 2015. Survey: http://DWQ-2015-017187.pdf

Utah Division of Water Quality (2016) Ecological characteristics of Great Salt Lake fringe wetlands. Utah Division of Water Quality. https://documents.deq.utah.gov/water-quality/standards-technical-services/gsl-website-docs/wetlands-program/wetland-monitoring-assessment/DWQ-2015-017187.pdf

Vest JL, Conover MR (2011) Food habits of wintering waterfowl on the Great Salt Lake, Utah. Waterbirds 34:40–50

Waheed A, Qureshi R, Jakhar GS, Tareen H (2009) Weed community dynamics in wheat crop of district Rahim Yar Khan, Pakistan. Pak J Bot 41:247–254

Webb JA, Wallis EM, Stewardson MJ (2012) A systematic review of published evidence linking wetland plants to water regime components. Aquat Bot 103:1–14

Weller MW (1999) Wetland birds: habitat resources and conservation implications. Cambridge University Press, Cambridge

Whalen MA (2015) *Frankenia pulverulenta*. In: Flora of North America Editorial Committee, eds. 1993+. Flora of North America North of Mexico. 20+ vols. New York and Oxford. Vol 6, p 411. http://beta.floranorthamerica.org/Frankenia_pulverulenta

Whyte RS, Bocetti CI, Klarer DM (2015) Bird assemblages in *Phragmites* dominated and non-*Phragmites* habitats in two Lake Erie coastal marshes. Nat Areas J 35:235–245

Willis CG, Baskin CC, Baskin JM, Auld JR, Venable DL, Cavender-Bares J, Donohue K, de Casas RR, The NESCent Germination Working Group (2014) The evolution of seed dormancy: environmental cues, evolutionary hubs, and diversification of the seed plants. New Phytol 203:300–309

Wilson SD, Keddy PA (1986) Species competitive ability and position along a natural stress/disturbance gradient. Ecology 67:1236–1242

Wu CA, Murray LA, Heffernan KE (2015) Evidence for natural hybridization between native and introduced lineages of *Phragmites australis* in the Chesapeake Bay watershed. Am J Bot 102:805–812

Wurtsbaugh WA, Miller C, Null SE, DeRose RJ, Wilcock P, Hahnenberger M, Howe F, Moore J (2017) Decline of the world's saline lakes. Nat Geosci 10:816–821

Zedler JB, Kercher S (2004) Causes and consequences of invasive plants in wetlands: opportunities, opportunists, and outcomes. Crit Rev Plant Sci 23:431–452

Zimmerman CL, Shirer RR, Corbin JD (2018) Native plant recovery following three years of common reed (*Phragmites australis*) control. Invasive Plant Sci Manag 11:175–180