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Research Article

Assessment of Methods to Control Invasive Reed Canarygrass (*Phalaris arundinacea*) in Tidal Freshwater Wetlands

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ABSTRACT

Reed canarygrass (*Phalaris arundinacea*) is invasive in temperate freshwater wetlands throughout the United States and Canada and presents challenges to restoring tidal freshwater wetlands. Methods for the prevention or elimination of reed canarygrass in palustrine wetlands are generally well established, typically involving herbicide application, mechanical treatments, prolonged inundation, or establishment of competitive plant species. These methods are often not suitable for the unique conditions in tidal wetlands and alternative strategies remain poorly understood. Prolonging inundation of tidal wetlands requires a loss of habitat forming processes, connectivity, and other functions. Treatments such as mowing, discing, or fire are not feasible in the perpetually wet conditions of tidal wetlands. Restoration practitioners aiming to design self-sustaining wetlands in the lower Columbia River estuary and the U.S. Pacific Coast have found that reed canarygrass is widespread and quick to establish post-restoration creating a management burden and impacting restoration goals. Here we report the results of a comprehensive effort to develop methods for control in tidal wetlands through systematic review of the scientific literature, interviews with experienced practitioners, and field observations at nine Pacific Northwest sites. The review framework evaluated key environmental conditions affecting reed canarygrass, control methods, and practical considerations. Findings support an integrated long-term control strategy at the largest possible scale to establish effective and self-sustaining control. Appropriate and practical strategies for tidal freshwater wetlands include implementing control pre-restoration to suppress existing populations; topographic modification such as scrape-downs and mounds to support competitiveness of desired vegetation communities; seeding or planting strong native competitors; limiting nutrient availability; and periodic, targeted control to limit reinvasion. These strategies are supported by the study, but long-term results are generally not available. Formal field experiments are recommended by the authors to better evaluate factors that influence reed canarygrass control in tidal freshwater wetlands.

Index terms: control; intertidal; invasive; *Phalaris arundinacea*; reed canarygrass; restoration; river floodplain; tidal wetland

INTRODUCTION

Reed canarygrass (*Phalaris arundinacea* L.; RCG hereafter) is an invasive grass that forms monocultures that adversely affect freshwater wetland ecosystems through the loss of biodiverse native grasses and forbs, including rare species (Lesica 1997; Schooler et al. 2006; Spyreas et al. 2010). The highly successful reproductive strategies (Maurer and Zedler 2002), broad physiological tolerances (Miller and Zedler 2003), and morphological plasticity to environmental conditions (e.g., Herr-Turoff and Zedler 2007; Kercher and Zedler 2004) of RCG make it a very effective ecosystem invader in freshwater wetlands throughout the temperate region of the United States and Canada (Lavergne and Molofsky 2004). RCG presents an ecological problem within riverine landscapes because of its water-borne spread (Coops and Van Der Velde 1995; Soomers et al. 2011). It impacts the export of organic material from floodplains (Kukulski 2017) and can adversely affect aquatic food webs by altering secondary production, species composition, and abundance (Maerz et al. 2010; Spyreas et al. 2010).

In North America, the modern invasive population has long been thought to be a hybrid of a noninvasive native population and agronomic cultivars brought from Europe in the early 1800s (Merigliano and Lesica 1998). Genetic analysis concluded that the early North American herbarium species are distinct from the Eurasian species (Jakubowski et al. 2013). In the Pacific Northwest, RCG was introduced and cultivated for livestock forage by the late 1800s, in part because of its high productivity in the low-lying wet areas ubiquitous to the region. Early cultivation of RCG began on the southern Oregon coast, and the Coquille Valley ultimately provided much of the seed for establishment along the Pacific Coast (Schoth 1938). In the lower Columbia River and estuary (LCRE; Figure 1), RCG does not grow in brackish waters near the mouth, but through cultivation and successful natural reproduction, it now covers extensive wetland areas in the 176 river-kilometer tidal freshwater region (Borde et al. 2020).

Natural area managers and restoration practitioners in Washington State's Puget Sound, California's Sacramento River estuary, and the LCRE identify widespread establishment of RCG in tidal wetlands as a significant challenge for restoration planning and design. The Columbia Estuary Ecosystem Restoration Program (CEERP), for example, is a collaborative program of the Bonneville Power Administration, the U.S. Army Corps of Engineers' Portland District, the National Marine Fisheries Service, and five sponsors implementing tidal wetland restoration (Ebberts et al. 2018). CEERP focuses on the hydrologic reconnection of tidal wetland habitats to restore

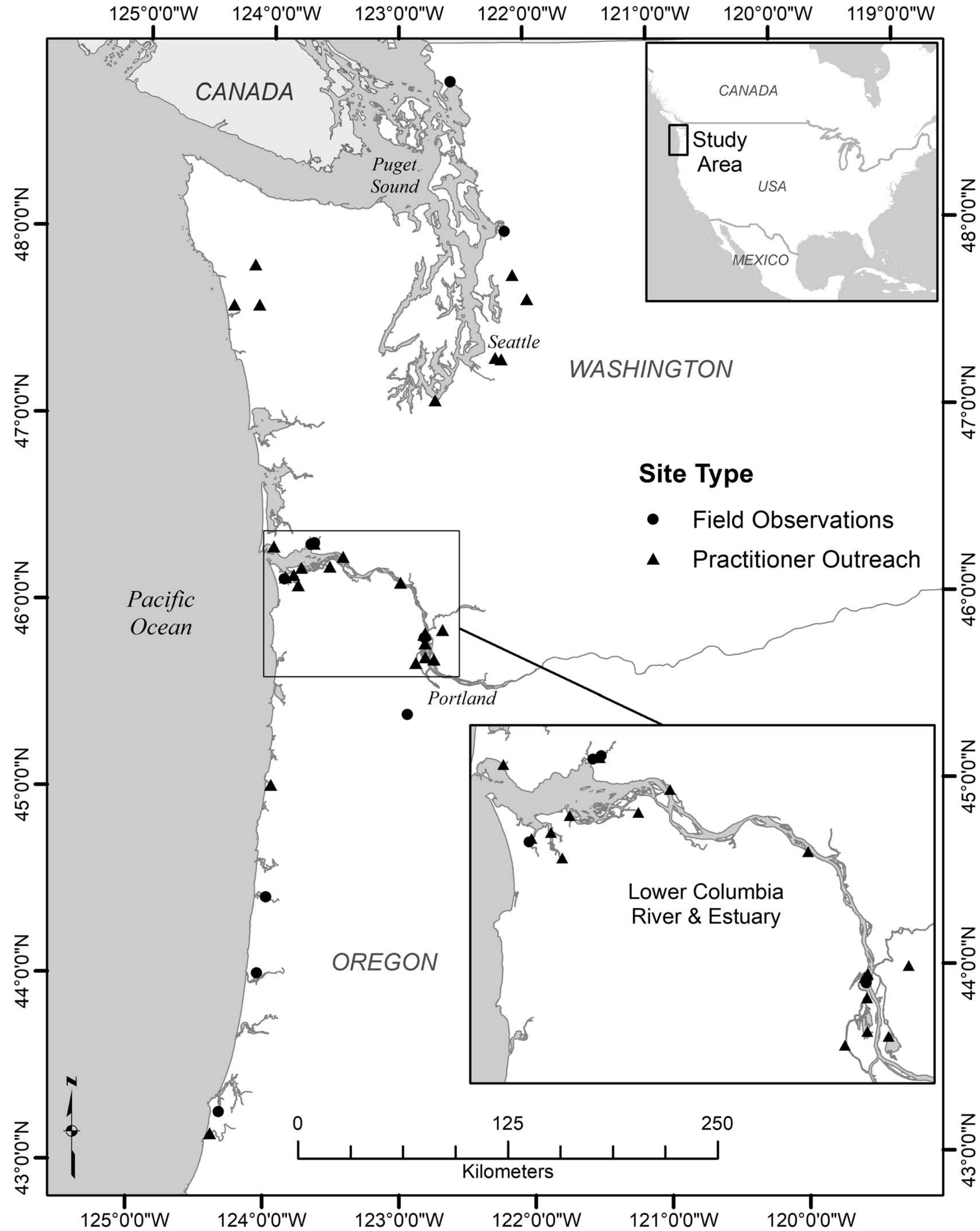

Figure 1.—Map of reed canarygrass sites in Washington and Oregon discussed in practitioner outreach and visited for field observations (the two California practitioner outreach sites are not shown). The study informs the Columbia Estuary Ecosystem Restoration Program (CEERP) in the Lower Columbia River and Estuary (LCRE).

ecological processes benefitting a variety of species, particularly salmonid fish species listed under the Endangered Species Act of 1973. Control of RCG is a key programmatic restoration challenge. The effects of RCG documented in the LCRE include slower growth of juvenile salmonids as compared to fish in marshes with native plant species (Klopfenstein 2016; McNatt et al. 2017), reduced diversity of macroinvertebrates (Weilhoefer et al. 2017), slower organic matter decomposition, and reduced quality of detritus compared to native communities dominated by *Carex* species (Hanson et al. 2016). Thus, managers anticipate that reducing the extent of invasive RCG in the tidal freshwater region of the LCRE could help to reestablish native plant communities, improve food web dynamics, prevent floodplain armoring, facilitate passive channel formation, and foster natural benthic communities (Ebberts et al. 2018).

In general, the evaluation of control methods in nontidal wetlands has produced recommendations focused on prolonged inundation, periodic intervention with chemical and mechanical controls, and establishment of competitive vegetation (Lavergne and Molofsky 2006). However, unique challenges within tidal environments preclude the use of prolonged controlled inundation because tidal dynamics are an essential process affecting biophysical aspects of the ecosystem. Moreover, typical mechanical approaches (e.g., mowing or tilling) are not possible due to operability limitations in saturated and regularly flooded soils. While science-based construction specifications for topographic control (i.e., elevation, slope) are emerging (Diefenderfer et al. 2018), other control methods to prevent or eliminate RCG are not well understood in tidal areas.

Therefore, we sought to identify practical methods for achieving effective control of RCG in tidal–fluvial ecosystems based on a synthesis of successful control strategies and an understanding of environmental conditions supporting RCG establishment and competitiveness. The objective of this study was to develop the basis for recommendations to control RCG in tidal systems, with a focus on wetland restoration, through literature review, practitioner interviews, and field data collection. While our data-development emphasis was on the LCRE, findings reported here are relevant to North American ecosystem restoration practitioners—particularly in freshwater tidelands of the North Pacific coastal temperate rainforest margin (Lievesley et al. 2017; Bidlack et al. 2021)—and managers responsible for tidelands elsewhere where RCG invasion and dominance threaten conservation goals.

METHODS

Our assessment included three approaches: (1) review of the knowledge base in the published scientific literature; (2) interviews with practitioners to gain insight from the experiences of others in the U.S. Pacific Northwest; and (3) field observations of the spatial distribution of RCG and environmental controlling factors on its productivity and relative dominance at restoration sites. Results were used to inform recommendations for restoration design and control strategies.

Literature Review

Web of Science and EndNote tools were used to conduct a systematic review of the available indexed literature published on RCG control (Science Citation Index Expanded 1900–October 2020). We developed primary keyword search strings to produce results most relevant to the objectives regarding tidal freshwater wetlands, control methods, and ecological restoration. This literature search was intended to build from previous reviews investigating RCG control methods (Apfelbaum and Sams 1987; Lavergne and Molofsky 2006). The final keyword search string used was the following:

> (("reed canarygrass" OR "phalaris arundinacea")) AND TOPIC: (tid* OR estuar* OR wetland) AND TOPIC: (restor*) AND TOPIC: (control*) (39 records).

To avoid overly limiting findings, a variant of the search string without restor* was also searched and returned 56 records.

An EndNote file was created with 95 records from the combination of the two searches and all abstracts were reviewed for relevance. Relevant studies were defined as those focused on methods of controlling existing populations of RCG, identifying the conditions under which native species can be more competitive to limit RCG invasions in wet environments, or defining the environmental conditions that facilitate RCG establishment. Studies of the pollutant removal capacity or habitat functions of RCG, for example, were not considered relevant. Based on these criteria, 34 articles were pulled for full-text review, development of an annotated bibliography, and synthesis (Supplemental Table S1).

While reviewing relevant literature, we found that papers and technical notes from a non-indexed journal (*Ecological Restoration*) were not included in the Web of Science search results. Therefore, we searched the entire publication history of the journal on its webpage using "reed canarygrass" as a search term. This search produced 105 potential publications, of which 16 papers and technical notes were considered potentially relevant based on their abstracts and subsequently reviewed in detail. Nine papers and technical notes met relevance criteria described above and were integrated into findings (Supplemental Table S2).

Practitioner Interviews

Practitioners have experience with the challenges of RCG control as part of their work to restore intertidal marsh habitats; however, this can be an individual pursuit with limited information sharing. Similarly, unpublished literature, such as county weed management guidelines, contains important lessons for the control of RCG in tidal habitats (e.g., Latterell et al. 2014). To these points, we sought to establish a baseline understanding for RCG control related to intertidal marsh habitats by including practitioner outreach as part of the study design.

We reached out to restoration practitioners on the LCRE, Puget Sound, and coastal Oregon (OR) and Washington (WA) to inform them of the study objectives, obtain feedback on our approach, and solicit input and advice on RCG control. Practitioners were selected based on their experience implementing tidal freshwater restoration projects in each of the geographic areas over the preceding 20 y. We restricted outreach to practitioners working in tidal freshwater and fluvial sites, because RCG control is generally accomplished by salt in brackish estuarine environments with salinities greater than 15 parts per thousand (Prasser and Zedler 2010). Practitioners with relevant project experience were identified through inquiries to project funders, regulatory agencies, and known practitioners. Each practitioner was further asked for recommendations of additional experts to ensure broad representation, which led to consideration of two sites in California. We note that it is likely that there are practitioners working on RCG control and intertidal marsh habitat restoration that were not included in this study.

Before each interview, we shared the following RCG discussion topics: *biological considerations*, e.g., inundation/salinity tolerance, reproductive strategies; *ecological effects*, e.g., plant community, food web, channel formation; *relevant site conditions for planning*, e.g., elevation, hydrologic regime, growth form; and *practical considerations*, e.g., regulatory constraints on

Table 1.—Practitioner organizations and associated restoration sites for the outreach discussions.

Organization	Restoration sites
LCRE	
Columbia Land Trust	Devils Elbow*, Kandoll Farm*, Mill Road
Columbia River Estuary Study Taskforce	Colewort Creek*, Otter Point, Gnat Creek, Charnelle Fee, Dibblee Point, South Tongue Point, North Unit Sauvie Island, Steamboat Slough
Cowlitz Tribe	Walluski-Youngs confluence, Clatskanie, Lower East Fork Lewis River
Lower Columbia Estuary Partnership	La Center Bottoms
Washington Department of Fish and Wildlife	Chinook Estuary
PC Trask and Associates, Inc.	Sauvie Is. North Unit (Ruby*, Deep Wigeon, and Millionaire Lakes), Buckmire Slough, Gilbert River, and Multnomah Channel (Metro site)
Oregon Department of Fish and Wildlife, Sauvie Island Wildlife Area	Sauvie Island Wildlife Area, Sturgeon Lake
Friends of Ridgefield National Wildlife Refuge	Ridgefield National Wildlife Refuge
Ash Creek Forest Management	Quamash (Gotter) Prairie (nontidal)*
Puget Sound	
King County	Cold Creek, Green River (Pautzke), Korn-Patterson (all nontidal)
U.S. Fish and Wildlife Service	Spencer Island*, Marietta Slough*
Washington State Department of Fish and Wildlife	Marietta Slough*, Nooksack Wildlife Area
Anchor QEA, LLC	Emerald Downs mitigation (nontidal)
Ducks Unlimited: Vancouver, WA and San Francisco, CA	Nisqually National Wildlife Refuge[(a)]
OR/WA Coast	
Institute for Applied Ecology, Estuary Technical Group	North Fork Siuslaw*, Salmon River (Pixieland), Anderson Creek, Bandon Marsh National Wildlife Refuge, Drift Creek
South Slough National Estuarine Research Reserve	Anderson Creek*
10,000 Years Institute	Olympic Peninsula (nontidal floodplains of the Hoh River, Queets River, and Clearwater River)

(*) Indicates sites where field visits were conducted.
(a) Also discussed two sites in California: Sears Point (Sonoma County, CA), Cullinan Ranch (Napa R. delta, CA).

control, operability, and cost. We held telephone and in-person discussions, generally 1–1.5 hr long, with nine practitioner organizations from the LCRE, five from the Puget Sound, and three from the OR/WA Coast (Table 1). The discussions systematically covered the practitioners' views on the topics listed above and encompassed multiple restoration sites (Figure 1).

Field Observations

We visited nine restoration sites identified by practitioners and through unpublished literature to make observations regarding methods for RCG control (Figure 1).

- Spencer Island, Snohomish River, Washington
- Marietta Slough, Nooksack River, Washington
- Colewort Creek, Lewis & Clark River, Columbia River estuary, Washington
- Kandoll Farm, Grays River, Columbia River estuary, Washington
- Devils Elbow, Grays River, Columbia River estuary, Washington
- Ruby Lake, Columbia River, Washington
- Quamash Prairie, Tualatin River, Oregon
- North Fork Siuslaw, Oregon
- Anderson Creek, South Slough, Coos Bay, Oregon

Observational characterizations based on focused inspection of restoration work areas included the presence and abundance of RCG, presence of other species, and other factors that could influence RCG based on the restoration strategy employed. Additionally, we conducted elevation surveys using real time kinematic (RTK)-GPS methods (Borde et al. 2020) at Spencer Island, Devils Elbow, and Ruby Lake. Surveyed elevations for Columbia River sites were converted to the Columbia River Datum (CRD), a fixed low-water datum originally developed and periodically updated by the U.S. Army Corps of Engineers (Hickson 1912), which is currently the chart datum identified by National Oceanic and Atmospheric Administration (NOAA) Tides and Currents landward of river mile 23.

To quantitatively assess RCG establishment at the Devils Elbow site, which was reconnected in 2004 without RCG control, vegetative cover data at fifteen 1 m^2 plots were collected four times between 2005 and 2015. Plant species were identified to species level where possible, and grouped into Native, Non-Native or Mixed categories (the mixed category occurred when two species within a genus could not be distinguished and one was native and the other nonnative). A species accumulation analysis (Gleason 1922) was conducted to determine whether 15 plots adequately represented the species on the site, and results indicated they were near the asymptote, thus adequate. Cover data from the 15 plots were averaged by species for each year. Plot elevations ranged between 1.83 m and 2.74 m, NAVD88.

RESULTS AND DISCUSSION

Published literature addressing RCG control in tidal or estuarine wetland restoration was surprisingly limited. Of the 95 published articles reviewed for relevance to RCG control and environmental conditions (Figure 2), only 34 were directly related in detail to our study questions. Most studies reviewed were conducted in nontidal environments (32 of 34) or located outside of the Pacific Northwest (26 of 34). Nevertheless, a number of common themes and findings applicable to tidal

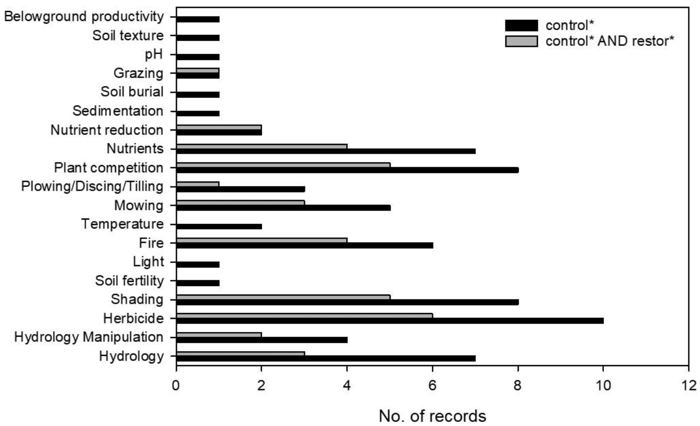

Figure 2.—Keywords in search string results for relevant papers on reed canarygrass control.

wetland restoration emerged from the review. We organized findings along with the practitioner inputs and field observations into three topics summarized below: ecological considerations, control methods, and practical considerations.

Ecological Considerations

The key environmental controls for RCG growth are salinity, shade, elevation/inundation, and nutrients (Box 1). Because of its height, vigor, growth habit, and longevity, RCG is a strong competitor for light (Eppinga et al. 2011). Thus, providing competition for light and other resources can reduce RCG establishment and vigor. Elevation is also important. At low wetland elevations, inundation can impede RCG growth, and at high wetland elevations reduced inundation can allow woody plants to become established and outcompete RCG.

RCG is generally intolerant of salinity (Prasser and Zedler 2010), but for the tidal Columbia River—like the lower Hudson, Scheldt, Yangtze and other rivers—much of the intertidal wetland habitat is naturally freshwater (Baldwin et al. 2009, 2019; Struyf et al. 2009; Strayer and Findlay 2010; Yu et al. 2014). Salinity may have been a factor limiting the extent of RCG at lower elevations on Spencer Island in the Snohomish estuary as indicated by modeled water surface elevation and salinity data from the area showing that oligohaline conditions (0.5–5.0 ppt) likely reached the site most of the year and mesohaline conditions (5.0–18.0 ppt) may have occurred during extreme low flows in the fall season (Hall et al. 2018).

The restoration strategy to avoid RCG establishment in intertidal marsh habitats of the LCRE has been to shift habitat types, either to low marsh or higher woody vegetation communities. Scrape-down to elevations below high marsh may facilitate competition by native plants with a high tolerance of inundation. In the LCRE, the lower limit of RCG is higher at the sites with a greater tidal range (Borde et al. 2020). For example, we determined that the lower elevations of RCG at the highly tidal Devils Elbow site was 1.71 m, CRD (1.83 m, NAVD88) while the lower threshold at the more riverine Ruby Lake site was 1.45 m, CRD (2.74 m, NAVD88). Likewise, the tidal range at Spencer Island is >3 m and likely precluded RCG below 2.0 m, NAVD88; above this, RCG occurred only on a small portion of the site.

A number of studies indicate a tolerance threshold for RCG at which increased inundation lowers cover, germination, and biomass. However, sea level rise is a consideration, particularly in reaches nearest the ocean, so relative future accretion rates should be evaluated before intentionally lowering land elevation. Scrape-down methods also potentially reduce the area of highly productive mid- and high-marsh habitats and surrender any remaining high-marsh to reed canarygrass where it is most

Box 1.—Ecological considerations for reed canarygrass control derived from literature review and practitioner input. Citations from literature review are included as numbers[(a)] referencing summaries in Tables S1 and S2 in the Supplemental Information.

Literature review

- RCG is a weak competitor for soil nutrients but a strong competitor for light (4).
- Vacant niches can be filled by RCG litter, which provides seeds and organic material, limiting native establishment, and a nutrient pulse, which can feed invasions (4).
- Increased temperature variation increased competitiveness of RCG and increased inundation gave a competitive advantage to native sedges (7).
- Disturbance combined with increased nutrients favors RCG invasion and monoculture development (14, S8).
- RCG can tolerate sediment burial up to 5–10 cm (23).
- Sediment removal to access buried native seed bank and remove RCG biomass can improve native species richness for a period of time, but is limited without continued management (34).
- At some invaded wetlands, RCG abundance was not correlated with other influences including hydrology, soils, and topography (29).
- System-scale approach to RCG control can limit invasion vectors (18).
- RCG had higher methane (CH_4) production in wet conditions compared to *Scirpus microcarpus* (31).

Practitioner input[(b)]

- Elevation and hydrology drive vegetation community development.
- Water control structures can be used, however typically are not desirable for the restoration of ecological processes.
- RCG appears to expand in low-flow years in the tidal river.
- Competition needs to occur above ground (canopy) and below ground (roots).
- Control methods depend on whether RCG was established prior to restoration. RCG can flourish if established prior to restoration since regeneration is primarily through vegetative colonization; establishment from the seed bank is also a concern. Prior control was recommended.
- Site-specific conditions seem to matter for RCG invasion. Seemingly small site differences can lead to differences in RCG competitiveness (i.e., elevation, hydrology, nutrients).

(a) Literature sources:
4 Eppinga et al. 2011
7 He et al. 2011
14 Kercher et al. 2007
18 Lavergne & Molofsky 2006
23 Pan et al. 2014
29 Schooler et al. 2006
31 Turnbull & Bridgham 2015
34 Winikoff et al. 2020
S8 Maurer et al. 2003

(b) Unpublished literature such as workshop proceedings and field reports, referred to by practitioners, is incorporated in this column.

competitive. Yet for biodiversity and habitat function, it is important to maintain a landscape mosaic of plant communities that includes native mid- and high marsh.

Another environmental condition important to RCG productivity is nutrient availability, and competition for this resource may be a mechanism for RCG control and native plant establishment. A number of studies found a positive correlation between nutrient abundance and RCG growth (Maurer and Zedler 2002; Martina and von Ende 2008; Bartodziej et al. 2011; Katagiri et al. 2011), although one species, *S. microcarpus*, may be able to outcompete RCG at high nitrogen concentrations (Seebacher 2008). When nutrients are scarce, some native sedges demonstrated a competitive growth advantage over RCG (Perry et al. 2004). Cover crops and the addition of carbon sources (e.g., sawdust) may be useful pre-restoration tactics to reduce nutrients at former livestock or agricultural sites and give a competitive advantage to native sedges (Iannone et al. 2008; Iannone et al. 2009).

Field observations made at Quamash Prairie, North Fork Siuslaw, Devils Elbow, and Ruby Lake all indicated that competitive advantages given to native species can limit RCG invasion for up to 10 y after restoration. Three of these four sites implemented active control and competitive strategies (herbicide application, increased inundation, and/or competitive planting) to limit RCG cover. At Devils Elbow no active RCG control was implemented, yet native vegetation increased as RCG cover decreased over time (Figure 3). This may indicate that native vegetation is outcompeting RCG. Two possible explanations are (1) nutrients at the site were reduced by removing cows 5 y prior to reconnecting tidal hydrology, and (2) the lower elevations of the site may result in inundation near RCG tolerance levels giving a competitive advantage to native species (Borde et al. 2020).

In addition to elevation, inundation, nutrients, and salinity, several field observations indicated the potential for plant species competition as a control method: (1) Woody vegetation was established at most (7 of 9) field sites as a primary RCG control strategy, where elevation/hydrology allowed. This appeared to be a successful approach, although it was too early in most cases to be certain because woody vegetation was still becoming established. It appeared that RCG was shaded out where older plantings (8 or more years old) were observed: Kandoll Farm, North Fork Siuslaw, and Anderson Creek. More recent planting areas such as Colewort Creek appeared to be on a positive trajectory toward RCG exclusion. (2) Observational characterization of vegetation at the North Fork Siuslaw restoration site, generally confirmed vegetation plot findings by Brophy and Brown (2014), finding that three native non-woody plants were beginning to compete with RCG: lady fern (*Athyrium filix-femina* L.), black vetch (*Vicia nigricans* Hook. & Arn.), and cow parsnip (*Heracleum maximum* W. Bartram). These plants are all high-marsh species that can grow taller than RCG, with higher leaf cover, and their competition for light may be useful for future control applications. (3) RCG control prior to restoration, and seeding prior to RCG establishment, seemed to have been a successful strategy at Ruby Lake, where tufted hairgrass (*Deschampsia cespitosa* L.) was established, and RCG invasion was avoided for at least 2 y after restoration as reported by the restoration project manager. (4) The nontidal restoration effort at Quamash Prairie was successful in controlling RCG through prior chemical treatment, intensive seeding and planting of diverse emergent native species, and ongoing maintenance control of new invasions. (5) A thatch containing the seed heads of slough sedge (*Carex obnupta* L.H. Bailey) and small-fruited bulrush (*Scirpus microcarpus* J. Presl & C. Presl), placed at the time of restoration, precluded the establishment of RCG at Anderson Creek in treated vs. untreated areas.

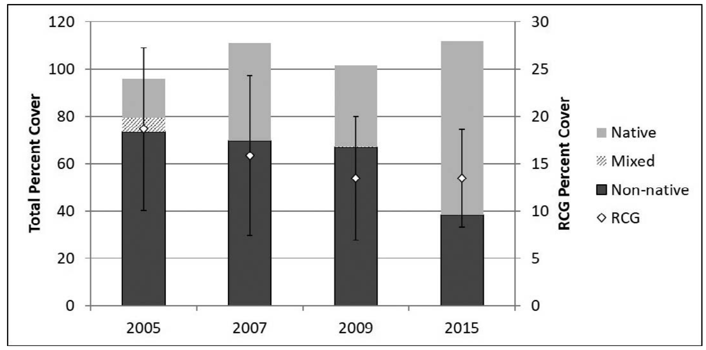

Figure 3.—Estimated average percent cover of native and nonnative species, including reed canarygrass (with standard error), post-restoration at the Devils Elbow site between 2005 and 2015.

Overall, environmental conditions providing competitive advantage to native species have the potential to increase restoration potential. Competition for space, limited nutrient availability, increased shade, and prolonged inundation all create environmental conditions shown to inhibit RCG establishment and growth.

Control

Manipulation of Environmental Conditions: Creating unfavorable environmental conditions for RCG invasion means manipulating one or more of four factors (Table 2). Restoration practitioners confirmed that RCG control using long-term inundation by water control structures at these tidal wetlands is not feasible or ecologically desirable, although it has been effective behind levees in the LCRE and elsewhere. However, control by scraping down to a land surface elevation below the inundation tolerance has been successful in a few cases (Figure 4C). Uncertainty remains about what will happen as sediment accretes at these sites, and their elevation approaches that suitable for RCG, i.e., whether competition from earlier established native plants will be effective. Maurer et al (2003) found that influxes of sediment decreased microtopography, species richness, and canopy cover, and increased RCG competitiveness. Additionally, scrape-down produces materials that require disposal, which presents both ecological and practical considerations.

Lindig-Cisneros and Zedler (2002) identified canopy complexity as a factor for light penetration and understory composition. In the Pacific Northwest, control using woody vegetation for overstory shade is a core strategy for RCG control (Figure 4E; Latterell et al. 2014), with mounds sometimes used to elevate trees and shrubs to suitable hydrologic conditions (Figure 4F; Diefenderfer et al. 2018). This approach has been successful, both according to the literature (Supplemental Table

Table 2.—Methods of reed canarygrass control by manipulation of environmental conditions, derived from literature review, practitioner interviews, and field observations. Citations from the literature review are included as numbers[(a)] referencing summaries in Tables S1 and S2 in the Supplemental Information**.**

Factor	Literature review	Practitioner input[(b)]	Field observations
Shade	• Shading from native species, including woody species, can be effective in limiting RCG (18, 21). • Willow spacing of 2- and 4-foot is recommended to reduce RCG aboveground biomass (17). • Establishing a complex canopy can reduce RCG germination by impacting light penetration (19). • Storage and soaking willow species prior to planting can increase potential for success and ultimate shading of RCG (22).	• Plant woody vegetation for shade competition. • Some tree species, such as Oregon ash (*Fraxinus latifolia*), have open canopies and late leaf development resulting in shade that is not sufficient to reduce RCG cover. • Sitka willow (*Salix sitchensis*) stakes 0.75–1.0 inch diameter were the most cost-effective size for establishing woody cover in areas dominated by RCG. Smaller stakes were cheaper but had lower cover and survival. Larger (1–2 inch) resulted in higher cover and better survival but cost more than the benefit (Hartema et al. 2015).	• When Hooker willow (*S. hookeriana* Hook.) and Sitka willow were planted, a very dense native understory common jewelweed (*Impatiens capensis,* Meerb.) established (Kandoll Farm). • Short woody species with a high density of stems are more effective than tall species (e.g., Pacific willow (*S. lasiandra*) and Oregon ash) in shading out RCG. • Larger patches with less relative light penetration from edges results in decreased RCG cover.
Inundation	• RCG seedling survival spanned a wide range of hydrologic regimes, however survival and biomass production were reduced at higher inundation (6, 21). • Increased inundation gave competitive advantage to native sedge and willows; increased inundation reduced carbon gain in RCG and slowed growth (7, 12).	• Excavation is conducted to increase inundation beyond RCG tolerance. • Mounds are used to decrease inundation and allow establishment of woody species. • Water control structures to maintain 2 feet of water for several months starting in February can prevent germination and spread. • Beaver "starter" structures (Wheaton et al. 2019) have been implemented to encourage natural water ponding and reduce RCG. Results have been mixed to date due to limited use of the structures despite active presence of beavers.	• Mounds that reduce inundation are effective in establishing woody vegetation cover and lower RCG cover (Drift Creek, Kandoll Farm, and Marietta Slough). • Excavation can increase inundation and reduce RCG cover (Ruby Lake). Resulting species composition depends on the amount of inundation. • Small differences in elevation and inundation can make a difference in RCG vs. native cover. Native cover increased at Devils Elbow as elevations approached RCG inundation limits.
Nutrients	• Woody material treatments reduced soil nitrogen (N) (26) but was not as effective as competition in reducing RCG (10, 11). Activated carbon to lower N may reduce community vulnerability to invasion (32). • RCG shoot growth stimulated by phosphorous rather than N; conditions of lower dissolved oxygen and higher organic matter supported RCG (13). • Positive relationship with RCG and nutrients, including total inorganic N, Ca, and cation exchange capacity in soils (20, 21). Reduced N can increase competitive advantage of *Carex* spp. (26). • Small-fruited bulrush may be able to compete with RCG at moderately high N levels (S9).	• Practitioners did not describe any nutrient strategies. One practitioner speculated about nutrient inputs and RCG cover related to livestock grazing prior to restoration: that allowing a pastured area to be fallow for a number of years prior to restoration may lower nutrient levels and give natives a competitive advantage based on a comparison of two sites (Devils Elbow and Kandoll Farm).	• Differences in RCG cover were noted between sites with different livestock histories, but attribution to nutrients could not be made.
Competition	• Control of RCG and planting (particularly for low efficiency/less competitive guilds) is critical early in the restoration process (1, 11). • Seeding increased species richness, but not enough to compete with RCG (8). • Cover crop reduced RCG establishment, but also other desired species. Select desired species with lower light requirements than RCG (10, 11, 25). • Even very low RCG seed density within a native community can result in RCG establishment (28). • Removing RCG biomass and sediment to access the native seed bank increases native species richness for a period of time (34).	• Planting using multiple methods (e.g., seed, plugs, bare root, pots) may be more effective than single methods. • Woody species establishment is generally effective at outcompeting RCG. • It is possible to have ~70% survival of shrub and tree plantings, while RCG cover is >90%. • Seeding competitive grass species can be effective, including tufted hairgrass, slough grass, bent grass, or turf-forming varieties of red fescue.	• Seeding of tufted hairgrass at Ruby Lake resulted in excluding RCG colonization. • Native species cover increases approaching the lower elevation limits for RCG based on soil moisture tolerance.

(a) Literature sources:
1 Aronson and Galatowitsch 2008
6 Fraser and Karnezis 2005
7 He et al. 2011
8 Healey and Zedler 2010
10 Iannone and Galatowitsch 2008
11 Iannone et al. 2008
12 Jenkins et al. 2008
13 Katagiri et al. 2011
17 Kim et al. 2006
18 Lavergne and Molofsky 2006
19 Lindig-Cisneros and Zedler 2002
20 Martina and von Ende 2008
21 Maurer and Zedler 2002
22 Miller-Adamany et al. 2017
25 Perry and Galatowitsch 2006
26 Perry et al. 2004
28 Reinhardt and Galatowitsch 2008
32 Uddin et al. 2020
34 Winikoff et al. 2020
S9 Seebacher 2008

(b) Unpublished literature such as workshop proceedings and field reports, referred to by practitioners, is incorporated in this column.

Figure 4.—Reed canarygrass control methods: (A) backpack sprayer, (B) wick applicator, (C) lower elevation (scrape-down), (D) removal of the rhizome mat and surface roughening, providing microtopography pre-restoration (discing), (E) shading, and (F) higher elevation (mounds; photo taken at high tide to clearly show elevated areas).

S1) and in practice (Table 2). Overstory shading, though, may not always be effective for maintaining a diverse understory, depending on specific growth characteristics of the overstory. For example, at Marietta Slough the tall growth habit of Pacific willow provided less shade compared to shrubby willow species (e.g., Scouler willow [*S. scouleriana*] and Sitka willow [*S. sitchensis*]). Similarly, practitioners at the Sauvie Island North Unit sites observed RCG persisting under a canopy of Oregon ash (*Fraxinus latifolia*), which has a tall growth habit and does not leaf out until late in the spring, limiting shade during the critical RCG growth period.

Competition from native species can reduce RCG cover, however reestablishment of native communities can be challenging when RCG is already established. Iannone et al (2008) found that reducing nutrient availability, often impractical in wetland environments, is less important than the rapid establishment of native perennial communities to prevent RCG invasion on restoration sites. Dense native plantings occupying every available growing space, including those vacated by RCG through control measures, can provide a means of outcompeting RCG (Maurer et al. 2003; Annen 2011). Pre-restoration planting is another method to provide competition prior to RCG establishment. The only known example of native planting prior to levee breaching in the LCRE was at Otter Point, which was planted with woody and herbaceous species a year in advance of the restoration actions. While the plants survived, irrigation was needed to maintain the plants prior to restoring the wetland hydrologic regime.

The ability of native plant species to compete with RCG in tidal environments has not been formally tested in the LCRE, but as discussed previously, we observed several examples in our study where native species were competing with or excluding RCG. Tufted hairgrass precluded the establishment of RCG when heavily seeded immediately following restoration. Other species have the potential to outcompete RCG at the lower end of its elevation range, when the species is reaching its inundation threshold, including nodding beggarticks (*Bidens cernua* L.), rice cutgrass (*Leersia oryzoides* L.), and small-fruited bulrush.

Active Control Methods: Active management of RCG in tidal wetlands is limited by regular inundation; therefore, any control strategy employed needs to be evaluated based on considerations related to site-specific conditions and scale. Burning, discing, mowing, and herbicide application (Figure 4A, B, D), strategies identified for seasonally inundated wetlands, are much more difficult to employ on a multi-acre scale during short windows of low tidal inundation (Table 3). For chemical control, glyphosate remains a "go-to" product, but grass-specific selective products remain to be tested in tidally influenced emergent wetlands. In unstructured trials and in cited literature, glyphosate has achieved control of RCG over the short term; however, without providing substantial competition or continued maintenance, RCG reinvades within several years. Based on qualitative observations at Kandoll Farm, a single post-emergent herbicide application initially reduced RCG cover with a corresponding increase in native species cover (primarily nodding beggarticks), yet 3 y after application no significant long-term impact on monocultural RCG was apparent. Additional applications, coupled with seeding or planting, are likely necessary for RCG to be controlled. The timing of herbicide application may assist in reducing RCG cover while not

Table 3.—Active methods of reed canarygrass control derived from literature review and practitioner interviews. Citations from the literature review are included as numbers[(a)] referencing summaries in Tables S1 and S2 in the Supplemental Information**.**

Factor	Literature review	Practitioner input[(b)]
Herbicide application	• Various herbicide combinations, rates, and timing reduced RCG cover with some efficacy (2, 5, 27, 30, S3). • RCG returned after herbicide application ended (2, 5, 8, 27).	• Limited success with spraying and viewed as a "never ending battle." • Limited short-term effects of spraying observed (Kandoll); coupled planting and longer-term management needed. This was the only field observation of active methods in this study.
Mowing	• Effective when combined with herbicide application (18, 24).	• Only effective when combined with herbicide application.
Burning	• A single early season burn failed to reduce RCG cover, shoot or root biomass, and enable native establishment (5). • Fire reduced thatch but allowed both seeded species and RCG to establish (8). • Spring burning did not reduce RCG biomass but did reduce seedbank (27).	• Deemed impracticable in tidal environments. No practitioners had implemented or expressed awareness of burning in tidal wetlands in the PNW.
Grazing	• Targeted livestock grazing and short-term exclusion may help control RCG dominance (15, S6).	• Grazing is employed by some land managers of nontidal wetlands as part of biomass control strategy and not specifically for RCG control.

(a) Literature sources:
2 Bahm et al. 2014
5 Foster and Wetzel 2005
8 Healey and Zedler 2010
15 Kidd and Yeakley 2015
18 Lavergne and Molofsky 2006
24 Paveglio and Kilbride 2000
27 Reinhardt and Galatowitsch 2006
30 Thomsen et al. 2012
S3 Annen et al. 2005
S6 Kleppel et al. 2011
(b) Unpublished literature such as workshop proceedings and field reports, referred to by practitioners, is incorporated in this column.

significantly impacting native species richness, because RCG often emerges before many native wetland species (Clark and Thomsen 2020), although application may be limited by late winter and spring water levels (Simpson 2009). Toxicity to mammals and aquatic life is also an outstanding concern (Landrigan et al. 2018; Portier 2020) and caution should be exercised to minimize exposure to humans, animals, and nontarget plants. Methods for minimizing undesired effects from herbicide include using targeted application methods (Figure 4A, B) under ideal conditions (i.e., low wind and no inundation), minimizing application frequency, and use of selective herbicides as allowed by regulation to target specific species (Annen et al. 2005; Annen 2010).

A number of studies recommend applying multiple methods in combination, similar to the findings of Lavergne and Molofsky (2006), with modifications necessary for implementation in tidal ecosystems. Common integrated approaches include chemical (spray or wick application of glyphosate or other herbicide), mechanical (mowing and discing), hydrologic manipulations (scraping, mounding, or water retention structures), and planting or seeding the growing space vacated by RCG (Table 4). In tidal systems, discing and water retention structures are not feasible, however integrating these methods pre-restoration may provide a benefit post-restoration. Integrated methods are typically implemented over 1–2 y, however longer management may be necessary for effective control. In the field, we observed two instances where multiple years of treatment led to RCG control due to a strong understanding of site conditions by wetland managers. These cases used a combination of physical and chemical site preparation, establishment of strong native plant communities filling belowground and aboveground growing space, and low-level maintenance consistently implemented over time (Table 4). Although neither of these cases were observed on tidal restoration sites, they were found at higher elevations in the Willamette Valley and at the head of tide in Coos Bay, Oregon. At this latter site manual, not chemical, treatments were used.

Practical Considerations

A number of practical considerations were identified in this study, primarily through outreach to practitioners (Box 2). Practitioners are challenged by difficult site conditions, funding limitations, and regulatory requirements, while focusing on process-based restoration strategies (Diefenderfer et al. 2021). Herbicide as a control method is challenging in tidal environments due to access, regular inundation, and regulatory constraints. Therefore, not many instances of herbicide application were included in the field observations.

Timing is another consideration for effective RCG control. Field observations and literature indicate that providing competitive advantage to native species has the potential to limit RCG invasion especially when established during the restoration process or even prior to restoration if RCG is already present. This strategy can be combined with RCG control to prevent its invasion and establishment. Control efforts post-restoration and after invasion will require a larger level of effort and be complicated by the tidal regime, difficult access, RCG seed delivery, and wetland regulatory concerns. These considerations require advance planning and resource allocation over a number of years to effectively address RCG. Little testing has been done in the LCRE or other tidal emergent wetland environments in the Pacific Northwest regarding the effectiveness and relative value of pre- and post-restoration control.

Taken together, the literature and the experiences of practitioners strongly indicated that long-term control strategies are required to limit RCG invasion, and specifically to allow

Table 4.—Combinations of active and environmental-manipulation methods for reed canarygrass control were recommended by findings from the literature review and practitioner interviews. Citations from the literature review are included as numbers[(a)] referencing summaries in Tables S1 and S2 in the Supplemental Information**.**

Factor	Literature review	Practitioner input[(b)]
Herbicide and planting	• Herbicide control was combined with planting for increased control over single methods (i.e. control only) (2, 8, 33, S2). • Fall site clearing, scarification, and application of pre-emergent herbicide delayed emergence of RCG. Summer application of a graminicide or glyphosate reduced cover from rhizomes. Native herbaceous and woody cover increased by the third year (30).	• Multi-year site preparation with chemical control then planting native communities filling all growing space followed by long-term low-level maintenance has been successful at Quamash Prairie.
Herbicide and plowing/discing	• Fall herbicide combined with plowing had the highest woody species establishment success (9). • Grass-specific herbicide was more effective when combined with discing (S1).	• Herbicide and discing on a 3–5 year rotation was utilized at nontidal sites.
Herbicide, mowing/fire, and planting	• Mowing in early summer and fall, application of glyphosate in the late fall, then planting a diverse mix of aggressive native species with follow-up spraying of new RCG growth with a grass-specific herbicide was found to be effective in reducing RCG cover and allowing native establishment (S7). • Mowing in fall, spring application of glyphosate, and planting three native species resulted in reduced RCG and higher survival and plant height of planted species compared to mowing alone. Long-term effects are unknown (S5). • Combined site treatments of herbicide and fire to reduce thatch, with seeding/planting demonstrated potential for native establishment but required intensive maintenance to control RCG re-establishment. Plantings accelerated diversity (S4, S10).	• Combining mowing and herbicide application for a minimum of 2 y then planting woody vegetation with continued maintenance proved effective at nontidal sites. • Where RCG was not previously established, large-scale invasion was prevented with manual control (hand pulling), mechanized cutting, spot application of herbicide, and densely planted and seeded emergent plants, bulrush, and slough sedge (Anderson Creek; Cornu 2005).
Water level manipulation, herbicide, and discing	• A combination of winter/spring water level maintenance, discing, and herbicide showed the highest effectiveness and native species richness, particularly with second-year follow up treatment (16, 18, 24).	

(a) Literature sources:
2 Bahm et al. 2014
8 Healey and Zedler 2010
9 Hovick and Reinartz 2007
16 Kilbride and Paveglio 1999
18 Lavergne and Molofsky 2006
24 Paveglio and Kilbride 2000
30 Thomsen et al. 2012
33 Wilcox et al. 2007
S1 Annen 2010
S2 Annen 2011
S4 Bohnen and Galatowitsch 2005
S5 Clark et al. 2020
S7 Kurtz 2003
S10 Simpson 2009
(b) Unpublished literature such as workshop proceedings and field reports, referred to by practitioners, is incorporated in this column.

native vegetation communities to become well established. Failure to do long-term control and facilitate native species establishment leads to the common experience of having RCG become well established and dominant in marsh habitats. RCG control studies described in the literature range in duration from 1 to 3 y, with poor to mixed results in terms of RCG control effectiveness. Based on this, control strategies likely need to be implemented for 5 or more years to be effective.

The literature review indicated that control strategies will be most effective if employed on a system or watershed scale, because seed and propagules spread through aquatic connectivity within watersheds (Coops et al. 1995; Lavergne and Molofsky 2006). Yet, a system-scale approach is challenging in the context of a hydrologic reconnection program such as CEERP, given the opportunity for widespread seed distribution with tides and river flows inundating the 1468 km^2 floodplain (Jay et al. 2016). Practitioners advised that control must be implemented at the largest practicable scale—at minimum, the site scale.

Key Findings

This study bridges the gap between the available published literature and practitioners' place-based knowledge, through outreach and site observations in the Pacific Northwest. A synthesis of key findings is provided here with recommendations for further study. It is our hope that future work builds on this baseline to make available the type of RCG control strategies

Box 2.—Practical considerations for reed canarygrass control provided by practitioners in interviews.

- Regulations limit herbicide application in wetlands.
- Working in tidal environments is difficult (operability).
- Maintenance of water control structures and tide gates for RCG control is expensive, labor-intensive, and is typically inconsistent with process-based restoration.
- Benefits of RCG control may not outweigh the costs, particularly for salmon-centric goals.
- Reduced RCG cover is less frequently a restoration performance criterion because it is viewed as unrealistic (Latterell et al. 2014; Hartema and Latterell 2015).
- RCG best management practices have been described for nontidal areas of the Pacific Northwest, but not tidal areas (e.g., Silver and Eyestone 2015).
- Short funding cycle limitations impact pre-restoration and/or long-term maintenance control. (Note: Three peer-reviewed articles found that long-term RCG control is required for success, see Supplemental Table S1: 1, 18, 34).

needed to ensure integrity and function of important habitats, particularly intertidal marsh systems.

Most importantly, we found that an integrated, long-term approach to control RCG is required. Successful eradication of RCG involved the use of multiple methods throughout the restoration process from site preparation pre-restoration to iterative planting and control measures post-restoration (Annen 2011). Most control studies showed that within 3 y after control cessation, RCG cover had returned to pre-treatment conditions and therefore investments in continued control or maintenance are required (Bohnen and Galatowitsch 2005, Lavergne and Molofsky 2006, Wilcox et al. 2007, Aronson and Galatowitsch 2008).

Recommendations and Remaining Uncertainties

When planning for RCG control as part of a restoration project, we recommend combining multiple methods (such as chemical control and planting native species) over multiple years to achieve cumulative beneficial effects. In tidal sites, comprehensive site preparation prior to restoration may be more ecologically effective and cost efficient than control efforts after hydrologic reconnection restoration actions. We also recommend planting or seeding strong competitors, such as small-fruited bulrush, rice cutgrass, tufted hairgrass, nodding beggartick, Lyngbye's sedge (*Carex lyngbyei* Hornem.), or slough sedge, to fill aboveground and belowground growing space. We recommend selecting locally appropriate species that develop a complex, multi-layered canopy and considering the taller competitors for light mentioned herein. Planting woody species to shade RCG can be an effective control method, however we noted that the effects of woody species on light availability change as certain species get taller (e.g., Pacific willow and Oregon ash) and with changes in canopy spacing and understory development. It is important that restoration planners consider the potential loss of mid and high marsh resulting from control methods that are focused on either establishing high elevations for woody species establishment or low elevations to increase inundation, thereby losing the native marsh plant communities in between. Finally, when possible, restoration practitioners should consider control at the largest possible scale, and even at the watershed scale, if feasible.

This study showed that proven methods have not been established to control the invasive plant RCG as part of restoration of tidal freshwater wetlands in the LCRE. However, the available information does indicate the potential for integrated strategies to succeed. Standardized, evidence-based methods are needed to build support among practitioners and funders to attempt RCG control in these systems (Zedler 2005). In the absence of proven methods in tidal wetlands, our final recommendation is that formal field scale experiments be conducted over a longer time period (i.e., 5 y) to answer the following questions: (1) Is application of aquatic-approved herbicide required in spring and fall or is a single season application sufficient? (2) Does the required frequency of herbicide application vary depending on the extent and cover of RCG establishment? (3) Does concurrent, competitive seeding with native plants improve the effectiveness of the long-term control strategy? (4) Does the effectiveness of the control method vary by elevation? Additional questions involve the effectiveness of various herbicides, including a grass-specific chemical such as Sethoxydim, using different seed application strategies to improve germination in tidal areas. The potential for multi-year pre-construction control with multiple control methods should also be evaluated. Such a study would assess the competitive ability of specific native species and evaluate specific hydrologic regime parameters and chemicals that appear to impact RCG growth and reproduction.

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