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Columbia Estuary Ecosystem Restoration Program: Restoration Design Challenges for Topographic Mounds, Channel Outlets, and Reed Canarygrass

Final Report

August 2016

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A Borde
I Sinks
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S Zimmerman

U.S. DEPARTMENT OF ENERGY

Prepared for the Bonneville Power Administration
as a Release issued under an
Intergovernmental Master Agreement
with the U.S. Department of Energy
Contract DE-AC05-76RL01830

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Pacific Northwest National Laboratory
Sequim, Washington 98382

[1] Pacific Northwest National Laboratory
[2] Columbia Land Trust

Preface

The Pacific Northwest National Laboratory (PNNL) conducted this research for the Bonneville Power Administration (BPA) (BPA Project No. 2002-077-00, Contract No. 56065-Release 7) in conjunction with the Columbia Land Trust (CLT) (BPA Project No. 2010-073-00). The work reported herein is a subset of the work conducted under these PNNL and CLT contracts. BPA's contracting officer's technical representative for the PNNL project was Chris Read (503-230-5321) and for the CLT project it was Anne Creason (503-230-3859). PNNL's project manager was Gary Johnson (503-417-7567) (PNNL Project No. 65387) and CLT's project manager was Ian Sinks (360-696-0131). The period of performance covered in this report is September 1, 2014 through August 31, 2015. The research on restoration design challenges reported herein was intended to provide Columbia Estuary Ecosystem Restoration Program restoration practitioners and managers with technical assessments relevant to on-the-ground implementation of restoration actions.

Suggested citation: Diefenderfer, HL, AB Borde, IA Sinks, VI Cullinan and SA Zimmerman. 2016. Columbia Estuary Ecosystem Restoration Program: Restoration Design Challenges for Topographic Mounds, Channel Outlets, and Reed Canarygrass. PNNL-24676, final report prepared for the Bonneville Power Administration, Portland, Oregon by the Pacific Northwest National Laboratory, Sequim, Washington and Columbia Land Trust, Vancouver, Washington.

Executive Summary

The purpose of this study was to provide science-based information to practitioners and managers of restoration projects in the Columbia Estuary Ecosystem Restoration Program (CEERP) regarding aspects of restoration techniques that currently pose known challenges and uncertainties. The CEERP is a program of the Bonneville Power Administration (BPA) and the U.S. Army Corps of Engineers (Corps), Portland District, in collaboration with the National Marine Fisheries Service and five estuary sponsors implementing restoration. The estuary sponsors are the Columbia Land Trust, Columbia River Estuary Study Taskforce, Cowlitz Tribe, Lower Columbia Estuary Partnership, and Washington Department of Fish and Wildlife. The intended outcome of this research was to produce tangible products that these practitioners and their partners can apply to implement better restoration projects.

Scope of Research

The scope of the research conducted during federal fiscal year 2015 included three aspects of hydrologic reconnection design that were selected based on available scientific information and feedback from restoration practitioners during project reviews: the design of mounds (also called hummocks, peninsulas, or berms); the control of reed canarygrass (*Phalaris arundinaceae*); and aspects of channel network design related to habitat connectivity for juvenile salmonids. At the outset of the study, we summarized the three challenge modules and conceptualized the challenge(s) associated with them as follows.

Mounds – Mounds or hummocks help defray costs of moving excavated material offsite and have been proposed in CEERP projects to provide topographic diversity with the potential to reduce the impacts of subsidence, accelerate the development of woody plant communities, control reed canarygrass, produce a plant community mosaic, and generally increase habitat complexity at the restoration site.

> *The design challenge is that science-based construction specifications for mounds (e.g., height, width, aspect, and slope) are not well established. What is the right balance between practical concerns and ecological function?*

Reed Canarygrass – Reducing the extent of invasive reed canarygrass in the extensive tidal freshwater region of the lower Columbia River and estuary (LCRE) is thought to facilitate establishment of native plant communities, improve food web dynamics, prevent floodplain armoring, allow passive channel formation, and avoid barriers to establishment of natural benthic communities. Concurrent research into reed canarygrass function is ongoing through BPA's Ecosystem Monitoring Program.

> *The design challenge is that science-based construction specifications for topography (e.g., elevation, slope) and specific biological control methods to prevent or eliminate reed canarygrass are not well established. What is the best way to achieve practical results and biological control in context of a tidal-fluvial system?*

Channel Networks – Optimal channel network design (e.g., density, number of outlets) results in establishment of natural channel-forming processes, increased fish access, improved hydrologic connectivity, and associated fluxes of nutrients and materials into and out of restored wetlands.

> *The design challenge is that science-based construction specifications for channel networks (e.g., number of outlets, extent and dimensions of excavation, passive versus active channel formation) are not well established for the tidal-fluvial system. What needs to be considered to optimize channel network design and achieve an unimpeded hydrologic regime for a given site and position in the LCRE?*

Two-Phased Research Approach

We approached this research in two phases: gathering and analyzing information, and synthesizing and reporting information. Both phases involved direct collaboration with CEERP restoration practitioners to sharpen the focus of the topic areas, share information, discuss ideas, and examine conditions at CEERP restoration sites. The first phase began with outreach to the estuary sponsors to explain the purpose of the project to their restoration practitioners, discuss key environmental and design considerations for the three topics, and identify potential restoration project sites for field examination. It also involved outreach to practitioners with experience in the three restoration design challenges in Puget Sound and the outer coast to seek insights, unpublished reports, and help in identifying the earliest hydrological reconnection projects conducted in tidal areas in the Pacific Northwest. This phase included systematic review of the literature and the compilation and development of targeted information from the earliest restoration sites in the LCRE, the outer coast, and Puget Sound with the cooperation and assistance of project proponents.

We found that a unique approach to data development and analysis was required for each restoration design challenge module. During the second phase, we collected and analyzed field data at 10 sites and analyzed available geographic information system (GIS) data. For field data collection, we were assisted by several organizations and departments in Oregon and Washington in identifying restoration sites of the greatest age with 1) mounds that may or may not have had plantings to control reed canarygrass, and/or 2) conditions that would provide information about active or passive reed canarygrass control and the lower limits of the species extent relative to hydrology and salinity. We synthesized findings from these tasks with information provided through discussions with restoration practitioners and restoration project reports and developed recommendations for the CEERP.

Challenge Modules

The mound challenge module consists of a relatively straightforward set of questions involving mostly physical design parameters, i.e., moisture and temperature constraints, with mostly biological response parameters, i.e. achievement of acceptable levels of planting success. We visited six sites with mounds, three on the LCRE, one on Puget Sound, and two on the outer coast. We recorded notes about observations, including vegetation establishment and herbivory, and took photographs to document site conditions and findings. On a subset of mounds at five sites, we measured elevation, height, soil temperature at 5 cm and 15 cm depths, and soil moisture at the 12 cm depth.

The reed canarygrass challenge module is more complex in that, in addition to environmental conditions for establishment, it involves control methods that include site design and other treatments such as herbicides. In general, the literature concludes that reed canarygrass simplifies habitat and has negative effects on ecological function, and practitioners mentioned that it also causes biological armoring that slows down the evolution of pilot channels. Therefore, control methods were a priority. We collected field data at one site on the Puget Sound and one site on the LCRE. In addition, we also made use of a large set of vegetation and elevation data previously collected by PNNL, and prepared a lookup table containing elevation limits on reed canarygrass at points throughout the LCRE as a restoration project planning tool.

The channel networks challenge module inherently had the largest number of metrics to consider as potential elements of this research, so we prioritized the metric voiced by four out of five estuary sponsors as leading in uncertainty during current restoration design processes: channel outlets. On this basis, we 1) examined recently released GIS data sets (the Ecosystem Classification and the Landscape Planning Framework) and developed methods for spatial data processing to summarize channel outlet counts and other features of reference wetlands within LCRE reaches, with the aim of providing a lookup table for each hydrogeomorphic reach, discriminating between wetlands on islands and the mainland; 2) tested the null hypotheses of no difference in basic tidal channel network descriptors between reaches, and no difference between wetlands located on the mainland and the islands of any given reach; and 3) developed linear regression models to the extent warranted by the existing data for wetland channel perimeter, wetland channel area, and the number of wetland channel outlets, all as a function of wetland area. Seventy-two linear regressions were performed, 36 of which are reported in detail and 5 of which provide good models.

Research Findings

Mounds. All findings from field work on mounds in this study must be interpreted in light of the fact that sampling occurred in the summer of 2015 at or near midday and that ambient air temperatures were very high relative to historical averages and trends. Based on these data, we concluded that statistical results strongly suggest that soil moisture in mounds can stratify. Statistical analysis of temperature was less conclusive, though it appears to be positively correlated with elevation, and mound aspect appeared to be less important to temperature and moisture than hypothesized. In some cases, qualitatively observed differences in plant mortality and the vigor of plantings appeared to correspond to differences in soil organic matter and/or soil moisture. In regard to mound size, the potential advantages to larger mounds include less edge and more canopy cover, i.e., environments more like interior woody plant communities. In contrast, there are also advantages to building a “sea” of small mounds; based on microtopography these would appear to better mimic the hummocky environment typical of forested wetlands, and may get more moisture benefit from tides in summer drought months. However, as a matter of fact, the sizes of mounds observed in restoration designs in the LCRE are often in between those two extremes.

Several implications for restoration practice in mound design emerge from these findings. The fact that soil moisture is negatively correlated with elevation reinforces the importance of relative vertical position in planting plans. Practitioners may wish to evaluate the importance of statistical results on soil moisture relative to tolerances of locally important native plants and plant associations, using the hydrologic regime and elevation data as the design basis. Findings in regard to moisture and aspect indicate that considering aspect *per se* is not necessary; light may be a more important feature but it was not examined in this study. Findings on plant vigor and success emphasize the importance of considering the source of mound material, whether it is from the bottom of a slough or the topmost layer of a floodplain, especially regarding organic matter content. If possible, it is desirable to place topsoil at the top of mounds while considering the potential for a weedy seed bed, which indicates perhaps implementing an intervening year of control to limit weed seeds before topsoil is moved to the top of mounds and hydrology is reconnected. Additional weed control may be needed in subsequent years. Finally, project goals will lead to different mound designs; e.g., for forested wetland goals, shading out reed canarygrass could be done by designing many small mounds at very close density to mimic forested wetland microtopography and using spruce and woody plants to achieve shading.

Three remaining uncertainties stand out in regard to mounds: planting success and the establishment of a viable native plant community with multiple habitat benefits, under variable tidal-fluvial hydrologic regimes; the size, shape, and configuration of mounds; and the relative utility of mounds in different ecosystem settings (e.g., restored marsh, shrub-dominated wetland, and surge plain forested wetland). Additional research that could be informative to restoration practitioners would include developing real-world examples from the LCRE, where baseline planting data are collected along with environmental conditions such as soil moisture and temperature, and tracked over time. Evaluation of the statistical results on soil moisture relative to locally important native plants and plant associations, to produce a list of general planting recommendations for the different vertical positions on mounds, could also be done to provide a tool for practitioners. Moreover, additional research on the effects of river reach and water surface elevation could be considered.

Reed canarygrass. Key environmental controls are shade, salinity, and elevation. Elevation is important at both the low and high ends of the spectrum: 1) through a feedback with the hydrologic regime (ensuring enough inundation that it cannot grow), and 2) at the high end, through providing less-frequently inundated substrate on which woody plants can become established and shade the grass. High marsh in freshwater regions is the plant community at the greatest risk, past and present, from reed canarygrass in the LCRE. Reed canarygrass is an impediment to the cost-effective pilot-channel excavation method because the invasive RCG mat prevents channel evolution in response to flows. Available nutrients may be important to reed canarygrass performance (literature has shown a positive correlation with high nutrients).

Most available information about reed canarygrass control is from non-tidal environments. The relative performance of native plant species in competing with reed canarygrass in tidal environments has not been formally tested in the LCRE, but *Deschampsia cespitosa* and *Scirpus microcarpus* have shown the ability to compete. Woody vegetation has the potential to compete over the long term, but the native understory is variable. This may depend on shade; for example, the tree-like growth habit of *Salix lucida* and *Fraxinus latifolia* provides little shade compared to shrubby willow species and reed canarygrass can be well established under the canopy as it matures. The only known example of planting prior to breaching in the LCRE was planted a year ahead and led to success, although it also highlighted the possibility that irrigation may be needed. There are elements of success in native plant establishment on sites where combinations of land elevation and hydrology are allowing native plants to compete.

Control is most likely to succeed if implemented at a watershed scale because of the distribution of propagules throughout hydrologically connected systems. This is challenging in the context of a hydrologic reconnection program such as CEERP, and must be interpreted as the largest practicable scale, at minimum, the site scale. A number of studies recommend applying multiple methods in combination, and this is consistent with the only success story in the Columbia region that we encountered, although this was not in the LCRE. Available methods applicable in the LCRE are mechanical (mowing and discing), hydrologic (inundation), chemical (grass-specific or general), and biological competition (seeding and/or planting). The timing of method implementation is critical to its success but specific to regional environments (growing season, hydrologic regime, etc.), and little testing has been done for the LCRE or other tidal environments in the Pacific Northwest. For chemical control, glyphosate remains a "go-to" product and grass-specific selective products need to be tested in tidal environments. Burning is not a suitable tool in environments where native plants are not fire-adapted and therefore cannot recover and compete. No biological control method is available.

In regard to the policy context, we note that the majority of projects/sponsors do not have funding for post-restoration stewardship or maintenance. Thus, it is practical and less expensive in the long run to control reed canarygrass to the greatest extent possible during the restoration project's construction phase.

Channel outlets. We found that the variability of channel network properties in the LCRE both longitudinally (i.e., between river reaches) and laterally (i.e., between mainland and island wetlands) is substantial and in many cases statistically significant. While our original intention in summarizing the channel network characteristics for each reach was to provide a lookup table type functionality to support new-project planning, the variability indicates that it would be inappropriate to advise the general use of mean or median values of channel network features on a reach-by-reach basis as a guide for restoration project design. Coefficients of variation for the nine main features analyzed were >80% for all reaches (excluding reach G, $n = 2$) with few exceptions.

Relative to the hypotheses, multiple comparisons testing of *mainland* wetland channel networks for the eight hydrogeomorphic reaches showed that four parameters differed significantly by reach: channel outlets, channel area, channel perimeter, and number of outlets:wetland area. The multiple comparisons testing showed *island* channel perimeter:wetland area and channel area:wetland area were significantly different between reaches, while the number of outlets:wetland area versus reach was not. We compared channel networks of wetlands on islands and the mainland using channel area:wetland area, channel perimeter:wetland area, and number of channel outlets:wetland area and found significant differences for all three parameters for Reach B, mixed significant differences for Reach C, and no significant differences between islands and the mainland for Reach A. (Reaches are defined in Simenstad et al. 2011.)

The linear regression of channel area, channel perimeter, and the number of channel outlets as a function of wetland area (island area had the same results) by reach, distinguishing islands from mainland wetlands, produces very few good predictive models. In virtually all cases, the use of a common slope (i.e., for all reaches) in the model causes R^2 to drop below acceptable values, discouraging prospects for any single regression model using these parameters suitable for the LCRE. We identified only five predictive models for specific combinations of reach, island or mainland position, and the response variable—all in the lowest three reaches of the river. Channel perimeter emerged as a metric that can sometimes be predicted based on wetland area. Methodological differences may explain differences from published regional literature, i.e., our analysis had a high sample size (n = 306 reference wetlands in the LCRE), considered a large geographic area (the LCRE floodplain), discriminated mainland and island wetlands, and considered hydrogeomorphic reaches individually and as a group.

Based on these results, the approach currently used by practitioners, i.e., developing a reference model from historical information and reference sites, is likely to produce no worse a model for ecosystem restoration than would a regression model that includes any of the parameters we have tested to date. The five predictive models we developed could be consulted by practitioners in addition to the evidence used routinely, but they should not be viewed as prescriptive given the great variability in these metrics even between sites within the same reach. Also, reference information from islands should only be applied to mainland wetlands with care, and vice versa. In addition to the tidal-fluvial gradient in hydrologic regime and variability in geologic features, the landscape setting of restoration projects is important to the design of channel networks. It would be a mistake to calculate the number of potential channel outlets based on wetland area without considering the effective reduction in perimeter based on landscape setting, e.g., features such as the proximity of upland slopes and location of waterways relative to the wetland area.

The CEERP takes an ecosystem approach to restoration of salmon habitat in the LCRE, which has been translated into clear guidance for water levels but does not as yet provide specific guidance or quantification for channel network features. The emphasis on channel outlets is premised on habitat connectivity for salmon, an important value for habitat restored in the CEERP, but connectivity also plays a role in channel evolution. The quantitative design guidance available to date for such features in the LCRE, developed through applied geomorphology methods, covers very limited combinations of reaches, plant community types, and landscape settings. Available data indicate that it is likely that reasonable models for channel network features as a function of wetland area can be developed if vegetation type and inundation are included. Given that we developed four predictive regression models with channel perimeter this metric should be explored further as a dependent variable.

Recommendations

To improve restoration project design, we recommend the following:

Mounds
At a few sites, collect baseline planting data along with environmental conditions such as soil moisture and temperature, and track the data over time.
Evaluate the statistical results on soil moisture in this report relative to locally important native plants and plant

associations and produce a list of general planting recommendations for the different vertical positions on mounds.
Develop a material management decision framework for practitioners, which describes potential uses, ecological objectives, and design considerations for material generated from tidal wetland restoration work.
Develop a work plan to further investigate mound design for the LCRE, including planting design, mound morphology, and ecosystem setting. We anticipate this would include developing a conceptual model of the ecosystem function of mounds, and identifying and characterizing the types of features that occur naturally in the LCRE, e.g., bar and scroll, natural levee, alluvial fan, and tree fall, and their association with types of hydrology, geomorphology, and plant communities in reference conditions.
Reed Canarygrass
Combine multiple methods to achieve cumulative beneficial effects. Comprehensive site preparation prior to restoration may be more effective and cost-efficient than post-restoration control efforts.
When possible, consider control at the largest possible scale and, if feasible, at the watershed scale.
Plant or seed strong competitors to fill aboveground and belowground niches.
Remember that the effects of woody species on light change as plants grow.
Consider the potential loss of high marsh caused by methods establishing mostly high and low elevations.
Consider removing heavy nutrient sources at least 1 year in advance of construction.
Study the efficacy of methods for 1) integrating control in a restoration project, and 2) controlling reed canarygrass plants that have become established after restoration. Outcome: cost-benefit analysis of control methods/timing.
Integrate mechanical control, chemical control, and seeding in a blocked field study, e.g., including early and late-spring spraying, discing, seeding, grass-specific spraying, and planting of forbs. Outcome: LCRE reed canarygrass management protocol.
Verify whether findings on the competitiveness of reed canarygrass in the Midwest apply in the LCRE by conducting nutrient-enrichment studies in LCRE field settings. Outcome: recommendation on site preparation time to discourage establishment of a reed canarygrass monoculture.
Channel Outlets
Convene a workshop on channel network design approaches, involving restoration practitioners, and focusing on one or more example restoration sites.
Investigate regression models on a reach-specific basis, separating island and mainland wetlands, with emphasis on reaches in which a large number of restoration projects are likely to occur.
Implement the habitat connectivity index that was developed under the Corps' Salmon Benefits project.
Conduct further research into channel network design uncertainties to inform designs, including an examination of the literature on regulated rivers for trends in floodplain channel network response.

Next Step

The next step to invite near-term feedback from the estuary sponsors in regard to engagement with the findings of this research. We would like practitioners to consider whether a workshop focused on specific restoration projects as case studies of these three challenge modules would be beneficial. We think it might be useful to include projects currently in the design phase in a workshop to examine how the findings of this research may be applied and whether we can test some of the remaining uncertainties on the ground through variation of specific design elements.

Acknowledgments

This study originated under the direction of Ben Zelinsky and was subsequently directed by Jason Karnezis, Bonneville Power Administration. We sincerely thank the restoration scientists, managers and practitioners named herein for their generosity in discussions, site visits, and examination of project files. We appreciate the cooperation of Allan Whiting and Haley Wagoner, PC Trask and Associates, Inc., and Jim O’Connor and Charlie Cannon, U.S. Geological Survey, in supplying data from the Landscape Planning Framework and Ecosystem Classification databases, respectively. We are grateful for the assistance in literature review, formatting, and editing provided by S. Ennor, M. Parker, N. Sather, and C. Trostle.

Acronyms and Abbreviations

ANOSIM	analysis of similarity
ANOVA	analysis of variance
BPA	Bonneville Power Administration
CEERP	Columbia Estuary Ecosystem Restoration Program
CLT	Columbia Land Trust
cm	centimeter(s)
Corps	U.S. Army Corps of Engineers
COTR	Contracting Officer's Technical Representative
CR	Columbia River
CRD	Columbia River Datum
CREST	Columbia River Estuary Study Taskforce
CV	coefficient of variation
CWD	coarse woody debris
ERTG	Expert Regional Technical Group
ft	foot(feet)
GIS	geographic information systems
GPS	Global Positioning System
ha	hectare(s)
hr	hour(s)
IPM	Integrated Pest Management
LCRE	lower Columbia River and estuary
LiDAR	Light Detection And Ranging
m	meter(s)
m^2	square meter(s)
MDS	multidimensional scaling
N	nitrogen
NMFS	National Marine Fisheries Service
NAVD88	North American Vertical Datum of 1988
NOAA	National Oceanic and Atmospheric Administration
RCG	*Phalaris arundinaceae* (reed canarygrass)
ppt	parts per thousand
RCG	reed canarygrass
rkm	river kilometer
RTK	Real-Time Kinematic
USGS	U.S. Geological Survey
WDFW	Washington Department of Fish and Wildlife

Contents

Figures

Tables

1.0 Introduction

The purpose of this study was to provide science-based information to practitioners and managers of restoration projects in the Columbia Estuary Ecosystem Restoration Program (CEERP) regarding aspects of restoration techniques that currently pose known challenges and uncertainties. The CEERP is a program of the Bonneville Power Administration (BPA) and the U.S. Army Corps of Engineers (Corps), Portland District, in collaboration with the National Marine Fisheries Service and five estuary sponsors implementing restoration. The estuary sponsors are the Columbia Land Trust, Columbia River Estuary Study Taskforce, Cowlitz Tribe, Lower Columbia Estuary Partnership, and Washington Department of Fish and Wildlife. This report is not intended to be a manual presenting existing standard practices for restoration design in the CEERP. The scope of the research conducted during federal fiscal year 2015 included three specific challenges in the design of hydrologic reconnection projects that were prioritized based on available scientific information and feedback from restoration program managers and practitioners: the design of mounds (also called hummocks, peninsulas, or berms); the control of reed canarygrass (*Phalaris arundinaceae*); and aspects of channel network design related to habitat connectivity for juvenile salmonids (Figure 1).

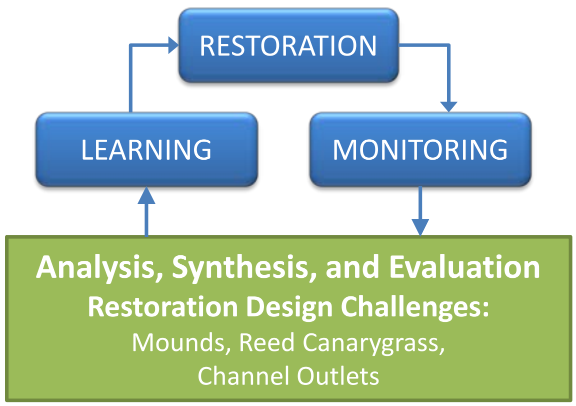

Figure 1. Using monitoring data, the Restoration Design Challenges work performs analysis, synthesis, and evaluation as the basis of learning in the CEERP process.

1.1 Challenge Modules

At the outset of the study, we summarized the three challenge modules and conceptualized the challenge(s) associated with them as follows.

Mounds – Mounds or hummocks help defray the costs of moving excavated material offsite and have been proposed in CEERP projects to provide topographic diversity with the potential to reduce the impacts of subsidence, accelerate the development of woody plant communities, control reed canarygrass, produce a plant community mosaic, and generally increase habitat complexity at the restoration site.

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> *The design challenge is that science-based construction specifications for topography (e.g., elevation, slope) and specific biological control methods to prevent or eliminate reed canarygrass are not well established. What is the best way to achieve practical results and biological control in context of a tidal-fluvial system?*

Channel Networks – Optimal channel network design (e.g., density, number of outlets[1]) results in establishment of natural channel-forming processes, increased fish access, improved hydrologic connectivity, and associated fluxes of nutrients and materials into and out of restored wetlands.

> *The design challenge is that science-based construction specifications for channel networks (e.g., number of outlets, extent and dimensions of excavation, passive versus active channel formation) are not well established for the tidal-fluvial system. What are the considerations to optimize channel network design and achieve an unimpeded hydrologic regime for a given site and position in the LCRE?*

1.2 General Approach

The intended outcome of this research is to produce tangible products that practitioners can apply to implement better restoration projects. We approached this research in two phases: gathering and analyzing information, and synthesizing and reporting information. Both phases involved direct collaboration with CEERP restoration practitioners to sharpen the focus of the topic areas, share information, discuss ideas, and examine conditions at CEERP restoration sites.

The first phase began with outreach to the estuary sponsors (Section 2.0) to explain the purpose of the project to their restoration practitioners, discuss key environmental and design considerations for the three topics, and identify potential restoration project sites for field examination. It also involved outreach to practitioners who have experience in the three restoration design challenges in Puget Sound and the outer coast to seek insights, unpublished reports, and help in identifying the earliest hydrological reconnection projects conducted in tidal areas in the Pacific Northwest. This phase included systematic review of the literature (Section 3.0) and the compilation and development of targeted information from the earliest restoration sites in the LCRE, the outer coast, and Puget Sound with the cooperation and assistance of project proponents.

The second phase began with developing the key elements of each challenge. The parameters defining the three modules are inherently different and we found that a unique approach to data development and analysis was required for each one (Section 4.0). In this phase we also analyzed data collected in the field, available geographic information system (GIS) data, and the results of the systematic literature review (Section 5.0). We synthesized findings from these tasks with information provided through discussions with restoration practitioners and restoration project reports and developed recommendations for the CEERP (Section 6.0). We conducted the recommended follow-up workshop for outreach to sponsors in February 2016 (Appendix A).

[1] This investigation assumes that dikes will not be removed in their entirety.

2.0 Outreach

Based on our own experience and a preliminary literature review, we developed a list of salient aspects of the restoration design challenges for discussion (Box 1). The purpose of this exercise was to generate the key elements for each challenge.

Box 1. Initial scoping of the key elements of the restoration design challenge modules.

1. **Topographic Mounds**
   a. Features (e.g., height, slope, material)
   b. Environmental Effects (e.g., soil temperature, time to plant establishment)
   c. Relevant Site Conditions for Planning (e.g., historical and existing topography, sediment regime, plant community)
   d. Practical Considerations (e.g., regulatory constraints, cost, constructability)
2. **Reed Canarygrass Control**
   a. Features (e.g., inundation/salinity tolerance, reproductive strategies)
   b. Environmental Effects of Control (e.g., plant community, food web, channel formation)
   c. Relevant Site Conditions for Planning (e.g., elevation, hydrologic regime, growth form)
   d. Practical Considerations (e.g., regulatory constraints on control, cost)
3. **Channel Network**
   a. Features (e.g., channel density, sinuosity, number of hydrologic connections, confluences)
   b. Environmental Effects (e.g., salmon habitat opportunity, flux)
   c. Relevant Site Conditions for Planning (e.g., historical/current channel network, tidal prism, levees; plant community; landscape position)
   d. Practical Considerations (e.g., local infrastructure)

2.1 BPA and Corps Estuary Sponsors

Initially, we conducted outreach for the purpose of informing practitioners about our objectives, sharpening the focus of the research to directly support current needs, and getting feedback from the CEERP estuary sponsors. We began the outreach process by sending each project the list of key aspects of the restoration design challenges (Box 1) to provide initial fodder for discussion. These practitioners referred us to many others who have been associated with their work or helped to inform it. We were able to hold nine discussions (Table 1), generally 1−1.5 hours long, but we were unable to contact all of the individuals referred by the estuary sponsors because of scope limitations.

Table 1. Outreach to BPA and Corps estuary sponsors for discussion of restoration sites.

Practitioner(s)	Organization	Restoration Sites
Ian Sinks	Columbia Land Trust*	Devil’s Elbow, Kandoll Farm, Mill Road
Matt Van Ess	Columbia River Estuary Study Taskforce*	Colewort Creek, Otter Point, Gnat Creek, Charnelle Fee, Dibble Point, South Tongue Point, North Unit Sauvie Island, Steamboat Slough
Rudy Salakory	Cowlitz Tribe*	Walluski-Youngs confluence, Clatskanie, Lower East Fork Lewis River

Table 1. (contd)

Practitioner(s)	Organization	Restoration Sites
Catherine Corbett, Jenni Dykstra, Marshall Johnson, Paul Kolp, Matt Schwartz	Lower Columbia Estuary Partnership*	Louisiana Swamp, Batwater Station, La Center Bottom, Horsetail Creek
Ashlee Rudolf, Donna Bighouse, Alex Uber	Washington Department of Fish and Wildlife*	Chinook Estuary
Allan Whiting	PC Trask and Associates, Inc.	Sauvie Is. North Unit (Ruby Lake, Deep Wigeon, Millionaire), Buckmire Slough, Gilbert River and Metro site (Multnomah Channel)
Mark Nebeker	Oregon Department of Fish and Wildlife, Sauvie Island Wildlife Area	Sauvie Island Wildlife Area, Ridgefield National Wildlife Refuge, Sturgeon Lake
Curt Mykut, Steve Liske, Randy Van Hoy, Austin Payne, Russ Lowgren	Ducks Unlimited: Vancouver, WA and San Francisco, CA	Sears Point (Sonoma County, CA), Cullinan Ranch (Napa R. delta), Nisqually National Wildlife Refuge
Lynn Cornelius	Friends of Ridgefield National Wildlife Refuge	Ridgefield National Wildlife Refuge
George Krall	Ash Creek Forest Management	Quamash (Gotter) Prairie

*BPA-Funded Estuary Sponsors. No asterisk = Partners Referred by Estuary Sponsors

2.2 Outer Coast and Puget Sound

In outreach to scientists and managers of restoration projects on the Puget Sound and outer coast (Table 2), we focused on identifying sites for field research on mounds and reed canarygrass. For the focus on reed canarygrass control, we restricted the scope to relevant tidal freshwater and fluvial sites because of the fact that reed canarygrass control is accomplished by salt in brackish estuarine sites. In the case of mounds, we also explored estuarine sites to gain information relevant to LCRE sites, with appropriate caveats related to differing physical processes in the tidal-fluvial gradient.

Table 2. Outreach regarding mounds and reed canarygrass on the Puget Sound and outer coast.

Practitioner(s)	Organization	Restoration Sites[(a)]
Josh Latterell	King County	Korn-Patterson, Cold Creek (both non-tidal), Green River (Pautzke)
Curtis Tanner	U.S. Fish and Wildlife Service	Spencer Island, Marietta Slough
Richard Kessler	Washington State Department of Fish and Wildlife	Marietta Slough
Peter Hummel	Anchor QEA, LLC	Emerald Downs mitigation (non-tidal)
Laura Brophy	Institute for Applied Ecology, Estuary Technical Group	North Fork Siuslaw, Pixieland, Anderson Creek, Bandon National Wildlife Refuge, Drift Creek
Craig Cornu	South Slough National Estuarine Research Reserve	Anderson Creek
Jill Silver	10,000 Years Institute	Olympic Peninsula (floodplains of the Hoh River, Queets River, and Clearwater River)

(a) In selecting sites at which to examine reed canarygrass conditions, both non-tidal and brackish areas were excluded because the central challenge for reed canarygrass control in the LCRE is tidal freshwater.

2.3 Synopsis

This synopsis includes all conversations we had with practitioners on the West Coast including the Columbia River, prior to site visits. Three of us (AB, HD, IS) participated in eight of nine discussions with Columbia River estuary sponsor practitioners and those they referred (Table 1), so we discussed and merged our notes to identify the areas of general agreement and areas where there were multiple views (Table 3). Contacts with the Puget Sound and outer coast practitioners were handled individually. We made an effort to identify themes that were voiced nearly universally by Columbia River estuary sponsor practitioners and their partners relative to the three challenge modules to help us prioritize further research (Metcalf et al. 2015). We summarize these in Table 3.

Table 3. Synopsis of discussions with restoration practitioners.

	Columbia River Practitioners	Other West Coast Practitioners
	Format: Discussion including 3 authors of this study and 1 or more practitioners, for 1−1.5 hr, covering all three restoration design challenges.	**Format: Phone call included 1 author of this study, seeking information about sites of interest in other regions, along with explanation and discussion of the design challenges.[(a)]**
Mounds		
Ecological Considerations	Appropriate for spruce swamp habitats and subsidence recovery; applicability less defined for other habitat areas. Used as a tool for creating a forested or shrub-dominated wetland edge, whether at the toe of a slope, a peninsula, or an isolated patch. Such edges can shade the riparian area and contribute wood over the long term. Loss of shrub and tree plantings on mounds to herbivory by beaver is common. The aspect (photosynthetically active radiation), slope, soils, and other environmental conditions on mounds are not considered in plant selection. Shape and landscape position are sometimes designed to mimic landforms such as natural levees, crevasse splays, or scroll bars, although size may differ from the reference forms. The concept of "topographic diversity" is used to describe the combination of habitat types derived from multiple elevations (marsh, shrub, and tree). When implemented as berms, consideration has been given to ensure placement in a depositional area of the floodplain.	Mounds are a natural feature of tidal forested wetlands not of tidal marshes. Mounds have been implemented on outer coast and Puget Sound projects for the purpose of recreating historically present topographic features, creating habitat near water, and planting. Mound-and-pool features have been constructed to mimic tree fall and root mass upheaval and increase vegetation diversity and shading. Small mound size can be limiting depending on hydrologic regime and configuration for shading. Mounds have been used to establish woody vegetation providing shade control of reed canarygrass (RCG). Herbivory on mounds is a common issue. Moisture has not been identified as limiting for woody vegetation establishment on mounds.

Table 3. (contd)

	Columbia River Practitioners	Other West Coast Practitioners
	Plant mortality and vigor on mounds is variable among sites and among the mounds within a single site, in some cases being very successful (this is associated with elevation and herbivory factors) and in others requiring repeated attempts to become established. It helps to adapt the planting plan following construction based on the final suite of mounds because engineering uncertainties in the volume of material to be disposed of mean this cannot be perfectly predicted in planning. Since a recent walk through by the Expert Regional Technical Group (ERTG), practitioners are thinking about shape; they are particularly considering mimicking nurse logs by designing long and narrow forms. Mounds are often seeded and mulched before planting, but the mounds themselves are often composed of inorganic mineral soils excavated from subsurface locations (i.e., channel excavated material). Avoiding compaction or smoothing of the surfaces of mounds is understood to be beneficial for water penetration and plant growth. Rough surfaces also provide greater microtopographic diversity. Resilience in response to sea-level rise was identified as a potential benefit of mound construction.	Woody species survival on mounds (436 small mounds 6 × 6 × 2 ft) can be high (76% cover), with RCG remaining dominant in the understory (72–92% cover). Recommendation: 1) mound minimum radius of 25 ft and relative height of 4 ft or more for highly saturated wetlands, where the mounds are likely to settle; and 2) taller willow stakes more densely planted that may better compete with RCG (Hartema and Latterell 2015a). Larger mounds are expected to provide less edge and higher elevation to promote greater diversity of woody species, higher survival, and lower cover of RCG. Red alder and black cottonwood plantings did not benefit from mulching, landscape fabric, or watering during year 1 summer months (Hartema and Latterell 2015b). Black cottonwood seed germination, seedling establishment, and seedling survival on alluvial spoils were improved by a watering regime during the summer months. Final results on the establishment of tree cover from this method are not yet available (Latterell et al. 2014)
Practical Considerations	Mounds are primarily used as an operational tool for disposing of material onsite. The 2-year flood elevation limit (an ERTG scoring criterion) and/or regulatory constraints that are not well defined for jurisdictional wetlands are used in engineering designs for the maximum heights of mounds. Design recommendations need to be explored to establish common understanding of these two elements (i.e., perhaps mounds need to be higher for ecological goals as opposed to habitat scoring or permitting issues). Size and configuration vary but all tend to be focused on practical considerations as well as ecological goals. A number of practitioners expressed a lack of understanding of what is best in terms of the configuration and pattern of mounds.	Mounds have been implemented on outer coast and Puget Sound projects for the purpose of using materials excavated on sites.

Table 3. (contd)

	Columbia River Practitioners	Other West Coast Practitioners
	The first choice for material that cannot be used in mounds is to deposit it on upland areas of the site. Local infrastructure is considered, e.g., transmission line locations relative to plantings. In rare cases, mounds are created by grading down upland area to restore wetland, and leaving behind higher-elevation islands of mature vegetation. In some cases, flooding and wet ground requires keeping equipment close to roads or levees. Some practitioners are using mounds in marsh habitats as a practical consideration as opposed to an ecological goal. "Taking liberty to insert spruce in a marsh for practical reasons." Some mounds have been constructed higher than design elevation to allow for settlement after restoration.	
General	Practitioners have many terms for mounds, some of which are also used in planning and design documents, including peninsula, hummock, and berm. The number of mounds planned is increasing on the Columbia, and more are planned than have previously been implemented. Seems to be a popular design element in the estuary at this point. Feedback loops: lowering a site to control RCG can produce material that needs disposal, i.e., in mounds; mounds can be densely planted to help control RCG.	In one outer coast project mounds are also termed "alluvial fans."
Reed Canarygrass		
Ecological Considerations	Elevation and hydrology drive vegetation community development. Competition belowground and aboveground (root space and sun space); i.e., planting with seed, plugs, bare root, pots. Perception that RCG expands in low flow years, in the tidal river	It is possible to have ~70% survival of shrub and tree plantings intended to control RCG, while RCG cover is >90%. Large (1- to 2-inch diameter) Sitka willow (*Salix sitchensis*) stakes resulted in higher cover and better survival when planted in established RCG areas than

Table 3. (contd)

	Columbia River Practitioners	Other West Coast Practitioners
		smaller stakes (0.25 – 0.5 in. or 0.75 – 1.0 in.) (Hartema et al. 2015).
Practical Considerations	Inability to spray herbicide is a limiting factor. Currently, discussions are focusing on potentially revisiting the Fish and Wildlife Implementation Plan Volume III (BPA 2003) in regard to the use of herbicide below ordinary high water levels in tidal areas.	Willow stakes that were 0.75 – 1.0 in. in diameter were the most cost-effective size for establishing woody cover in areas dominated by RCG. Smaller (0.25- to 0.5-in. diameter) were cheaper but had lower cover and survival. Larger (1- to 2-in. diameter) cost proportionally more than the benefit (Hartema et al., 2015). Practitioners from several locations stated that complete reed canarygrass control is unrealistic from a cost-benefit perspective. In some cases, reduced RCG cover is no longer a performance metric (Latterell et al. 2014); it was acknowledged that even if woody species thrived and control methods were implemented there could still be >50% cover of RCG and any performance metric less than that would be unrealistic (Hartema and Latterell 2015a).
Control Methods	Potential to control RCG exists if proper (multiple year) site preparation control (primarily chemical) is implemented, strong native plant communities are established filling all ecological niches, and low-level maintenance is implemented over time. Requires strong understanding of site conditions to be successful. Woody vegetation control strategy is a core approach, sometimes using mounds. Shading is often not effective to maintain native understory habitat. With few exceptions, most practitioners are not using mounds as a priority project element for RCG control. Water control/inundation of RCG is not feasible or effective in tidal restoration sites (exception is for scraped-down areas). It can be done in low swales behind water control structures, with 2 ft of water for several months starting in February, to prevent germination and spread; however, this method is most effective when done *entirely within levees*, water availability is subject to the vagaries of annual Columbia River managed flows, and RCG on the wetland	A distinction exists between restoration sites where RCG was and was not established prior to restoration. Mounds have been implemented on outer coast and Puget Sound projects for the purpose of planting, including woody plantings for RCG control. Integrated control methods with continued maintenance are required. Mow and herbicide application for a minimum of 2 years is generally required to establish woody vegetation. Consistent treatment needs to last at least 2–3 years. Then it is important to continue to address sources and vectors, to eliminate small source populations through a combination of manual and chemical treatments (Silver 2015).

Table 3. (contd)

	Columbia River Practitioners	Other West Coast Practitioners
	edges cannot be controlled. Combination approaches are sometimes used, e.g., mounds for shade, scrape-down to lower the floodplain, and beaver starter structures for inundation. Spraying and discing have had limited success and are a never-ending battle. With a 2 ft scrape-down followed by farming non-native crops it can be controlled in the Columbia River floodplain. Like tide gates, maintenance of water control structures is expensive and labor-intensive.	RCG control techniques generally only offer temporary control in emergent communities. An exception was Anderson Creek, where RCG was not previously established and large-scale invasion has been prevented with manual control (hand pulling), mechanized cutting, spot application of herbicide, and densely planted and seeded emergent plants, particularly bulrush (*Skirpus microcarpus*) and slough sedge (*Carex obnupta*) (Cornu 2005). Woody species establishment is generally effective at out-competing RCG. Seeding competitive grass species can be effective, including tufted hairgrass, slough grass, bent grass, or turf-forming varieties of red fescue. Best management practices have been described for non-tidal areas of the Pacific Northwest.
General	Practitioners almost universally felt that management of chronic populations is not feasible. There is little post-restoration management or control implemented by most practitioners, even though the potential to achieve historical species richness of the plant community at many sites is (or is anticipated to be) lost to RCG as a result.	At least one agency has found that research pays off and in particular there is high value in adding an experimental control to help assess the utility of planting-related techniques including those intended for RCG control. There is a lot of variability between practitioners, and standardized evidence-based methods are needed.
Channel Networks		
Ecological Considerations	Practitioners seek to restore site-specific historical channel networks because they can be discerned. They do not have a target for a certain number of openings, for example. Reference sites are used as analogues for restoration design if historical channels cannot be defined or if they cannot be restored for practical considerations. Some environmental controlling factors on the channel network are infrequently considered; e.g., the fetch over the Columbia River, embedded wood, and the effect of drainage ditches in the vicinity on flow conveyance.	

Table 3. (contd)

	Columbia River Practitioners	Other West Coast Practitioners
	Generally, the number of channel outlets present at restoration sites under historical conditions is lower than the number predicted by information from other coastal systems and the most tidal portions of the Columbia estuary.	
Practical Considerations	Practical considerations weigh heavily on what can be restored, particularly constraints such as local infrastructure and land uses, cost-benefit analysis, and the Columbia Estuary Ecosystem Restoration Program evaluation criteria.	
	Under Section 408 (Section 14 of the Rivers and Harbors Act of 1899, codified in 33 USC 408, and commonly referred to as "Section 408"), complete levee removal in some cases requires an Act of Congress and has not been pursued for that reason.	
	Practitioners have a level of caution regarding the applicability of findings in the Skagit River delta and other tidal environments by Greg Hood, ERTG, to the lower Columbia River, particularly the more fluvial reaches.	
Engineering Design	There is uncertainty about the "pilot-channel" method, in which a channel is cut to part of its planned length based on the assumption that flows will cut the remainder to the needed length over time.	Design guidelines for scroll bar and other geomorphological fluvial areas of the lower tidal Columbia River have not been promulgated; the only design guidelines are for hydrogeomorphic Reaches C, D, and F (ESA PWA, Ltd. and PC Trask & Assoc., Inc. 2011).
	Uncertainty about the pilot-channel method has ramifications for RCG control, because RCG can clog the channels and because of its mat-forming habit it stabilizes the banks and protects the floodplain surface, preventing or significantly delaying further channel cutting by flows.	
	One approach is to slightly undersize the predicted channel width and depth, and let the system determine the effective final morphology over time.	
	Some projects have been designed primarily to reconnect tidal flow without regard to historic channel network configuration due to physical constraints such as development along the lower portion of the floodplain.	

(a) Unpublished literature such as workshop proceedings and field reports, which practitioners referred us to, is cited in this section.

2.3.1 Mounds

For mounds, we heard that cost is the primary driver for their inclusion in engineering designs when upland disposal sites within the acquisition boundary are not available. The use of mounds in restoration projects on the LCRE is rapidly increasing because of regrading requirements associated with other elements of project design (i.e., channel excavation and levee removal). In designs, practitioners are thinking about mimicking the natural topography of the landscape to the extent possible, though size and configuration are also driven by the quantity of material requiring disposal. Practitioners are thinking about providing habitats with trees and shrubs in addition to emergent vegetation, and the possibility of shading marsh and channel areas. The primary design guideline used concerns elevation; engineers keep the mounds below the 2-year flood elevation and/or regulatory limits on jurisdictional wetlands. In other words, plans avoid converting wetland to upland, instead adding topographic variation to the wetland site. Biological components such as the effects of aspect and slope on moisture and radiation, soil type and organic matter content, are not currently considered in mound design, though in one case an effort was made to steepen slopes to minimize mid-elevation habitat suitable for reed canarygrass. Mound stability and slope considerations relative to the potential for erosion are elements of the engineering process. Planting success on mounds has been variable and often requires multiple years of planting for establishment.

2.3.2 Reed Canarygrass

For reed canarygrass, we heard that control using long-term inundation by water managed through control structures is not feasible or effective in tidal restoration sites (it has been effective behind levees). Control by scraping down to below the plant’s tolerance for inundation has been successful in a few cases but there is uncertainty about what will happen as sediment accretes at these sites and their elevation approaches that suitable for reed canarygrass, i.e., whether competition from earlier established native plants will be effective. Also, scrape-down produces more material that requires disposal. Control using woody vegetation is a core strategy, and mounds are sometimes used to elevate trees and shrubs to suitable hydrologic conditions. However, shading is not seen as effective for maintaining a diverse understory. While it is understood that salinity controls reed canarygrass, responses to passive reconnection with no reed canarygrass control in freshwater areas were variable and the combinations of controlling factors on site response were uncertain; it is clear that seed and propagules are distributed throughout the lower river and are made available to restoration through channels and flooding.

In rare cases, with a very strong understanding of site conditions and multiple years of treatment, reed canarygrass has been controlled with a combination of physical and chemical site preparation, establishment of strong native plant communities filling all ecological niches below- and aboveground, and low-level maintenance implemented over time. Though none of these cases were on Columbia River tidal restoration sites, they do exist at higher elevations in the Columbia River and we observed one at the head of tide in Coos Bay, Oregon, where manual not chemical treatments were used.

Some specific recommendations came from the remote coastal watersheds of the Olympic Peninsula, where there were limited control options due to constraints similar to those found in tidal areas, such as limitations for mowing, tilling, chemical use, or burning. Methods for control in this area were developed based on Early Detection/Rapid Response (ED/RR) and Integrated Pest Management (IPM) strategies, which are especially useful for areas where infestations are small. Many of the related areas are experiencing recent introductions and are therefore conducive to these methods; however, there is also potential utility for these methods at restoration sites and for continued eradication after large-scale treatment. Specific recommendations of the ED/RR method include the following:

- Implement 2–3 years of consistent treatment; the observed average time that seeds remain viable (Tu 2004).
- Target source locations of seed, especially those that can easily be transported by water or human activities.
- Use manual techniques for small clumps <0.5 m^2 including:
  - hand pulling, if all roots can be pulled
  - clapping and bagging all seed heads
  - removing all loose stem fragments from water bodies to avoid rooting and relocation
  - lifting stems off the ground to reduce vegetative spread.
- Use chemical treatment for larger areas, but use the lowest risk aquatically labeled herbicides such as glyphosate and imazapyr following these guidelines:
  - Application rates: 1–2% aquatically labeled surfactant and marker dye
  - Equipment: low-pressure backpack sprayer with slotted tips or hand sprayer
  - Timing: treat before flowering and seed production starts, but the most effective time is in the fall when plants are translocating nutrients to the rhizomes
  - Move target plants away from water and native vegetation prior to spraying to avoid harm.

2.3.3 Channel Networks

We heard that universally, practitioners seek to restore site-specific historical channel networks because they can be discerned from available information such as historical photos. They use information from reference sites as analogues when needed, if historical channels cannot be defined, or if they cannot be restored because of practical considerations. Many practical considerations weigh into channel network design, particularly local infrastructure, land uses, and stakeholder concerns such as flooding. Practitioners have a level of caution regarding the applicability of findings in other tidal environments to the lower Columbia River, particularly to the more fluvial upper reaches, where design guidelines are lacking. They are concerned in particular about the applicability of channel outlet findings from other regions or the lowermost tidally influenced Columbia River to projects on more fluvially dominated parts of the floodplain either lateral to the main stem on tributaries, or upriver. In project design, practitioners have typically found fewer channel outlets under historical conditions at restoration sites in LCRE freshwater than would be predicted by results from other coastal systems and the Columbia estuary proper.

3.0 Literature Review

We conducted a systematic review of the literature on reed canarygrass and mounds using Web of Science and EndNote tools. First we developed primary keyword search strings that produced the most relevant results. We used a variety of secondary search terms, and the graphs of these secondary terms provide an overview of the composition of topics. We assessed the resulting abstracts to ensure relevance and reviewed the full text of relevant papers for findings of interest to practitioners: key control methods and environmental conditions for reed canarygrass, and key environmental conditions for planting success on mounds. We developed annotated bibliographies for key references in the tables in this section, but copyright prohibits reprinting abstracts in this report; EndNote libraries for reed canarygrass and mounds are available upon request.

3.1 Mounds

Topographic heterogeneity in ecosystems has been shown to affect abiotic patterns, ecosystem processes, the distribution of organisms, competitive exclusion, animal habitat use, animal behavior, herbivory and other trophic interactions, development, and genetic and reproductive attributes (Larkin et al. 2006). For coastal restoration, the germination and establishment of plants is one of the most important criteria for any technique under consideration. In the most rigorous experimental study of mounds in the Pacific Northwest, mounding during restoration of Puget Sound lowlands has been shown to have positive, neutral, or negative effects by plant species (Ewing 2002). The following additional key points relevant to salt marshes are found in Larkin et al. (2006), which considers topographic heterogeneity in all ecosystems relative to restoration:

- Quantifying topographic heterogeneity must include vertical and horizontal measurements.
- Smoothly mounded higher-elevation islands made from dredged material at a San Diego Bay salt marsh restoration site caused salts to be wicked to the surface preventing plant establishment because of soil salinity.
- While intertidal wetland plant distribution is widely understood to be controlled by elevation, it is also influenced by proximity to tidal creeks (Zedler et al. 1999).
- Plants in swale and dune habitats with better drainage than poorly drained marshes respired aerobically in contrast to those in the lower habitats (Burdick and Mendelssohn 1987).
- At the hummock and hollow scale, seasonal mean water table position can explain the variability in methane emissions (Bubier et al. 1993).
- Plant species richness on hillocks in salt marshes of southeastern Denmark is higher (Vestergaard 1998).
- Microtopography can contribute to maintenance of non-equilibrium in salt marshes, favoring annual species (Tessier et al. 2002), and microtopography and flood disturbance are interacting on plant species (*ibid*., Pollock et al. 1998).
- The surface area of tussocks is positively correlated with species richness (Werner and Zedler 2002).
- Seed banks in sheltered micro-habitats in salt marshes are larger than other areas with greater sediment mobility (Inglis 2000).

Restoration was a required element of our search, thus limiting more general findings regarding environmental factors. The following primary search string yielded 75 records: restor* AND (tid* OR estuar* OR wetland) AND (mound* OR microtopograph* OR microform*). Key secondary keywords were soil/sediment, height/elevation, function, nutrient, retention and root (Figure 2). In summary, little evidence was available for estuarine and tidal freshwater wetland systems such as restoration areas of the CEERP. Some research on these systems focused on pools and tidal creeks not mounds (e.g., Larkin et al. 2008). However, many papers focused on microtopography (height, elevation) had relevant findings (Table 4). Microtopography was typically much finer than the mounds currently being designed on the LCRE, i.e., on the order of tussocks (Werner and Zedler 2002) or furrows of a smaller size that added roughness to the land surface. Additionally, some findings from other ecosystems indicated differences in environmental controls (e.g., moisture, temperature) based on aspect or elevation, and related effects on plantings.

It should be noted that information about depressions and tidal creeks, i.e., areas below the marsh plain, was not included in this literature review.

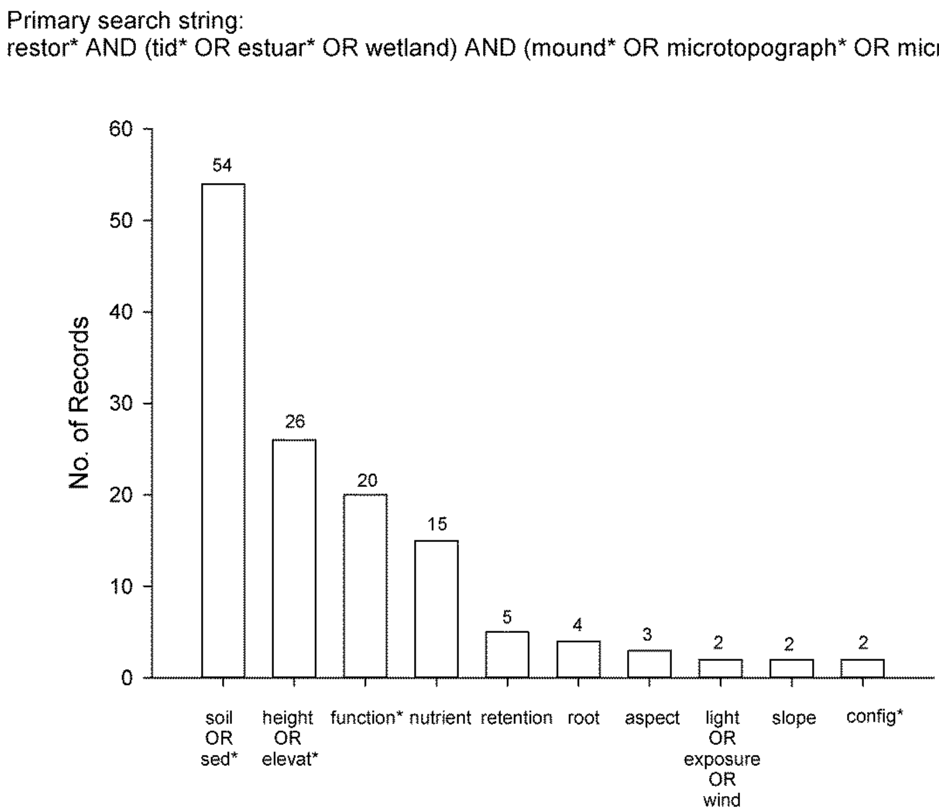


Figure 2. Composition of topics within the mounds primary search string. Topics identified through the Web of Science search tool include any information within the title, abstract, author keywords, and keywords.

Table 4. Review of the relevant literature on topographic features called mounds, hummocks, etc.

Publication					Mound Features		
Authors (Publication)	Year	Title	Region	Tidal	Method/Parameters	Finding	Notes
Jennifer Courtwright; Stuart E. G. Findlay (Wetlands 31(2):239-249)	2011	Effects of microtopography on hydrology, physicochemistry, and vegetation in a tidal swamp of the Hudson River	New York	Yes	Microtopography	Small-scale differences in elevation add complexity to inundation patterns. Hydrology significantly affects redox conditions, nutrient availability, oxygen penetration, and decomposition rates. Conditions affect herbaceous plant distribution.	
Amy J. Alsfeld Jacob L. Bowman; Amy Deller-Jacobs (Biological Conservation 142(2):247-255)	2009	Effects of woody debris, microtopography, and organic matter amendments on the biotic community of constructed depressional wetlands	Delaware	No	Efficacy of treatments for land surface ridges and furrows, coarse woody debris (CWD).	CWD enhanced biodiversity but more research is needed to determine the effects of microtopography (furrows and ridges) and organic matter amendments.	
Ariane Drouin; Diane Saint-Laurent; Luc Lavoie; Claudine Ouellet (Wetlands 31(6):1151-1164)	2011	High-precision elevation model to evaluate the spatial distribution of soil organic carbon in active floodplains	N. Vermont	No	Soil organic carbon	Frequent floods and vertical aggradation maintain soil in an immature state and deplete soil organic carbon levels.	
M. Peach; J. B. Zedler (Wetlands 26(2):322-335)	2006	How tussocks structure sedge meadow vegetation	Wisconsin	No	Light, temperature, and litter	Species richness positively correlated with tussock (mound) size but patterns varied with location. Height, surface area, and circumference were variables in the pattern. Tussocks enhance species richness by increasing the surface area, providing multiple micro-habitats, and undergoing seasonal changes in composition.	Tussocks 15−25 cm tall
G. L. Bruland; C. J. Richardson (Restoration Ecology 13(3):515-523)	2005	Hydrologic, edaphic, and vegetative responses to microtopographic reestablishment in a restored wetland	North Carolina	No	Hydrology, soils, and vegetation	Reestablishment of microtopography provided a variety of hydrologic, edaphic, and vegetative conditions at any given time and over the course of the growing season.	
James M. Doherty; Joy B. Zedler (Restoration Ecology 23(2):15-25)	2015	Increasing substrate heterogeneity as a bet-hedging strategy for restoring wetland vegetation	Wisconsin	No	Soil moisture and vegetation	Wetland surface heterogeneity builds vegetation resilience in variable or unpredictable environments. Study evaluated small (8 cm), medium (16 cm), and high (32 cm) mounds with and without organic amendments mimicking *Carex* tussocks. Study found lowest moisture on highest “mounds” with organics incorporated. Variable conditions over 2 years supported *Carex stricta* growth high or lower depending on conditions.	

Table 4. (contd)

Publication					Mound Features		
Authors (Publication)	Year	Title	Region	Tidal	Method/Parameters	Finding	Notes
G. Vivian-Smith (Journal of Ecology 85(1):71-82)	1997	Microtopographic heterogeneity and floristic diversity in experimental wetland communities	New Jersey	No	Microtopography	Small-scale microtopography (1×3 cm) produced significant differences in plant community structure. Many species showed distinct differences in microhabitat preferences (hummock or hollow).	
Nate Hough-Snee; A. Lexine Long; Lacey Jeroue; Kern Ewing (Ecological Engineering 37(11):1932-1936)	2011	Mounding alters environmental filters that drive plant community development in a novel grassland	Washington	No	Vegetation and physical environmental effects	Novel plant community analysis. Position on a given mound - mound top or intermound - drove both vegetation composition and soil moisture parameters 10 years after restoration.	Mound size: 40−70 cm high with base widths of 50−70 cm
Matthew E. Simmons; X. Ben Wu; Steven G. Whisenant (Restoration Ecology 19(1)136-146)	2011	Plant and soil responses to created microtopography and soil treatments in bottom land hardwood forest restoration	Texas	No	Analysis of microtopography in landfill borrow pit restoration	Microtopography strongly influenced hydrologic condition, soil properties, seedling survival and growth, and pioneer species abundance and distribution.	
Matthew E. Simmons; Xinyuan Ben Wu; Steven G. Whisenant (Restoration Ecology 20(3):369-377)	2012	Responses of pioneer and later-successional plant assemblages to created microtopographic variation and soil treatments in riparian forest restoration	Texas	No	Microtopography and soil treatments	After two growing seasons pioneer assemblages were equal among treatments but survival of later-successional species was higher on ridges than on flats and mound-and-pool features.	Ridges, flats and mound-and-pool creation
Laurel Pfeifer-Meister; Bart R. Johnson; Bitty A. Roy; Santiago Carreno; Julie L. Stewart; Scott D. Bridgham (Ecosphere 3(2):3)	2012	Restoring wetland prairies: tradeoffs among native plant cover, community composition, and ecosystem functioning	Oregon	No	Topsoil removal and solarization	Topsoil removal has little impact on species diversity but lowered productivity, soil carbon and nitrogen, microbial biomass, and mycorrhizal fungal infection rates.	Relevant to scrap-down treatment, not mounds
Irene M. Rossell; Kevin K. Moorhead; Huma Alvarado; Robert J. Warren, II (Restoration Ecology 17(2):205-214)	2009	Succession of a southern Appalachian mountain wetland six years following hydrologic and microtopographic restoration	North Carolina	No	Microtopography of depressions and low ridge performance analysis	Edaphic conditions similar in depressions and ridges. Floral richness higher on ridges.	
L. P. Rozas; P. Caldwell; T. J. Minello (Journal of Coastal Research pp. 37-50)	2005	The fishery value of salt marsh restoration projects	Texas	Yes	Fisheries response and cost of marsh terracing, island construction, and mounds	High interspersion of water and marsh benefits fish species	
Robert D. Jarzemsky; Michael R. Burchell, II; Robert O. Evans (Ecological Engineering 58:35-43)	2013	The impact of manipulating surface topography on the hydrologic restoration of a forested coastal wetland	North Carolina	No	Hydrologic response to three surface restoration treatments: plugging ditches without surface treatment (P), plugging and roughening surface (R), and plugging and removing field	C produced wettest surface condition and lowest flow output; P and R produced similar hydrologic conditions and tracked against reference. P may be adequate to restore hydrology to match reference, but R is a low-cost approach to increase surface storage and introduce	Not very mound related.

Table 4. (contd)

Publication					Mound Features		
Authors (Publication)	Year	Title	Region	Tidal	Method/Parameters	Finding	Notes
					crown (C).	microtopographic diversity. C is costly and may produce wetter than desired conditions.	
Anna R. Armitage; Chuan-Kai Ho; Eric N. Madrid; Michael T. Bell; Antonietta Quigg (Restoration Ecology 23(1):15-25)	2014	The influence of habitat construction technique on the ecological characteristics of a restored brackish marsh	Texas	Yes	Mound and terrace formations	Temporal variation affected parameters more than construction techniques. High or low water, with corresponding salinity, between study years drove changes. Different approaches can create greater habitat heterogeneity on a landscape scale with corresponding ecological benefits.	
Anna R. Armitage; Chuan-Kai Ho; Antonietta Quigg (Plos One 8(2):10)	2013	The interactive effects of pulsed grazing disturbance and patch size vary among wetland arthropod guilds	Texas	Yes	Grazing disturbance regime analysis on invertebrate guild	Mounds (0.5 m diameter) used to establish patches for disturbance regime study.	

3.2 Reed Canarygrass

We worked through 17 search strings to refine the search strings for reed canarygrass to exclude non-fluvial freshwater wetlands with conditions inherently different than the LCRE, and focus on control. Two strings returned data most relevant to practitioners:

- The string (("reed canary grass" OR "phalaris arundinacea") AND (riv* OR fluvial)) returned 77 records.
- The string (("reed canary grass" OR "phalaris arundinacea")) AND (tid* OR estuar*) returned 11 records.

However, many of the results of these two searches did not include reed canarygrass control. Therefore, we modified the search as follows.

- The string (("reed canary grass" OR "phalaris arundinacea")) AND TOPIC: (tid* OR estuar* OR wetland) AND TOPIC: (restor*) AND TOPIC: (control*) returned 28 records relevant to control.

To avoid having the topic of restoration limit finding results that were relevant to control in general, we conducted a final search:

- (("reed canary grass" OR "phalaris arundinacea")) AND TOPIC: (tid* OR estuar* OR wetland) AND TOPIC: (control*), which returned 46 records.

We created an EndNote file with 74 records for reed canarygrass, representing the combination of the third and fourth searches. Plots of the composition of topics within the third and fourth primary search strings on reed canarygrass control (Figure 3) should be viewed as a data description; the most important depiction of the topic areas derives from the review of abstracts and full text discussed further below.

The abstracts of 74 published studies were reviewed for relevance to reed canarygrass control and environmental conditions. Of these, 29 were pulled for full review and synthesis. These studies focused on methods of controlling existing populations of canarygrass, understanding the conditions under which native species can be more competitive to limit canarygrass invasions, or defining the environmental conditions that facilitate reed canarygrass establishment (Table 5).

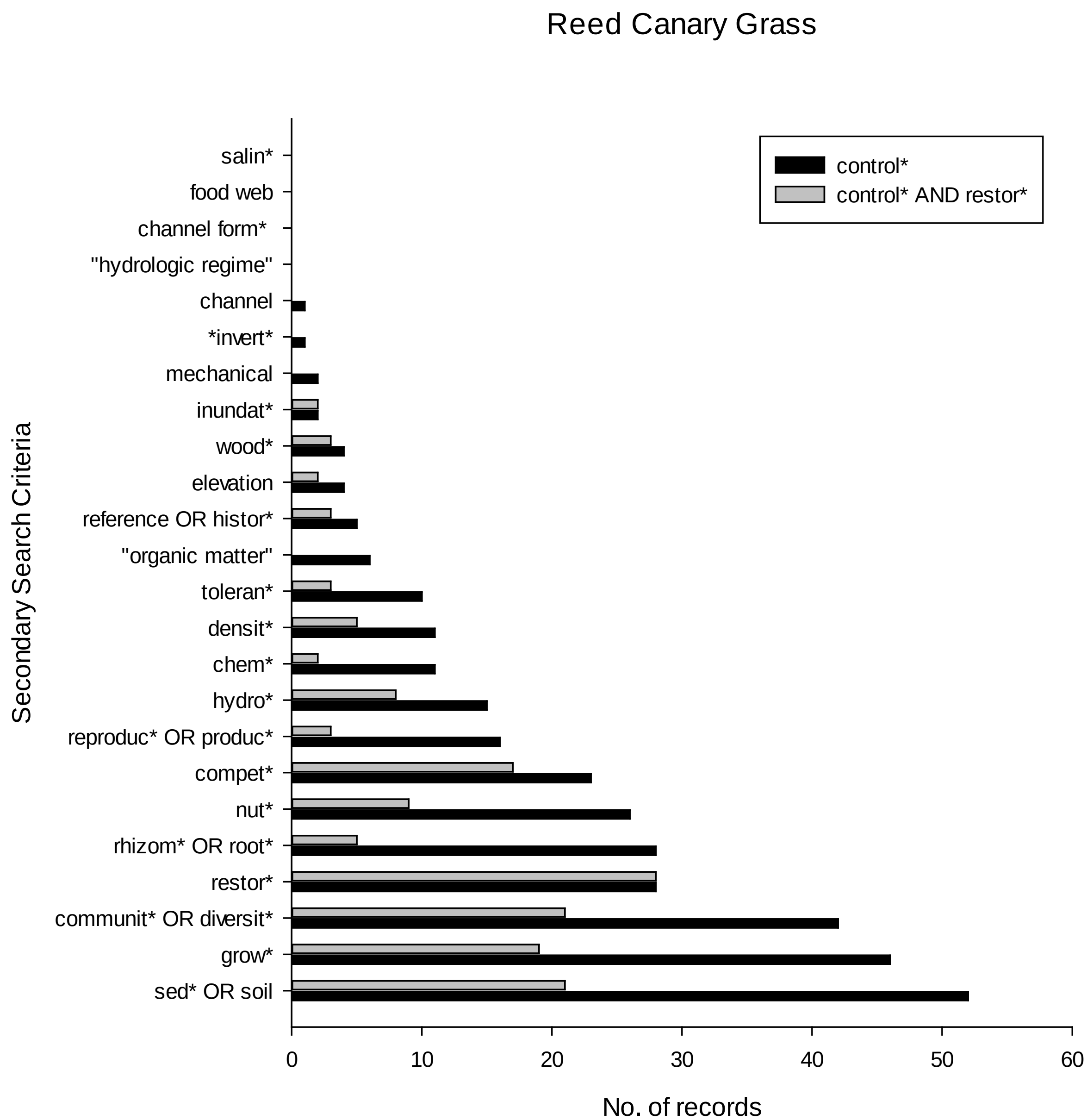


Figure 3. Composition of topics within the final reed canarygrass primary search strings. Topics identified through the Web of Science search tool include any information within the title, abstract, author keywords, and keywords.

Table 5. Review of the relevant literature on reed canarygrass (*Phalaris arundinacea* [RCG]) control.

Publication				Control Methods or Environmental Conditions			
Authors (Publication)	Year	Title	Region	Tidal	Method/Conditions	Findings	Notes
Maarten B. Eppinga; Matthew A. Kaproth; Alexandra R. Collins; Jane Molofsky (Journal of Ecology 99(2):503-514)	2011	Litter feedbacks, evolutionary change and exotic plant invasion	North America	No	Soil fertility, light	RCG is a weak competitor for soil nutrients but a strong competitor for light. Model predictive analysis: RCG litter creates competitive advantage even in low-nutrient environments. "Vacant niches" are smothered and filled by RCG litter. Feedback loop of litter, including nutrient pulse, can feed invasions	Resource competition model for nutrients and light, litter amounts
R. D. Foster; P. R. Wetzel (Restoration Ecology 13(2):318-324)	2005	Invading monotypic stands of *Phalaris arundinacea*: A test of fire, herbicide, and woody and herbaceous native plant groups	Tennessee	No	Herbicide, fire	A single early season application of glyphosate created a window for native establishment that did not persist beyond 2 years. A single early season burn failed to reduce RCG cover, shoot or root biomass, and enable native establishment.	2-year study
Zhiyu He; Lisa Patrick Bentley; A. Scott Holaday (American Journal of Botany 98(1):20-30)	2011	Greater seasonal carbon gain across a broad temperature range contributes to the invasive potential of *Phalaris arundinacea* (Poaceae; reed canary grass) over the native sedge Carex stricta (Cyperaceae)	Indiana	No	Hydrology manipulation, temperature	Increased hydrology gave competitive advantage to native sedge; increased soil saturation reduced carbon gain in RCG. Increased temperature variation increased competitiveness of RCG	RCG competitive capability related to temperature, net carbon gain, water regime. Water regime manipulation identified as a control strategy.
Michael T. Healy; Joy B. Zedler (Restoration Ecology 18(2):155-164)	2010	Set-backs in Replacing *Phalaris arundinacea* Monotypes with Sedge Meadow Vegetation	Wisconsin	No	Herbicide, shading, fire	Annual graminicide application in May/June for 3 years of stunted growth but no lasting ong-term effects. Seeding increased species richness, but not enough to compete with RCG. Fire reduced thatch and allowed seeding and RCG to both establish.	Authors suggest a broad-spectrum herbicide for multiple years while delaying the restoration of native species. After RCG no longer emerges, burning and seeding of natives would more likely achieve the desired outcome
Koji Katagiri; Kazuo Yabe; Futoshi Nakamura; Yoshifumi Sakurai (Limnology 12(2):175-185)	2011	Factors controlling the distribution of aquatic macrophyte communities with special reference to the rapid expansion of a semi-emergent *Phalaris arundinacea* L. in Bibi River, Hokkaido, northern Japan	Japan		Nutrients	Nutrients and RCG expansion. RCG shoots grew best with deep mud, high suspended solids and total phosphorus, which in turn increase with lower flow; this is a feedback loop because RCG lowers flow. RCG shoot growth is stimulated with phosphorus rather than nitrogen. Low dissolved oxygen and high organic matter supported RCG population.	

Table 5. (contd)

Publication					Control Methods or Environmental Conditions		
Authors	Year	Title	Region	Tidal	Method/Condition	Findings	Notes
Suzanne M. Kercher; Andrea Herr-Turoff; Joy B. Zedler (Biological Invasions 9(6):657-665)	2007	Understanding invasion as a process: the case of *Phalaris arundinacea* in wet prairies		No	Hydrology, sediment, nutrients	Three-step invasion process: water level and sedimentation reduces natives; flooding, sedimentation, and nutrients increase RCG growth; and RCG monocultures developed with each disturbance. Least disturbed communities maintained natives.	
K. M. Kilbride ;F. L. Paveglio (Wildlife Society Bulletin 27 (2):292-297)	1999	Integrated pest management to control reed canary grass in seasonal wetlands of southwestern Washington	SW WA	No	Multiple methods	IPM efficacy: discing, mowing, Rodeo®, water and combinations of each. Water level control is key. Same study as Paveglio and Kilbride 2000.	
C. Kurtz (Proceeding of the 18th North American Prairie Conference: Promoting Prairie, pp.136-137)	2003	Reed canary grass control (displacement by a diverse native species mix)	Mississippi valley	No	Seeding	Observation of seeding, fire, herbicide application	
R. Lindig-Cisneros; J. B. Zedler (Oecologia 133(2):159-167)	2002	Relationships between canopy complexity and germination microsites for *Phalaris arundinacea* L	Wisconsin	No	Competition, shading	Canopy complexity affects light penetration and therefore RCG germination. Microsite factors for germination: matrix spp, # spp in canopy, soil water level.	
D. A. Maurer; J. B. Zedler (Oecologia 131(2):279-288)	2002	Differential invasion of a wetland grass explained by tests of nutrients and light availability on establishment and clonal growth	Wisconsin	No	Light, nutrients	Open canopies and increased nutrients facilitate RCG. Light stimulates aboveground growth to capture more light and low nutrients stimulate root development to increase belowground foraging.	
Ying Pan; Bai-Han Pan;Yong-Hong Xie; Zhi-Yong Hou; Xu Li;Ya-Jun Xie; Dong-Dong Pan (Annales Botanici Fennici 51(2-Jan):29-38))	2014	Ability to acclimate to sedimentation gradually decreases with burial time in two emergent macrophytes from Dongting Lake wetlands in China	China	No	Burial	RCG showed sediment burial tolerance at 5 and 10 cm depths over 3 months, albeit with decreased vigor.	Burial effects on RCG compared to another species
F. L. Paveglio; K. M. Kilbride (Wildlife Society Bulletin 28(3):730-	2000	Response of vegetation to control of reed canarygrass in seasonally managed wetlands of southwestern Washington	SW WA	No	Herbicide, hydrology, mechanical	Early and late-season application with mowing/discing within managed wetlands. Combination of mechanical and chemical methods showed highest	Managed wetland hydrology for waterfowl habitat. Hydrology was control variable with mean

Table 5. (contd)

Publication					Control Methods or Environmental Conditions		
Authors	Year	Title	Region	Tidal	Method/Condition	Findings	Notes
740)						control effectiveness and native species richness, particularly with second year follow-up treatment. Mowing only had no effect on RCG and native diversity	water depths during inundation period between 44 and 55 cm. Tied to Kilbride study above..
Shon S. Schooler; Peter B. McEvoy; Eric M. Coombs (Diversity and Distributions 12(4):351-363)	2006	Negative per capita effects of purple loosestrife and reed canary grass on plant diversity of wetland communities	Pacific NW	No	Competition	RCG is capable of reducing plant diversity. Invader abundance is not correlated with other influences including hydrology, soils, and topography.	
Lisa C. Turnbull; Scott D. Bridgham (Soil Science Society of America Journal 79(3):057-967)	2015	Do two graminoids, the invasive *Phalaris arundinacea* and the Native Scirpus microcarpus, have similar ecosystem effects in a wetland?	South Slough National Estuarine Research Reserve, Oregon	No	Soil conditions	Community differences in ecosystem processes and characteristics between RCG and *Scirpus microcarpus*. Soil temperature, belowground productivity, soil texture and pH were secondary to seasonal and edaphic factors.	
Myla F. J. Aronson; Susan Galatowitsch (Wetlands 28(4):883-895)	2008	Long-term vegetation development of restored prairie pothole wetlands	Midwest US	No	Hydrology	Development of restored wetlands is generally low due to isolation, low colonization of native species, infrequent flooding and invasive species. Control of RCG and planting (particularly for low efficiency/competitive guilds) is critical early in the restoration process. Long-term RCG control is required.	
Matt A. Bahm; Thomas G. Barnes; Kent C. Jensen (Natural Areas Journal 34(34):459-464)	2014	Evaluation of herbicides for control of reed canarygrass (*Phalaris arundinacea*)	South Dakota	No	Herbicide, shading	Herbicide control study evaluating herbicide combinations, rates, and timing. All combinations reduced RCG cover with some efficacy variation but RCG returned after the third season in all treatments. Herbicide control was combined with planting. After 3 years planted vegetation response was minimal.	Eight treatments with chemical combinations and a control. Reduced RCG over two growing seasons.
L. H. Fraser; J. P. Karnezis (Wetlands 25(3)520-530)	2005	A comparative assessment of seedling survival and biomass accumulation for fourteen wetland plant species grown under minor water-depth differences	Eastern US	No	Hydrology manipulation	Mesocosm experiment investigating growth response in incremental hydro regimes. RCG was one of four species (N=14) that had seedling survivorship across all regimes (-6 to +6 cm). Flooding above 0 cm may reduce RCG seedling survival and biomass production.	Hydrologic regime affects seedling survival

Table 5. (contd)

Publication					Control Methods or Environmental Conditions		
Authors	Year	Title	Region	Tidal	Method/Condition	Findings	Notes
Stephen M. Hovick; James A. Reinartz (Wetlands 27(1):24-29)	2007	Restoring forest in wetlands dominated by reed canarygrass: the effects of pre-planting treatments on early survival of planted stock	Wisconsin	No	Herbicide, mowing, plowing, burning	Tested approaches for site preparation for planting success. Treatments included herbicide, mowing, plowing and burning combinations. Fall herbicide with plowing had highest woody species establishment success.	
Basil V. Iannone, III; Susan M. Galatowitsch (Restoration Ecology 16(4):689-701)	2008	Altering light and soil N to limit *Phalaris arundinacea* reinvasion in sedge meadow restorations	Minnesota	No	Competition, nutrients	Cover crop and wood material treatments to reduce soil nitrogen (N). Cover crop reduced native establishment and is more important than N in limiting RCG.	
Basil V. Iannone, III; Susan M. Galatowitsch; Carl J. Rosen (Ecoscience 15(4):508-518)	2008	Evaluation of resource-limiting strategies intended to prevent *Phalaris arundinacea* (reed canarygrass) invasions in restored sedge meadows	MN	No	Plant competition, nutrient reduction	Cover crop competition experiment combined with N reduction (sawdust). Cover crop and sawdust both reduced RCG invasion. Cover crops also reduced desired species, some of which are favored over others. Understanding the needs of desired species is critical to the approach. Sawdust resulted in only moderate, short-term reductions and is not practical in most cases. Study shows that reducing initial resource levels is less important than the rapid establishment of perennial communities when trying to prevent invasions of restoration sites.	
Noah J. Jenkins; J. Alan Yeakley; Elaine M. Stewart (Wetlands 28(4):1018-1027)	2008	First-year responses to managed flooding of lower Columbia River bottomland vegetation dominated by *Phalaris arundinaceae*			Hydrology	RCG cover was negatively correlated to greater depth of flooding. After flooding RCG grew more slowly. Greater decline in RCG cover coincided with regenerating willow forest. RCG cover declines ranged from 6−11%, making willows a potentially useful tool for control.	
Kee Dae Kim; Kern Ewing; David E. Giblin (Ecological Engineering 27(3):219-227)	2006	Controlling *Phalaris arundinacea* (reed canarygrass) with live willow stakes: A density-dependent response	Seattle	No	Shading	Willow planting density experiment. Findings recommend 2- and 4-ft spacing of willows to reduce RCG above ground biomass.	Two growing season study.
S. Lavergne; J. Molofsky (Nature Areas	2006	Control strategies for the invasive reed canarygrass (*Phalaris arundinacea* L.) in	Literature review of control		Multiple methods review	Control methods review study showing integrated approaches achieve greater control and stand alone. Herbicide,	High genetic variability of RCG makes it adaptable in a wide range of

Table 5. (contd)

Publication			Control Methods or Environmental Conditions				
Authors	Year	Title	Region	Tidal	Method/Condition	Findings	Notes
Journal 26(2):208-214)		North American wetlands the need for an integrated management plan	strategies			mechanical and hydrologic combined approaches work best. Shading from woody species is effective. Light (non-woody plant) and nutrient competition is promising. Fire is possible in appropriate systems. Long-term (5-year) control is not achieved without maintenance. A system-scale approach would limit invasion vectors.	environments. No biological control methods are currently available for RCG.
Jason P. Martina; Carl N. von Ende (American Midland Naturalist 160(2):430-437)	2008	Correlation of soil nutrient characteristics and reed canarygrass (*Phalaris arundinacea*: Poaceae) abundance in northern Illinois (USA)	N. Illinois	No	Nutrients	Positive relationship with RCG and total inorganic N and cation exchange capacity. Understanding soil chemistry may be a key parameter for control.	
L. G. Perry; S. M. Galatowitsch (Euphytica 148(2-Jan):121-134)	2006	Light competition for invasive species control: a model of cover crop-weed competition and implications for *Phalaris arundinacea* control in sedge meadow wetlands		No	Shading	Theoretical model of plant competition using cover crops to limit RCG. Cover crops tend to equally limit RCG and desired herbaceous species. Desired species should have lower light requirements than RCG and cover crop shade production should be matched to RCG and desired species requirements. RCG invasion requires rapid establishment that when limited can favor slower growing native species.	
Adams Carrie Reinhardt; Susan M. Galatowitsch (Applied Vegetation Science 11(1):131-138)	2008	The transition from invasive species control to native species promotion and its dependence on seed density thresholds	MN	No	Plant competition	Bare ground seed density competition experiment suggests that a propagule pressure (restoration) threshold exists, but even very low RCG seed density within native presence will result in RCG establishment.	
Carrie Reinhardt Adams; Susan M. Galatowitsch (Restoration Ecology 14(3):441-451)	2006	Increasing the effectiveness of reed canary grass (*Phalaris arundinacea* L.) control in wet meadow restorations	Midwest US	No	Herbicide	Late-season glyphosate application was more effective than spring application to in reducing RCG biomass. Recolonization was rapid after 2 years. Spring burning did not reduce RCG biomass but did reduce seedbank. Recolonization was rapid.	Burning, herbicide trials over multiple years
Meredith Thomsen; Kurt Brownell; Matthew Groshek; Eileen Kirsch	2012	Control of reed canarygrass promotes wetland herb and tree seedling establishment in an upper Mississippi River	Upper Mississippi	No	Herbicide	Fall site clearing and scarification with fall application of pre-emergent herbicide delayed emergence of RCG. Summer application of a graminicide or	Scarification and herbicide to establish native vegetation

Table 5. (contd)

Publication					Control Methods or Environmental Conditions		
Authors	Year	Title	Region	Tidal	Method/Condition	Findings	Notes
(Wetlands 32(3):543-555)		floodplain forest				glyphosate reduced cover from rhizomes. Native herbaceous species and woody seedling cover increased by third year.	
Julia C. Wilcox; Michael T. Healy; Joy B. Zedler Natural Areas Journal 27(4):354-365)	2007	Restoring native vegetation to an urban wet meadow dominated by reed canarygrass (*Phalaris arundinacea* L.) in Wisconsin	Wisconsin	No	Herbicide, mechanical, planting	Two consecutive fall applications of glyphosate with biomass burning in early winter the second year and seeded with native species. Sethoxydim trials also with seeding. After t3 years desired outcome not achieved. RCG clipping and seasonal seeding experiment. After 3 years desired RCG resistant community outcomewas not achieved. Seeding rates and timing (once vs twice) results were not conclusive due to other potential factors. Fresh seed tested for germination rates is important to results.	Herbicide (glyphosate and sethoxydim), clipping, and seeding to reduce RCG. Initial control with post-emergent followed up with grass-specific applications might be a strategy to employ in appropriate systems. Concerns about environmental impacts of selective herbicides. Nutrient-rich runoff can aid RCG establishment.

Based on this review, the following common themes and findings can be applied to the LCRE restoration work:

- Reed canarygrass is adaptable to a wide range of environments. In general, nutrient-rich areas increase the competitive advantage of reed canarygrass over many native species. Methods that seek to reduce available nitrogen through incorporation of woody material into the soil provided marginal competitive advantage to some native species.
- Successful control of reed canarygrass requires an integrated approach where multiple methods are applied over multiple years. Chemical, mechanical, and hydrologic manipulations are common integrated approaches.
- Most methods are not successful over a longer term without investments in continued control or maintenance. A majority of control studies found that within 3 years after control reed canarygrass cover had returned to pre-treatment conditions.
- Many native species can out-compete reed canarygrass if given sufficient competitive advantage. Light competition has been shown to be effective, particularly where shading with woody species can be employed. Light competition in emergent communities is often unsuccessful.
- Methods that work to suppress reed canarygrass typically have a similar impact on desired native species.
- Application of post-emergent herbicides (i.e., glyphosate) is a commonly employed approach. Early season application will limit seed production but not rhizomatous re-sprouts. Late-season application is more effective at controlling both vegetative and root growth. Selective herbicides (e.g., sethoxydin) can control grasses to allow forb establishment, and pre-emergent herbicides can prevent seed germination of all species. Potential environmental concerns were expressed about selective herbicides in wetland environments.
- Fire can be applied to reduce biomass and the cover of reed canarygrass, but likely will only be effective in fire-adapted systems.
- Control strategies will be most effective if employed on a system or watershed scale, which is challenging in the context of a hydrologic reconnection program such as CEERP, and must be interpreted as the largest practicable scale, at minimum, the site scale.

It should be noted that the majority of studies were conducted in non-tidal environments and were located outside of the Pacific Northwest.

3.3 Channel Networks

Many combinations of keywords were attempted (similar to the process for reed canarygrass and mounds) when performing the literature search for channel outlets. However, very few papers uncovered used the term “channel outlets” identified by practitioners. The following primary search string yielded 18 records: restor* AND (tid* OR estuar* OR wetland) AND channel outlet. Four of the papers produced by this string concerned the use of habitat by various fish species; we excluded two of these from this discussion because of a focus on examining the effects of water control structures on fish habitat, and the other two because they did not offer any information regarding channel networks. Six papers (three related to the Mississippi River) discussed long-term, large-scale geomorphological changes, e.g., related to deltaic sedimentary processes outside the scope of this diked wetland restoration design focused effort for the LCRE. Two papers treated nutrient concentrations within floodplain wetlands and adjacent river channels. Three others were not related, e.g., presumably included because the term “outlets” was used to reference the media, or because of reference to groundwater-fed wetlands.

The remaining three papers discuss channel outlets within contexts more relevant to the CEERP. Diefenderfer et al. (2012) demonstrated the relationships between the number of channel outlets breached and the area of the floodplain wetted in a study of the Grays River, but did not provide design recommendations. Hood (2014a) showed that reference marshes in the Skagit River delta have more channel outlets than marshes within dikes that historically were accidentally breached. Hood (2015a, not returned by the search engine) analyzed orthophotos of salt marshes with herbaceous and/or shrub vegetation, calculating the area and perimeter of salt marsh islands and blind sloughs. Using regression methods, the paper found that channel count (defined as the number of channel outlets on the perimeter of an island) and several other metrics were correlated with storm-significant wave height and/or tidal range. Hood (2015b) extended the analysis of Hood (2015a) to a comparison of tidal wetland restoration and reference sites, and included an analysis based on Cathlamet Bay and the Youngs River area of the LCRE. (Key results in this paper for the LCRE were previously presented by Hood [2014b] in Astoria, Oregon.) No other papers directly considered the engineering of channel outlet density in tidal wetland restoration areas, though extensive literature covers channel network features in general (cf. Fagherazzi et al. 2004).

Hood (2015b) warrants additional discussion because of its direct focus on the channel count (outlet) metric. Two-way analysis of variance (ANOVA) combining Puget Sound and LCRE sites indicated that channel outlet counts were significantly lower for restoration than reference sites. Using methods of landscape allometry, the paper highlights two restoration project designs in the LCRE region that are near the linear regression line for channel outlet count as a function of island area (Hood 2015b, Figure 2); from Hood (2014b) these projects appear to be Karlson Island and Kerry Island. Given the large proportion of islands in the set of reference sites, and the fact that Hood (2014b) indicates that the other restoration sites analyzed in Reach B (Simenstad et al. 2011) are on the mainland, this result gives rise to a question about whether differences between island and mainland wetland channel networks have an effect. The paper states in the abstract and conclusions that "completed and proposed tidal marsh restoration projects had 5-fold fewer channel outlets than reference marshes" and "an 80% deficit in channel outlet count diminishes fish access to dike breach restoration sites and thereby reduces the value of the restoration project for fish, and in this case for salmon recovery in the Pacific Northwest."

Analyses such as these using allometry have an important place in the historical development of scientific descriptions of estuarine and tidal freshwater marsh channel networks (e.g., Steel and Pye 1997) as well as the development of channel design guidelines for estuarine restoration in the USA (e.g., Coats et al. 1995; Haltiner et al. 1997; Zeff 1999; Williams et al. 2002). Allometric approaches have previously been applied to limited project areas and reaches of the LCRE and have not included the number of channel outlets as a response variable (Diefenderfer et al. 2008; ESA PWA, Ltd. and PC Trask and Associates, Inc. 2011). In summary, the availability of literature on design guidelines for wetland channel outlets in estuarine and tidal freshwater regions is sparse. However, the assessment of the general literature on estuarine channel networks in an effort to extract design rules was beyond the scope of this study.

4.0 Technical Approach

For each of the three challenge modules—mounds, reed canarygrass, and channel networks—we developed a separate technical approach to address needs expressed by practitioners during the initial telephone outreach phase of this research. These approaches involved literature review, field data collection and analysis, and/or GIS data development and analysis.

4.1 Summary Overview of Approaches to the Challenge Modules

4.1.1 Mounds

The mound challenge module consists of a relatively straightforward set of design questions, although the ecological benefits of mounds are uncertain. Practitioners have not yet had the means to use certain information that is available in the literature, in part because its relevance to the LCRE was unknown. The design parameters investigated are mostly physical (i.e., moisture and temperature constraints), though soils have both physical and biological components. The response parameters of interest are mostly biological, i.e., identifying the correct design features and species to achieve acceptable levels of planting success, but also can be physical, i.e., avoiding erosion. We took a four-part approach to the mound challenge module: 1) literature review; 2) sampling design and field data collection; 3) data summary and statistical analysis; and 4) synthesis and evaluation.

4.1.2 Reed Canarygrass

The reed canarygrass challenge module is more complex in that, in addition to environmental conditions for establishment, it involves control methods that include site design and other treatments such as herbicides. In general, the literature concludes that reed canarygrass simplifies habitat and has negative effects on ecological function, and practitioners mentioned that it also causes biological armoring that slows down the evolution of pilot channels. Therefore, control methods were a priority. Our approach to this module also had four parts: 1) literature review, including following up on workshop information identified in the initial outreach effort; 2) sampling design and field data collection; 3) data summary and statistical and GIS analysis; and 4) synthesis and evaluation. For the third step, in addition to analysis of data collected under the scope of this research, we used a large set of vegetation and elevation data (Amy Borde, unpublished data) to prepare a lookup table containing the elevation limits on reed canarygrass at points throughout the LCRE, as a tool for restoration project planners.

4.1.3 Channel Networks

The channel networks challenge module inherently had the largest number of potential metrics to consider as potential elements of this research, because of the complexity of channel networks and the long history and amount of literature on measurement of geomorphology (e.g., Fagherazzi et al. 2004). Therefore, we prioritized the metric voiced by four out of five estuary sponsors as leading in uncertainty during current restoration design processes: channel outlets, also sometimes called channel confluences. Channel confluences have been recognized as an important habitat feature for many years in CEERP research; e.g., the Ecosystem Classification and Landscape Planning Framework sponsored by BPA identified confluences as nodes of productivity (Simenstad et al. 2011, 2015). Recently, in a talk at the Columbia River Estuary Workshop, Hood (2014b) focused specifically on the channel outlet count, i.e., the number of outlets draining the perimeter of a marsh, as a quantitative measure useful to engineers. During the course of this research, two supplementary papers on this topic were published (Hood 2015a, 2015b) (see Section 3.3). On this basis, we 1) examined recently released GIS data sets and developed methods for spatial data processing to summarize channel outlet counts and other features of reference wetlands within LCRE reaches with the aim of providing a lookup table for each hydrogeomorphic reach, differentiated between wetlands on islands and the mainland; 2) tested the null hypotheses of no difference in basic tidal channel network descriptors between reaches, and no difference between wetlands located on the mainland and the islands of any given reach; and 3) developed linear regression models to the extent warranted by the existing data for wetland channel perimeter, wetland channel area, and the number of wetland channel outlets—all as a function of wetland area.

4.2 Field Methods: Mounds and Reed Canarygrass

We set criteria seeking sites of the greatest age with 1) mounds that may or may not have had plantings to control reed canarygrass, and/or 2) conditions that would provide information about active or passive reed canarygrass control and the lower limits of the species extent relative to hydrology and salinity. The final set totaled 10 sites visited (Table 6, Figure 4−Figure 13 [in alphabetical order by restoration project name]) with the assistance of several organizations and departments in Oregon and Washington (Table 7).

At six sites with *mounds*, we recorded our observations, including vegetation establishment and herbivory, and took photographs to document site conditions and findings. On a subset of mounds at five sites, we measured physical features in a synoptic survey approach, as follows. For each face of each mound, i.e., east, south, west and north, we used 1) a Real-Time Kinematic Global Positioning System (RTK-GPS) to measure the height of the mound and the angle or slope of its sides; 2) a set of 10 Durac soil analogue thermometers to simultaneously measure temperature at 5 cm and 15 cm depths along transects and air temperature; and 3) a soil moisture sensor (Campbell Scientific, HydroSense II) to measure moisture at the 12 cm depth. However, at Marietta Slough, faulty equipment prevented us from measuring soil moisture.

For sites where *reed canarygrass* control strategies were employed, we made observational assessments of species status and control effectiveness. Descriptive notes and photographs were taken to document site conditions and findings. On one site without active reed canarygrass control, Devil's Elbow, vegetation plot data were collected to follow up on annual data collection conducted between 2005 and 2009. The purpose was to evaluate vegetative change within a site restored to tidal influence in 2003. A 1 m^2 quadrat was placed on plot center and the percent of herbaceous plant cover (%) was visually estimated. RTK equipment was used to measure the elevation of the plot centers. A total of 15 plots were measured (11 repeat samples for a sixth year). For the North Fork Siuslaw River site, baseline and very recent vegetation cover data from Green Point Consulting were available, so the sampling plots were reviewed in the field (Brophy 2008, 2009; Brophy and Brown 2014). Monitoring methods at this site included cover estimates (%), planting survival, and woody stem counts within four vegetation blocks (totaling 0.65 acre in area) established in 2006. At the Spencer Island site, a 20-year-old dike breach where no active reed canarygrass control had occurred, we recorded visual observations of reed canary grass cover, delineated areas of reed canarygrass with a GPS, and took RTK elevation measurements at vegetation community boundaries. The GPS delineations were collected to overlay on recent aerial photos using GIS for the purpose of determining whether reed canarygrass patches could be defined and compared to delineations conducted in 1998, 4 years after restoration (Tanner et al. 2002). The elevations were collected for use in analysis of the inundation regime when coupled with water surface elevation (WSE) data to evaluate whether hydrology might be a factor in the observed reduction of reed canarygrass at the site.

Table 6. Ten hydrologically reconnected sites visited in three regions of the Pacific Northwest.

Region	Site Name	Primary Contacts	Primary Year	Data Collection on Mounds[(a)]	Mound Terminology	RCG Control Method[(b)]	Data Collected on RCG Control	Data Reports
Columbia River	Ruby Lake (Sauvie Is.)	CREST, PC Trask and Associates	2013	4 mounds (5 transects) + 1 reference mound (1 transect)	Peninsula, Topographic Bar and Scroll	Passive control, mound plantings, other plantings	Observational[(c)]	CREST 2013
	Colewort Creek Phase 2 (Fort Clatsop)	National Park Service, CREST	2012	2 mounds (5 transects) (1 mound observational only)	Mound, Toe of Slope	Passive control, mound plantings, other plantings	Observational	–
	Devil's Elbow (Grays River)	CLT	2003	–	–	Passive control	Observational and Quantitative: 11, 1 m^2 plots repeat-sampled for a 6th year	CLT, unpublished
	Kandoll Farm (Grays River)	CLT	2005, 2013	Qualitative	Mounds	Late-season herbicide	Observational	CLT, unpublished
Outer Coast	Anderson Creek (Coos Bay)	South Slough National Estuary Research Reserve	2001	2 mound features (4 transects)	Nurse Log with Adjacent Dirt Berm	Passive control, plantings, manual removal	Observational and Monitoring Report	Cornu 2005
	North Fork Siuslaw River	Oregon Dept. Transportation, Green Point Consulting	2007	–	–		Observational and Monitoring Report	Brophy 2008, 2009; Brophy and Brown 2014
	Drift Creek (Alsea River)	MidCoast Watershed Council, USFS	2005	2 mounds (4 transects)	Alluvial Fan	Passive control	Observational	–
Puget Sound	Spencer Island[(d)]	USFWS	1994	–	–	Passive control	Observational and Quantitative: GPS polygons compared to historical data.	Tanner et al. 2002
	Fisher Slough	TNC	2011	–	–	Passive control	Observational and Monitoring Report	Beamer et al. 2013
	Marietta Slough	WDFW	2003−2005	4 mounds (2 half transects)	Mound	Passive control	Observational	Ducks Unlimited project design plans

(a) Quantitative data collection on mounds consisted of soil moisture, temperature, and elevation.
(b) Hydrologic change occurred at all sites, but none of the sites planned controlled inundation as a RCG control method; thus, hydrologic change is considered "passive control" for the purpose of this study.
(c) Observational data included field notes, photographs, and discussions with project managers.
(d) Spencer Island is substantially older than any other restoration project and served almost like a control site to look at passive reconnection.

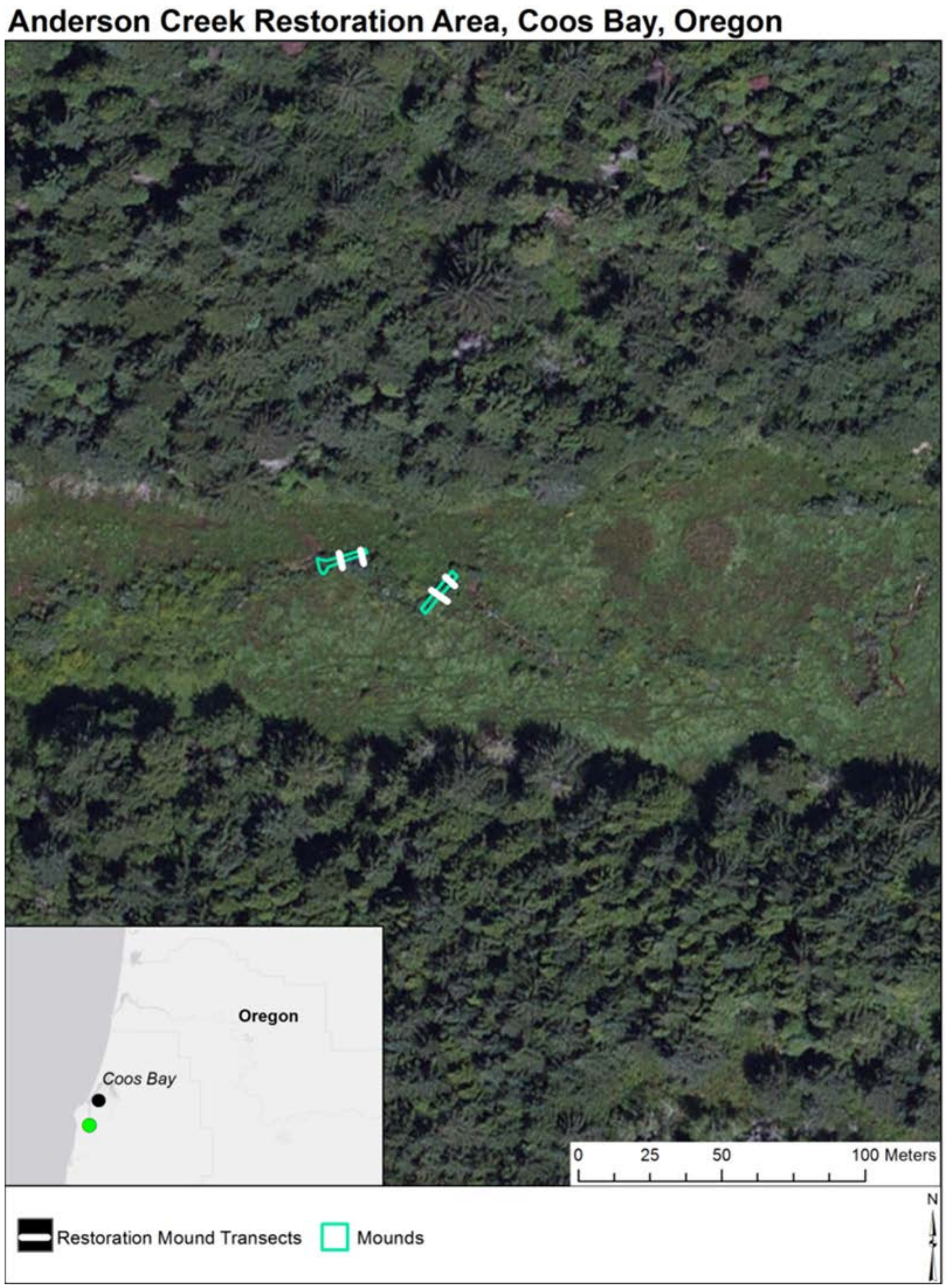


Figure 4. Anderson Creek restoration area on the South Slough National Estuarine Research Reserve, Oregon.

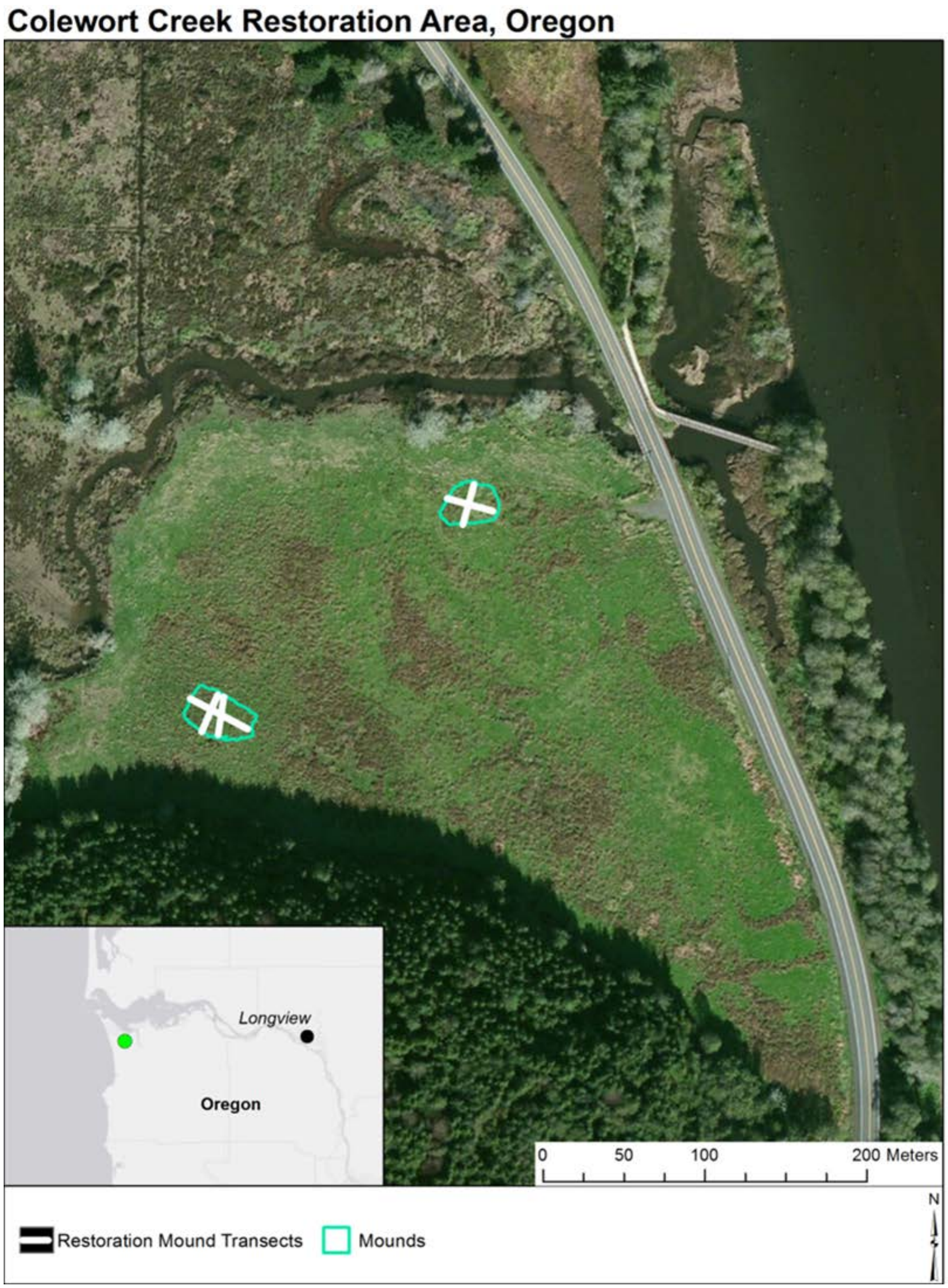


Figure 5. Colewort Creek restoration area at the Lewis and Clark National Historical Park, Oregon.

Figure 6. Devil’s Elbow restoration area on property owned by Columbia Land Trust on the Grays River, Washington.

Figure 7. Drift Creek restoration area in the Alsea River basin near Waldport, Oregon.

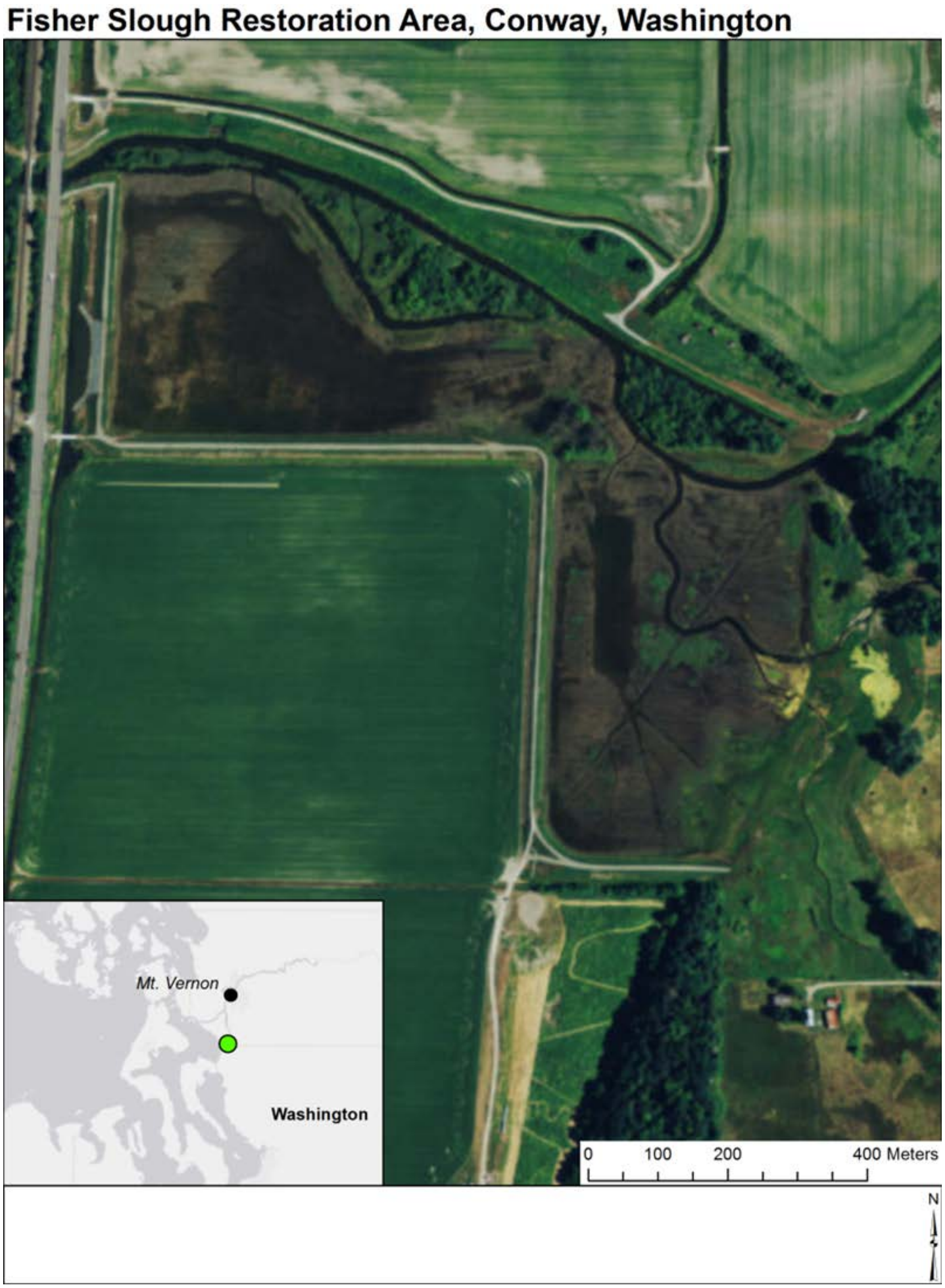


Figure 8. Fisher Slough restoration area, Conway, Washington.

Figure 9. Kandoll Farm restoration area on property owned by Columbia Land Trust on the Grays River, Washington. (Aerial photo is dated between Phase I and Phase II of restoration.)

Figure 10. Marietta Slough restoration area on the Nooksack unit of the Washington Department of Fish and Wildlife, Whatcom Wildlife Area on the eastern bank of the Nooksack River.

Figure 11. Ruby Lake restoration area on the Oregon Department of Fish and Wildlife, Sauvie Island Wildlife Area, Oregon.

Figure 12. North Fork Siuslaw River restoration area, Oregon Department of Transportation, near Florence, Oregon.

Figure 13. Spencer Island restoration area on the Snoqualmie River delta, a joint acquisition and co-management agreement by Snohomish County Parks and Recreation Department and Washington Department of Fish and Wildlife, Spencer Island Unit, Snoqualmie Wildlife Area, Washington.

Table 7. Leaders of site visits.

Site	Site Visit Leader	Organization
Columbia River		
Colewort Creek	Carla Cole	National Park Service
Colewort Creek	Matt Van Ess, Jason Smith	CREST
Ruby Lake	Tom Josephson	CREST
Devil's Elbow, Kandoll Farm	Ian Sinks	CLT
Puget Sound		
Marietta Slough	Richard Kessler	Washington Department of Fish and Wildlife, Whatcom Wildlife Area
Fisher Slough	Not recorded	Not recorded
Spencer Island	Not recorded	Not recorded
Outer Coast		
Drift Creek	Wayne Hoffman	Mid-Coast Watersheds Council
Anderson Creek	Craig Cornu	South Slough
North Fork Siuslaw	Irene Ulm	Oregon Department of Transportation

4.3 Data Analysis: Mounds and Reed Canarygrass

4.3.1 Mounds

In addition to field observations, for each site with sufficiently large sample sizes, Pearson pairwise correlation and scatter plots were used to assess the relationship between elevation (ft), soil temperature (^{0}F) at 5 and 15 cm depth, and soil moisture (%). For each mound and site, a Kruskal-Wallis multiple comparison test comparing the median moisture was conducted between the relative vertical location on the mound (toe, lower side, upper side, top of slope, and top of mound) with and without the toe and top of mound, and between aspects (N, S, E, and W). A general linear model was fit for each class type using elevation as a covariate.

4.3.2 Reed Canarygrass

4.3.2.1 Field Data Analysis

In addition to field observations, quantitative field data were analyzed for two sites: Devil's Elbow and Spencer Island. Vegetation data from 17 1 m square plots collected between 2005 and 2015 at the Devil's Elbow restoration site were summarized for comparison between plots and between years. Two plots were not located in 2015, while other plots were not found in previous years, reducing the comparison to 11 plots. In four of the years, data from 15 plots were consistently collected, so a species accumulation analysis was conducted to determine whether these plots adequately represented the species observed in the plots. The results indicated that 15 plots are close to the asymptote where sampling would be deemed adequate (Figure 14). The cover from the 15 plots was averaged by species for each year.

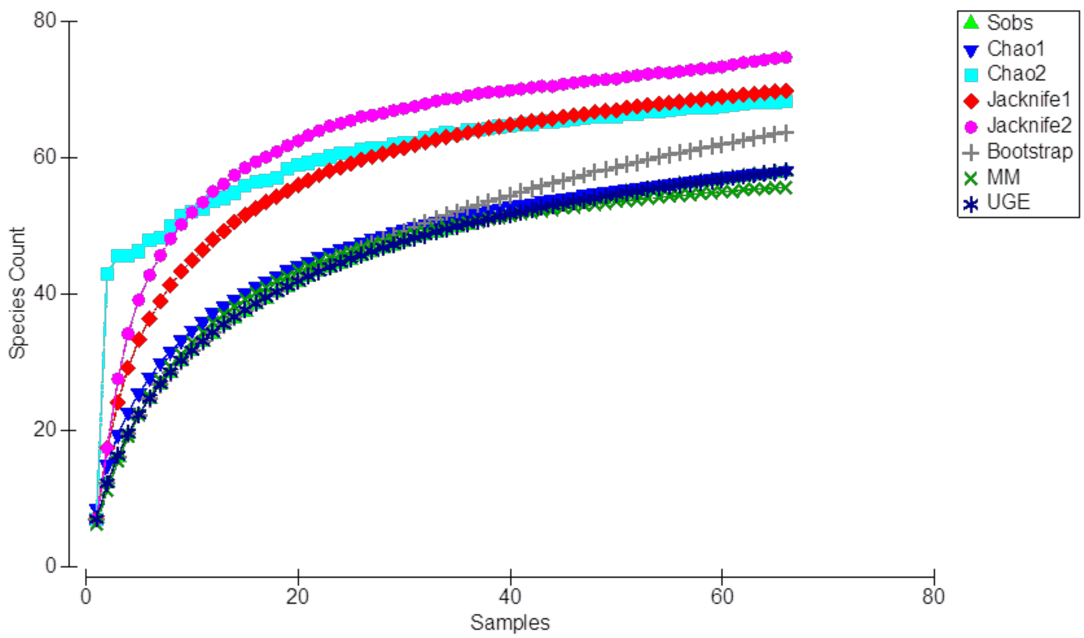


Figure 14. Plant species accumulation analysis at Devil's Elbow.

The data were square root transformed and a Bray-Curtis similarity index analysis was conducted using Primer® v.6, producing a resemblance matrix of similarities. Multidimensional scaling (MDS) plots and an analysis of similarity (ANOSIM) were calculated based on this underlying matrix.

GPS delineations of vegetation communities were collected in the field within the restored wetland area at Spencer Island. These were overlaid on aerial imagery in GIS and some vegetation communities were readily apparent (e.g., cattails and bulrush), however Lyngbye's sedge (*C. lyngbyei*) was a dominant vegetation type at the site and this was not distinguishable from reed canarygrass in the imagery.

Modeled WSE data (based on averages of the past 50 years) were acquired for a location on the east side of Spencer Island near the eastern breach of the restoration site (personal communication, Zhaoqing Yang, PNNL, 8/14/15). The WSE data were compared to elevations of known vegetation communities measured in the field. Inundation frequencies were calculated during the growing season for Everett, Washington (April 5 – October 28; NRCS 2015).

4.3.2.2 Elevation Data Analysis

Elevation data from 35 reference marsh sites (Borde et al. 2011; Diefenderfer et al. 2013) were used to determine the lower elevation of reed canarygrass along the LCRE. The lower elevation varies along the river due to differing hydrologic inputs and changes in site elevation with the rise of the river bed. Data for previous studies (Borde et al. 2011; Diefenderfer et al. 2013) were reported in meters relative to the Columbia River Datum (CRD), which enabled comparisons between sites; however restoration practitioners need elevation data that are relevant to their sites. In an effort to provide data more conducive to practitioner needs, we converted the elevations of reed canarygrass at the reference sites to feet relative to the North American Vertical Datum of 1988 (NAVD88), interpolating between sites to provide data for every 5 rkm (~3 miles) of the LCRE. In addition, where available we included data on the lowest marsh elevations and the lowest shrub elevations (Borde et al. 2011); these data were not interpolated because data on these elevations were more limited.

4.4 Spatial Data Processing and Statistical Methods: Channel Networks

4.4.1 Analysis of Marsh Area and Channel Network Data

We used two primary sources of data, the Ecosystem Classification (Simenstad et al. 2011) and the Landscape Planning Framework. The following portions of each data set were used in data processing for this analysis.

Columbia River Estuary Ecosystem Classification:

- Hydrogeomorphic reach (Figure 15) – division of LCRE study area into comparable units
- Biocatena – island identification and type
- Ecosystem complex – mainland wetlands complexes
- Land cover – tidal wetlands area
- Cultural features – fill areas, dikes, and ditches

Landscape Planning Framework

- Indirect drainage – (channel type, area, and perimeter)
- Landscape features – channel outlets and confluences.

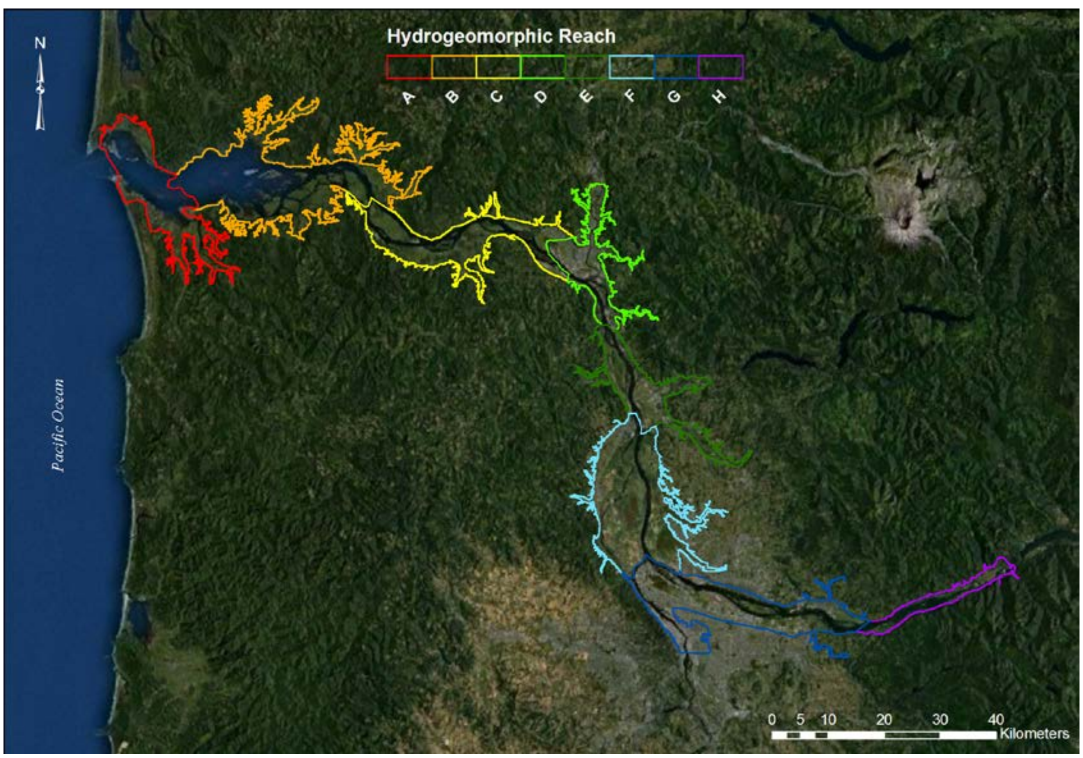


Figure 15. Hydrogeomorphic reaches (Simenstad et al. 2011) with the 2012 floodplain perimeter (courtesy of J O'Connor, USGS).

4.4.1.1 Rules

Only wetlands with channels were included in the analysis. We included islands that had greater than 70% wetlands and we only included wetland areas that were larger than 0.1 hectares (ha). Wetland area was aggregated on islands and reported as a single wetland area per island. The Ecosystem Complex layer was used to aggregate tidal wetlands on the mainland; complex types included the surge plain, floodplain, and backwater swamp. Other complexes were included as necessary to encompass all relevant tidal wetlands (backwater embayments, floodplain bar and scroll, crevasse splay, tributary floodplain, and tributary fans). We included four channel types from the indirect drainage that consistently occurred in wetlands as follows: small channels, tidal channels, floodplain channels, and tie channels. In some cases, portions of additional channel types were included (e.g., tidal sloughs, minor tributaries, embayments) when the upper extent was channelized and encompassed by the wetlands; all wetlands were individually evaluated for this condition. Wetlands that were altered by fill or ditches were not included in the analysis.

4.4.1.2 Limitations of the Analysis

Confluences within wetlands were not evaluated as a metric in the analysis because confluences between channels of the same type were not delineated in the Confluence data set. This also resulted in the inability to categorize channel order using existing data because in some areas, especially the islands, complex channel networks with a high level of bifurcation were single polygons with no confluences defined. Confluences were defined when two different channel types converged. A category defined as small channels was present in the Indirect Drainage layer; however, these were not present in the Confluence layer, where instead they were categorized as tidal channels.

Tidal wetland areas were patchy within forested wetland areas. For example, at two tidal forested swamp sites, the area categorized as wetlands was 48 and 52 percent of the total area within the wetland perimeter.

4.4.2 Statistical Analysis

A simple linear regression analysis was conducted by reach with the $\log_{10}$ transformed channel area, channel perimeter, and the number of outlets regressed against the $\log_{10}$ transformed area of the island or area of the wetland. Common (Reduced Model) and separate slopes (Full Model) across reach were fit and compared using an F-test to compare the nested models. The statistic (F_{calc}) used to compare models was

$$F_{calc} = \frac{\left(\dfrac{\text{Full}(MSS) - \text{Reduced}(MSS)}{\text{Full}(mdf) - \text{Reduced}(mdf)}\right)}{\text{Full}(EMS)}$$

which was compared to an $F_{\alpha=0.05,\ \text{full(mdf)} - \text{reduced (mdf)},\ \text{full(edf)}}$ where MSS, mdf, EMS, and edf are the model sum of squares, model degrees of freedom, error mean square, and error degrees of freedom, respectively (Ramsey and Schafer 1996). A nonparametric run's test of the goodness-of-fit to the full and reduced linear models was also conducted. Variables were calculated with and without small channels. In total, 72 linear regressions of channel area, channel perimeter, and number of outlets by reach were conducted, including 21 mainland regressions against wetland area (with 7 reaches, not including Reach G [n = 2]); 9 island regressions against island area with small channels included by reach (A,B,C); 9 island regressions against island area without small channels included by reach (A,B,C); 9 island regressions against wetland area with small channels included by reach (A,B,C); 9 island regressions against wetland area without small channels included by reach (A,B,C); and 15 for common slopes across reach. For a given variable, individual regressions conducted for each reach were independent.

Ratios of the channel perimeter, channel area, and number of outlets to the wetland area were calculated and summarized by reach with descriptive statistics and box plots. The nonparametric Kruskal-Wallis test followed by a multiple comparisons procedure of equal pairwise-medians was used to compare reaches and channel types.

5.0 Results

5.1 Mounds

Results include field observations of vegetation and surface and soil conditions, and statistical analysis of soil moisture and temperature relative to potential environmental drivers: aspect and relative vertical position.

In reporting statistical results in this section, significance is stated if $p < 0.05$.

5.1.1 Field Observations

Mounds bore distinctively different appearances at the restoration sites in terms of height, shape, and vegetation (Figure 16). At four of the five sites, the mounds had been formed from fill material available from restoration-construction activities. The mounds at Anderson Creek were unique in that they had been formed by placing a dead tree, including the root wad, at an angle to the creek, pushing dirt up to it on one side and planting trees in the dirt. At most sites, mounds were stand-alone features surrounded by floodplain at elevations typical of the site. The primary exception to this was Drift Creek, where mounds had been designed to replicate natural alluvial fan structures in the region, and extended from the roadbed out onto the floodplain. Also, one mound at Colewort Creek was immediately adjacent to a forested hillslope from which it extended, and some mounds at Ruby Lake extended similarly from higher-elevation treed areas.

Figure 16. Photographs of mounds observed in this study. Colewort Creek mounds fenced for protection from herbivory with A) floodplain topsoil and relatively high plant survival and vigor compared to B) formed with material from channel excavation; Anderson Creek nurse-log–based mounds at water's edge, C) planted with Sitka spruce and D) with willows; Marietta Slough mounds planted with E) (left center of photo) Scouler's willow (*Salix scouleriana*) and Sitka spruce, with a shaded environment and some development of understory plant species richness, and F) Pacific willow (*Salix lucida*) with a relatively bright environment and a reed canarygrass understory; G) Ruby Lake transition zone from water to mound (at left) with Oregon ash-forested reference peninsula in the background; and H) alluvial-fan–shaped mound at Drift Creek, which was not planted, is now covered mostly with reed canarygrass.

Surface and Soil Conditions

Though it is understood that avoiding compaction or smoothing of the surfaces of mounds is beneficial for water penetration and plant growth, this is not always possible given environmental conditions (e.g., rain, relative consolidation of the sediments at the time of construction), so very hard consolidated mounds can result. The source of mound material, i.e., whether it is from the bottom of a slough or the topmost layer of a floodplain, appears to result in visibly different soil color, texture, and organic content, which may correspond to different plant responses as observed at Colewort Creek. The heights of mounds examined were quite different between sites: Colewort Creek –4.3 m and 4.5 m, Drift Creek – 1.3 m and 1.4 m, and Ruby Lake – 1.7 m, 2.3 m, 2.7 m, and 3.4 m. We only visited a small number of mounds at the extensive complex of mounds at Marietta Slough, and measured the heights of two at 1.4 m and 3.2 m. At Anderson Creek, mounds were about 1.0 – 1.5 m—i.e., the diameter of the log in addition to some material below and alongside it—and variable because of the channel's proximity (tree cover on these mounds prevented the collection of dense RTK data).

Vegetation

Differences in plant mortality and the vigor of plantings were observed that appeared to correspond to differences in soil organic matter (a factor corroborated by the literature). The relatively low-elevation mounds at Drift Creek were intended to imitate alluvial fans characteristic of the coastal mountains; they were not planted and natural recruitment resulted in red alder as the only tree, Himalayan blackberry dominating the shrub layer, and a variable herb layer dominated by reed canarygrass. In contrast, the mounds at Anderson Creek were intended to imitate nurse logs intersecting with slough channels, with dirt pushed up against logs to enable planting of Sitka spruce and willow, and plantings were successful (aside from spruce budworm) in creating a shady environment over and around slough channels. Both Anderson Creek and Drift Creek were near the head of tide. Relatively higher mounds at Marietta Slough and Colewort Creek were planted with willows, shrubs, and Sitka spruce with variable success. Mounds at Ruby Lake were planted with willows with variable success, and extensive early natural recruitment of cottonwood was evident.

5.1.2 Overview of the Results of Statistical Analyses for Colewort Creek, Drift Creek, and Ruby Lake

We summarized all of the statistical analyses of soil moisture and temperature data in a single table to help make the overall pattern of results easier to grasp (Table 8). By looking at the boxed and/or shaded entries in this table, indicating significance at $p < 0.05$ and $p < 0.1$, respectively, it is clear that most of the significant results were for soil moisture, although several analyses of temperature also produced significant and interesting results. If there are only two categories being tested then the overall Kruskal-Wallis result does not change; if more than two categories are tested then the Kruskal-Wallis pairwise comparison is also added. In a few cases, the overall Kruskal-Wallis text was not significant but the pairwise comparison was significant, which can happen based on the structure of the variability.

Table 8. Summary of statistical analysis of soil moisture and temperature and driving variables at mounds. For each pair of driving and response variables, the first row is the p-value for the Kruskal-Wallis test of equal medians, the second row is the trend or significant result of pairwise comparisons, and the third line is the pairwise p-value. Black-outlined box indicates significant at p < 0.05 and gray shading indicates “trend only.” NS = Non-significant at p < 0.05, significant at p < 0.10.

Response Variable	Driving Variable	CC (2 Mounds)	CC-1	CC-2	DC (2 Mounds)	DC-East	DC-West	RL (5 Mounds)	RL-0	RL-1	RL-2	RL-3	RL-4
Moisture (%)	Relative Vertical Position	0.062	0.022	0.033	0.006	0.027	0.09	0.003	0.197	0.095	0.004	0.666	0.426
		toe > top of mound (p = 0.004)	toe and lower side appear > than upper side and top of slope NS	toe > top of mound (p = 0.004)	toe > top of mound (p = 0.001)	toe and upper side nearly > than top of mound NS	toe nearly > than upper side and top of mound NS	toe > than upper side, top of slope, and top of mound (p > 0.004)		toe nearly > than lower side NS	toe > top of mound (p = 0.0006)		
	Aspect without tops and toes	0.232	0.972	0.01	0.404	0.954	0.052	0.016	0.034	0.289	1	0.867	0.439
				S nearly < N and W (NS)			N nearly < E and W (NS)	W < N and S (p < 0.006)	E > W				
				ANOVA W > S p = 0.012									
	Relative Vertical Position without tops and toes	0.852	0.031	0.911	0.104	0.035	0.75	0.312	0.368	0.738	0.056	0.888	0.259
			lower side > upper side (p = 0.01)			upper side > top of slope (p = 0.01) ANOVA adds lower slope > top of slope (p = 0.01)					lower side nearly > top of slope NS		
	Aspect+Vert Position without tops and toes	0.856	NA	NA	0.451	NA	NA	0.074	NA	NA	0.243	NA	NA
								W-upper side nearly < E-lower side NS					
Soil Temp 5 cm Depth	Relative Vertical Position	0.004	0.095	0.005	0.429	0.487	0.108	0.704	0.618	0.064	0.334	0.112	0.947
		lower side < top of slope (p = 0.004)	lower side nearly < top of slope NS	toe < top of mound (p = 0.004)						upper side nearly > than top of slope NS			

Table 8. (contd)

Response Variable	Driving Variable	CC (2 Mounds)	CC-1	CC-2	DC (2 Mounds)	DC-East	DC-West	RL (5 Mounds)	RL-0	RL-1	RL-2	RL-3	RL-4
	Aspect without tops and toes	0.665	0.99	0.558	0.2	0.356	0.388	0.02	0.719	1	0.667	0.773	0.102
								E < S (p = 0.004)					
	Relative Vertical Position without tops and toes	0.008	0.03	0.013	0.223	0.328	0.779	0.795	0.641	0.084	0.48	0.203	0.632
		lower side < top of slope (p = 0.002)	lower side nearly < upper side and top of slope NS	lower side < top of slope (p = 0.004)						upper side nearly > than top of slope NS			
	Aspect+Vert Position without tops and toes	0.308	NA	NA	0.286	NA	NA	0.256	NA	NA	0.477	NA	NA
Soil Temp 15 cm Depth	Relative Vertical Position	0.02	0.052	0.03	0.121	0.73	0.123	0.727	0.674	0.146	0.443	0.255	0.958
		lower side < top of mound (p = 0.001)	toe nearly > lower side NS lower side nearly < top of mound NS	toe and lower side nearly < top of mound NS									
	Aspect without tops and toes	0.895	0.621	0.512	0.517	0.19	0.442	0.006	0.714	0.105	0.943	0.867	0.121
								E < S and N (p = 0.008)					
	Relative Vertical Position without tops and toes	0.026	0.194	0.091	0.918	0.937	0.937	0.834	0.63	0.195	0.393	0.377	0.861
		lower side < top of slope (p = 0.008)		lower side nearly < top of slope NS									
	Aspect+Vert Position without tops and toes	0.186	NA	NA	0.276	NA	NA	0.199	NA	NA	0.651	NA	NA

We plotted the elevation of mounds against soil temperature at 5 cm and 15 cm depths, and soil moisture at the12 cm depth, for all transects at Colewort Creek, Drift Creek, and Ruby Lake (Figure 17−Figure 20).

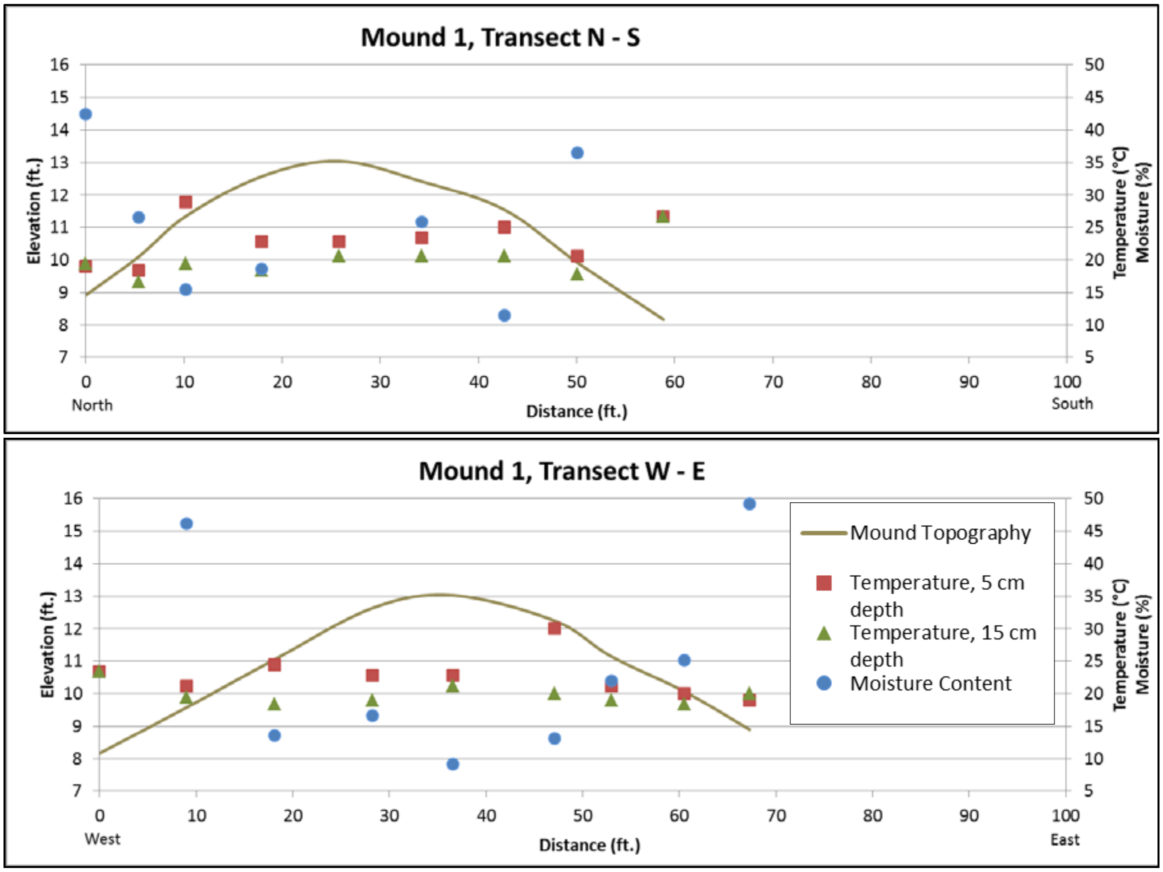


Figure 17. The elevation, soil temperature (at 5 cm and 15 cm depth), and soil moisture at 12 cm depth of transects on Mound 1 at Colewort Creek.

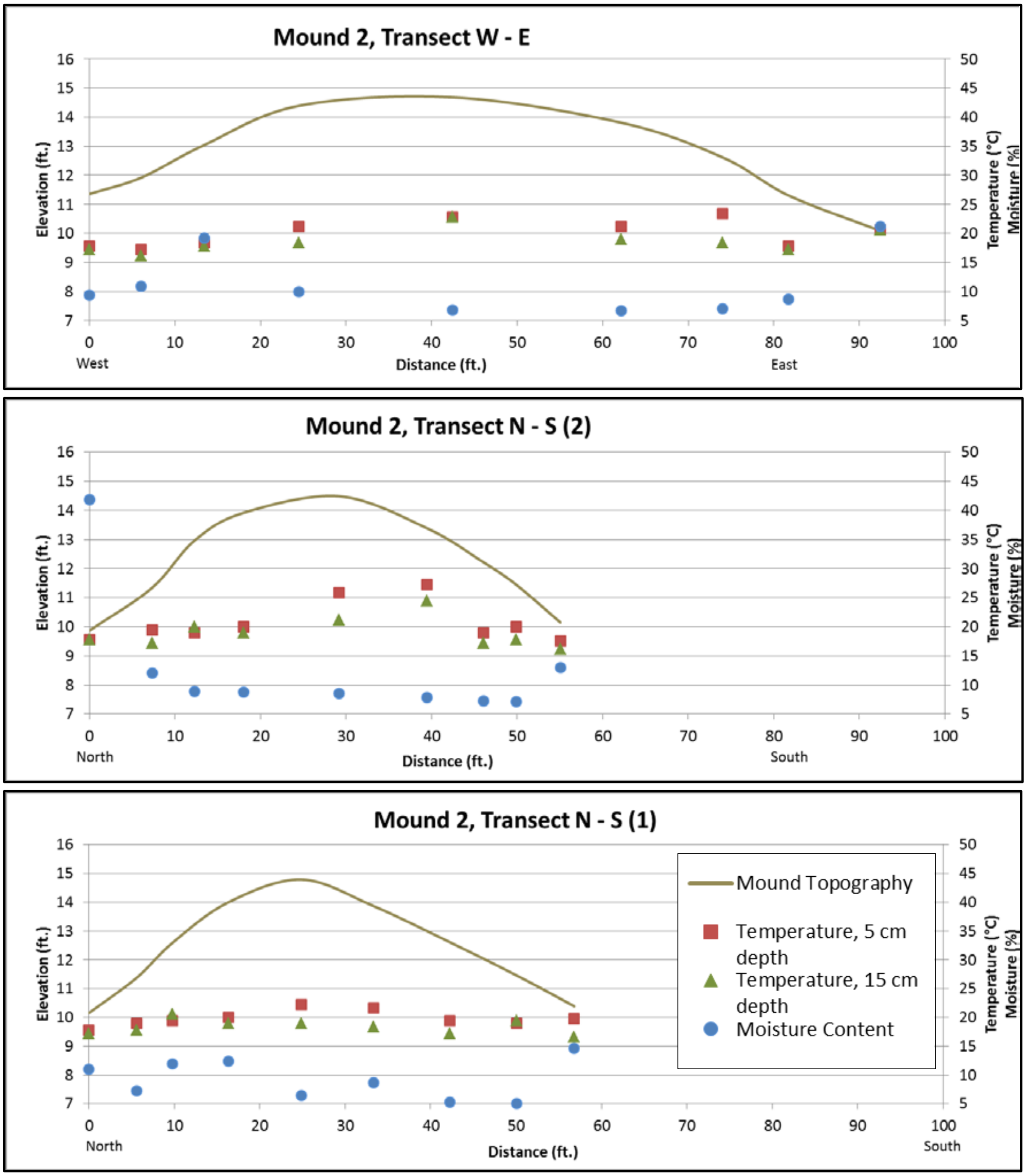


Figure 18. The elevation, soil temperature (at 5 cm and 15 cm depth), and soil moisture at 12 cm depth of transects on mound 2 at Colewort Creek.

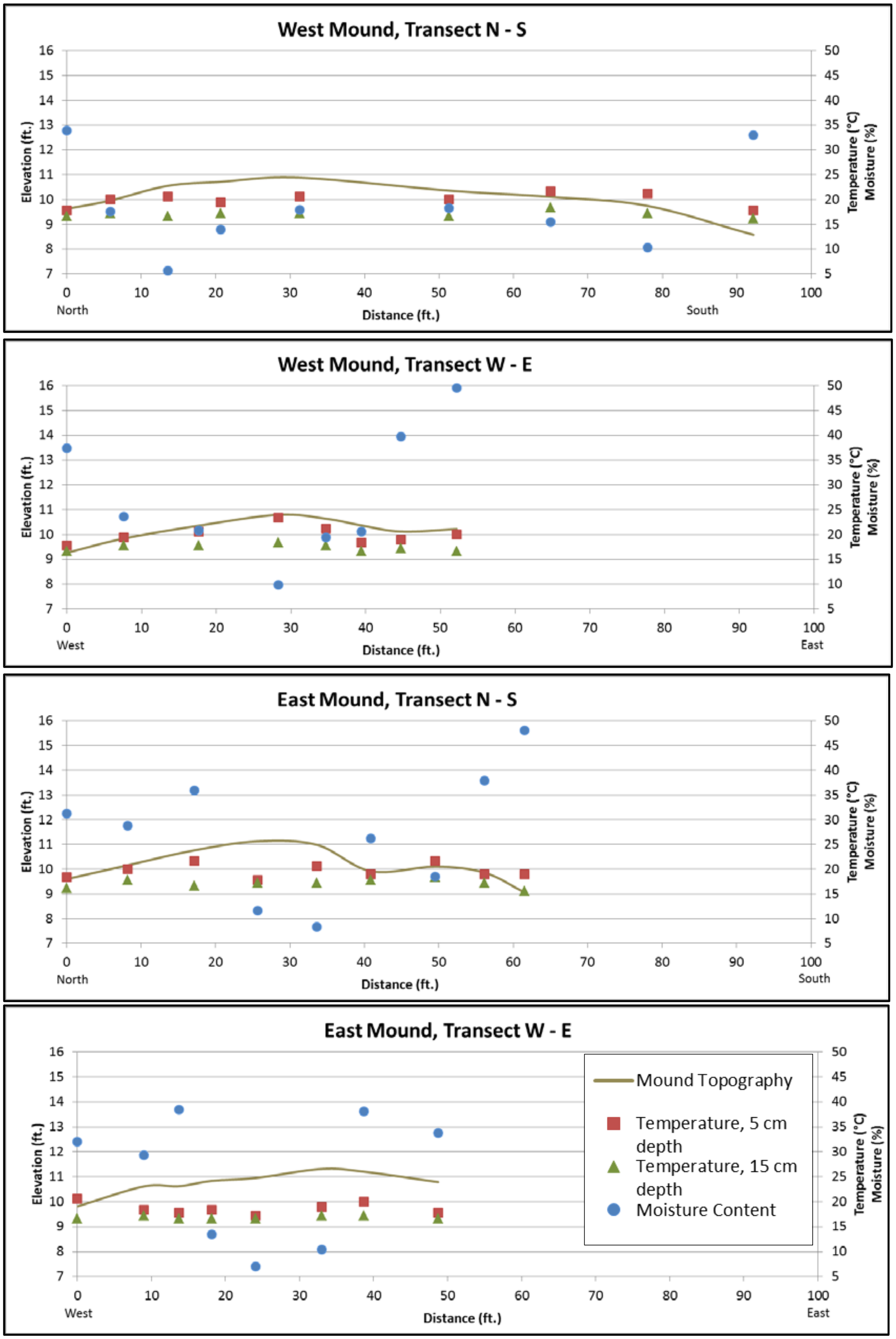


Figure 19. The elevation, soil temperature (at 5 cm and 15 cm depth), and soil moisture at the 12 cm depth of transects on eastern and western mounds at Drift Creek.

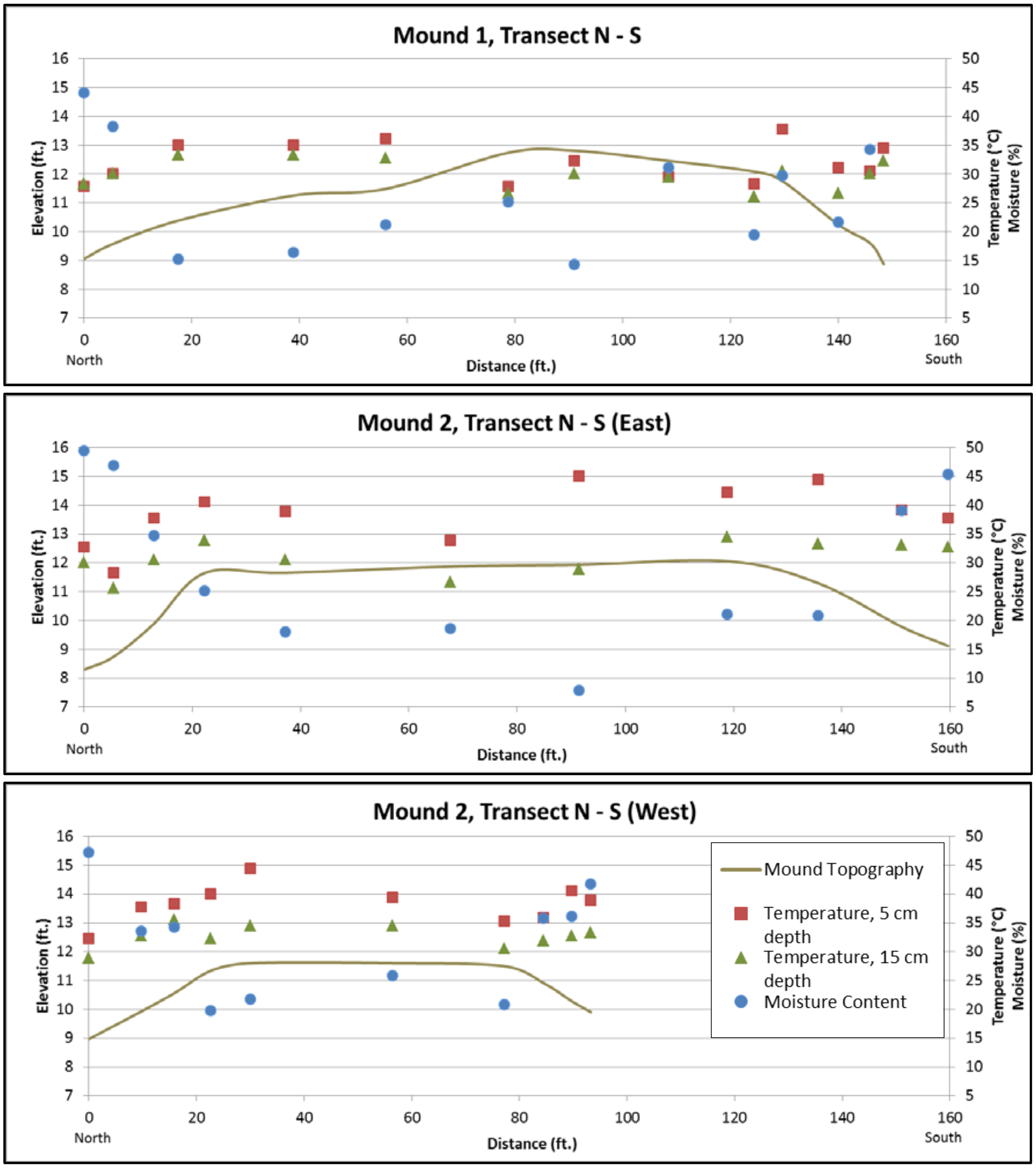


Figure 20. The elevation, soil temperature (at 5 cm and 15 cm depth), and soil moisture at the 12 cm depth of transects on mounds at Ruby Lake.

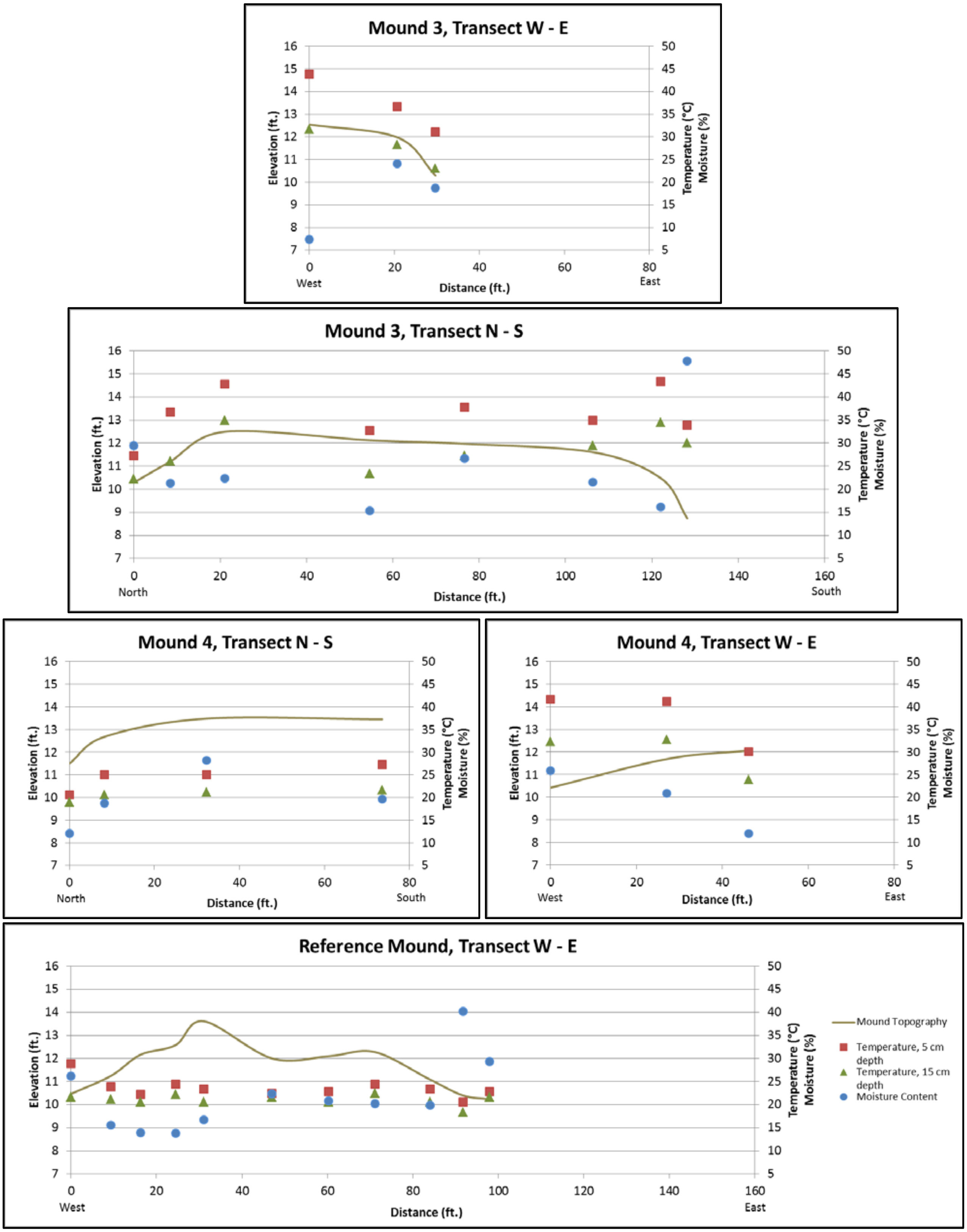


Figure 20. (contd)

Moisture and Relative Vertical Position

For all mounds at the Colewort Creek and Drift Creek sites, the median moisture at the toe of the mound was significantly greater than that at the top of the mound (Colewort Ck. n = 12, p = 0.0038; Drift Ck. n = 12, p = 0.0011). At these sites, in general moisture was negatively correlated with elevation at all mounds and this was significant for certain transects on certain mounds (Figure 21). At Ruby Lake, the median moisture at the toe of the mound was significantly greater than that at the top of the mound, the top of slope, and the upper side (total n = 49 for the four categories, p < 0.0041 for the three analyses). Differences in the minimum and maximum values of moisture (%) between the toe and the top of mound ranged from 2.9% to 40% with a median of 15.2% for minimum values and 27.6% for maximum values. There were some indications of similar trends along the sides of some other mounds.

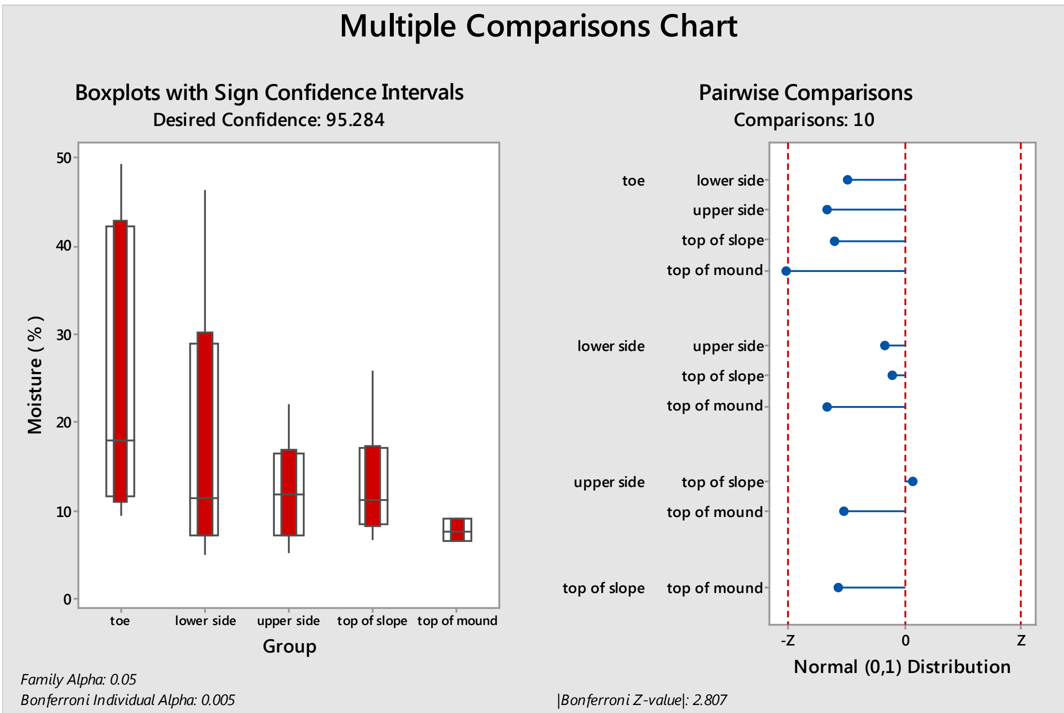


Figure 21. Moisture at mounds at Colewort Creek by relative vertical position.

For instance, there were significant differences in multiple comparisons for Mound 1 at Colewort Creek (n = 14, p = 0.022) and Drift Creek East Mound (n = 18, p = 0.027), though none of the pairwise comparisons were significant (Figure 22). (In these cases, it is likely that a combination of medians is driving the multiple comparisons result not the pairwise comparisons.)

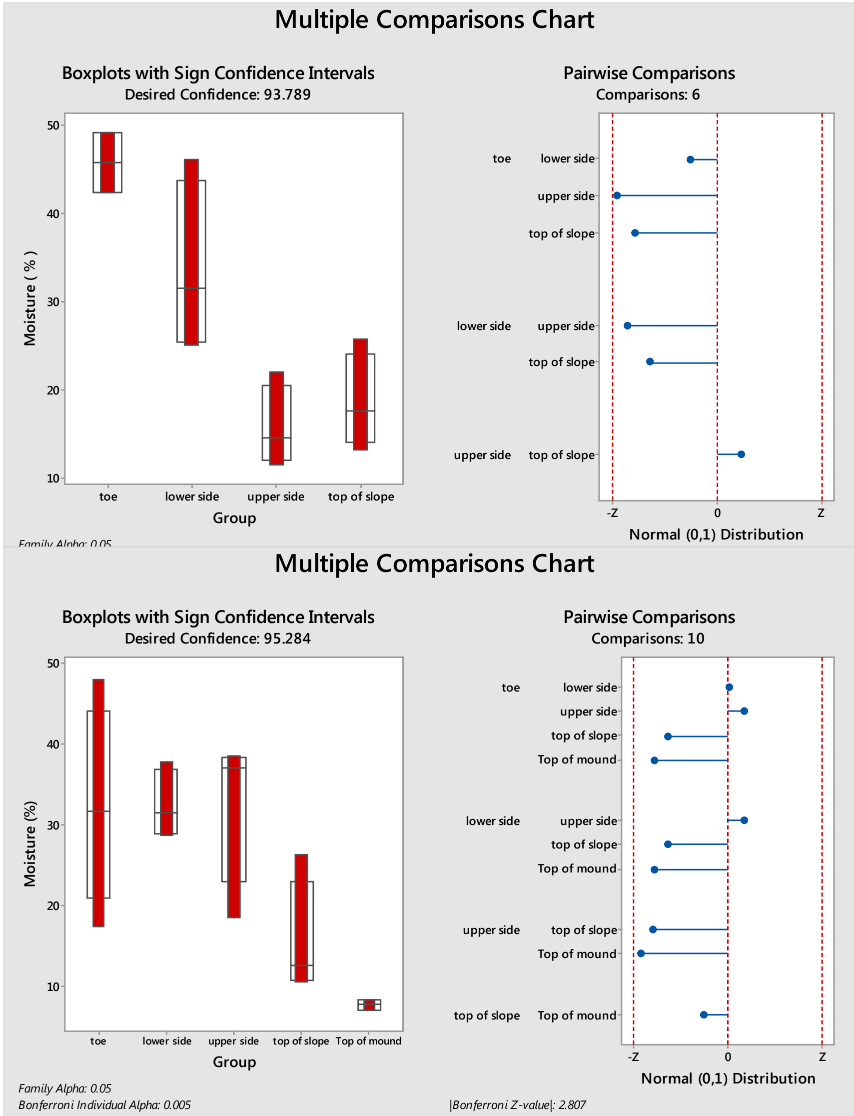


Figure 22. Moisture by relative vertical position at a single mound on Colewort Creek (Mound 1) (top) and Drift Creek Eastern alluvial fan (bottom).

When both the top of the mound (not to be confused with the top of slope) and the toe of the mound are removed from this analysis, we see a significant difference between the lower and upper side, and the trend suggests the top of the slope is also dryer than the lower side of Mound 1 at Colewort Creek, but in contrast the condition of the top of slope is similar to that of the lower side on the East Mound of Drift Creek (Figure 23). One possible explanation for this is the presence of red alder (*Alnus rubra*) tree cover on the top of the mound at Drift Creek, in contrast to Mound 1 at Colewort Creek where plantings had low success and vigor and would be unlikely to cast shade.

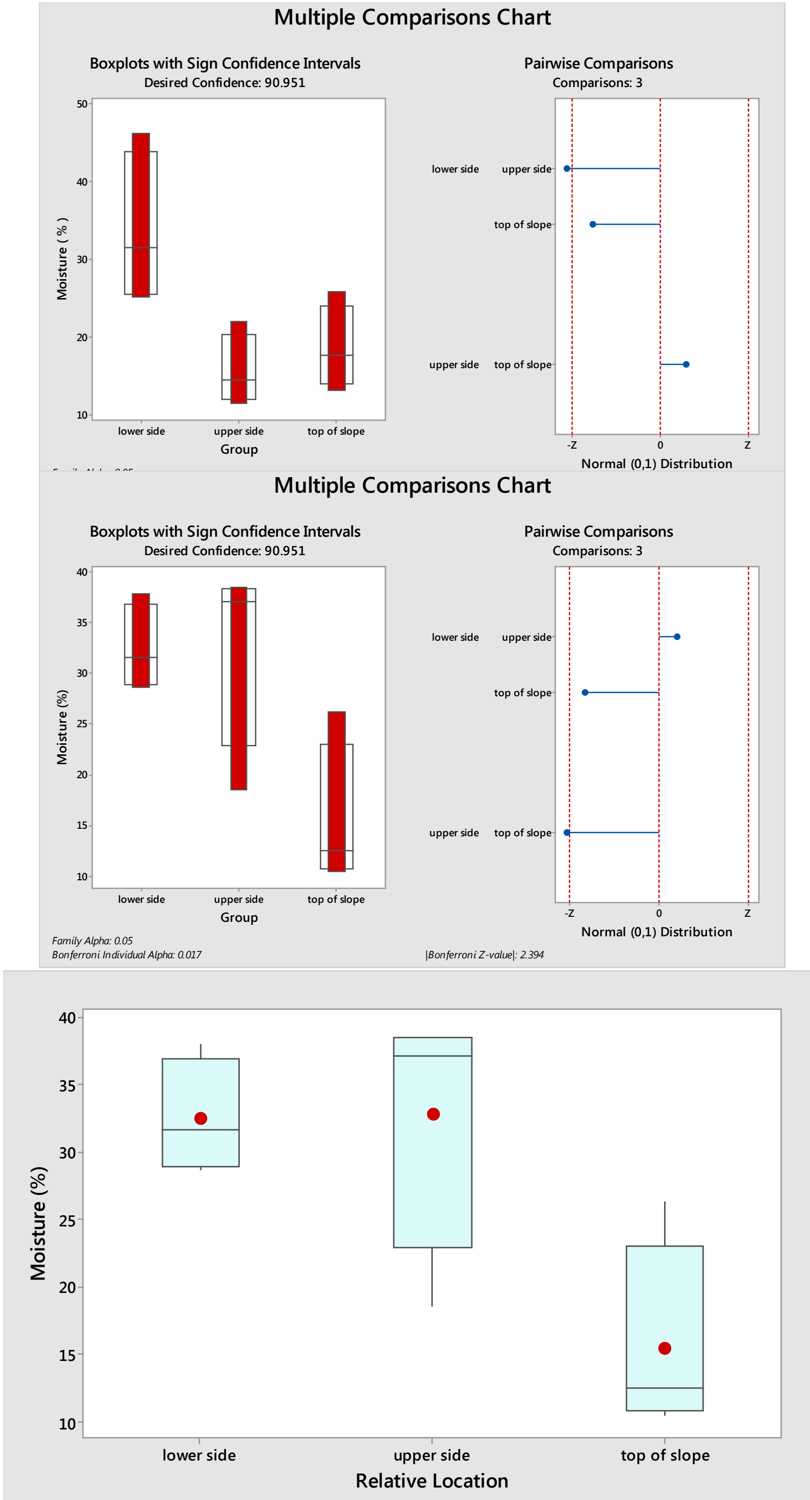


Figure 23. The moisture at three positions on the sides of a single mound at Colewort Creek (Mound 1, upper panel); Drift Creek (East Mound, middle panel); and boxplot of ANOVA results for Drift Creek (lower panel).

For Colewort Creek Mound 2, there was a significant difference in multiple comparisons for (n = 27, p = 0.033) and the pairwise comparisons of toe to top of mound was significant (n = 9, p = 0.004) (Figure 24).

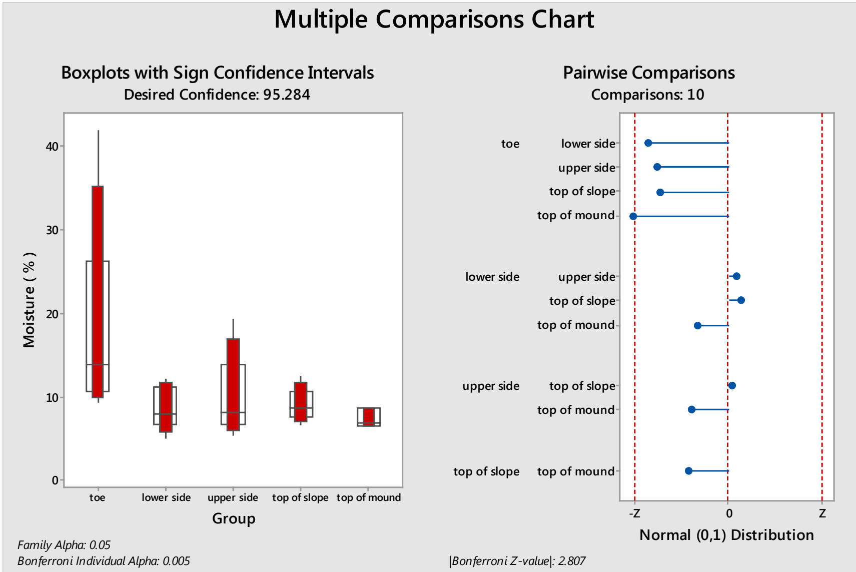


Figure 24. Multiple comparisons were significant as were pairwise comparisons of moisture between toe and top of mound at Colewort Creek Mound 2.

Temperature and Relative Vertical Position

On 11 of 14 transects at Colewort Creek, Drift Creek, and Ruby Creek (those with more than 5 observations) soil temperature at 5 cm was positively correlated with elevation. At 10 of the 14 transects soil temperature at 15 cm was positively correlated with elevation. Temperature was significantly different between the toe and top of the mound at Colewort Creek Mound 2 and when tops and toes were removed between the lower side and top of slope. For all transects at Colewort Creek but not at Drift Creek, median soil temperature at the 5 cm depth was significantly greater at the top of the slope than at the lower side (n = 20, p = 0.0035) (Figure 25). At Colewort Creek, the temperature at the 5 cm depth was significantly cooler on the lower sides of mounds than at the top of slope.

Aspect

Examination of the data for temperature and moisture relative to cardinal direction or aspect indicated that there could be substantial differences between the sides of a particular mound. However, those differences were not consistent between mounds. For example, the soils on the north and west sides of Colewort Creek Mound 2 were moister than those on the south and east sides, while soils on the east side of Ruby Lake Mound 0 (the reference mound) were significantly moister than those on the west side (n = 7, p = 0.034). Examination of residuals on Colewort Creek Mound 2 supported parametric analysis with ANOVA and Tukey's pairwise comparison, which showed a significant difference between soil moisture on the south and west sides (Figure 26a). Aspect was nearly significant (n = 11, p = 0.052) for the western mound at Drift Creek, where moisture is high on the eastern side along the channel (Figure 26b).

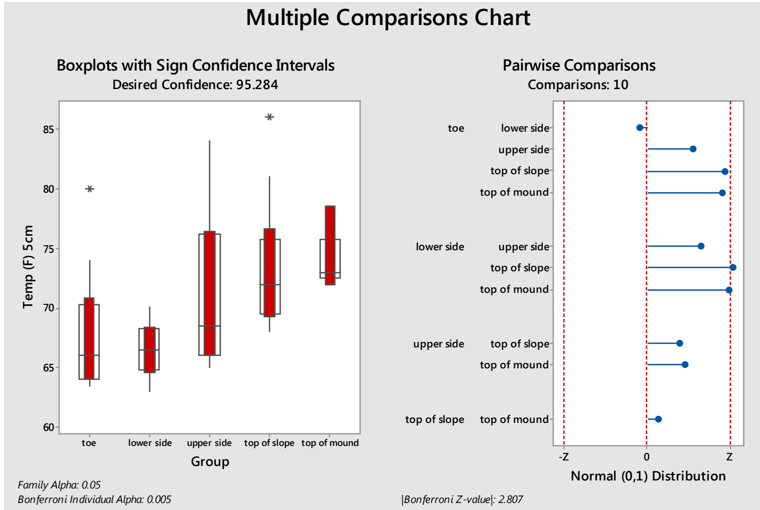


Figure 25. Temperature at the 5 cm depth for all five transects at Colewort Creek.

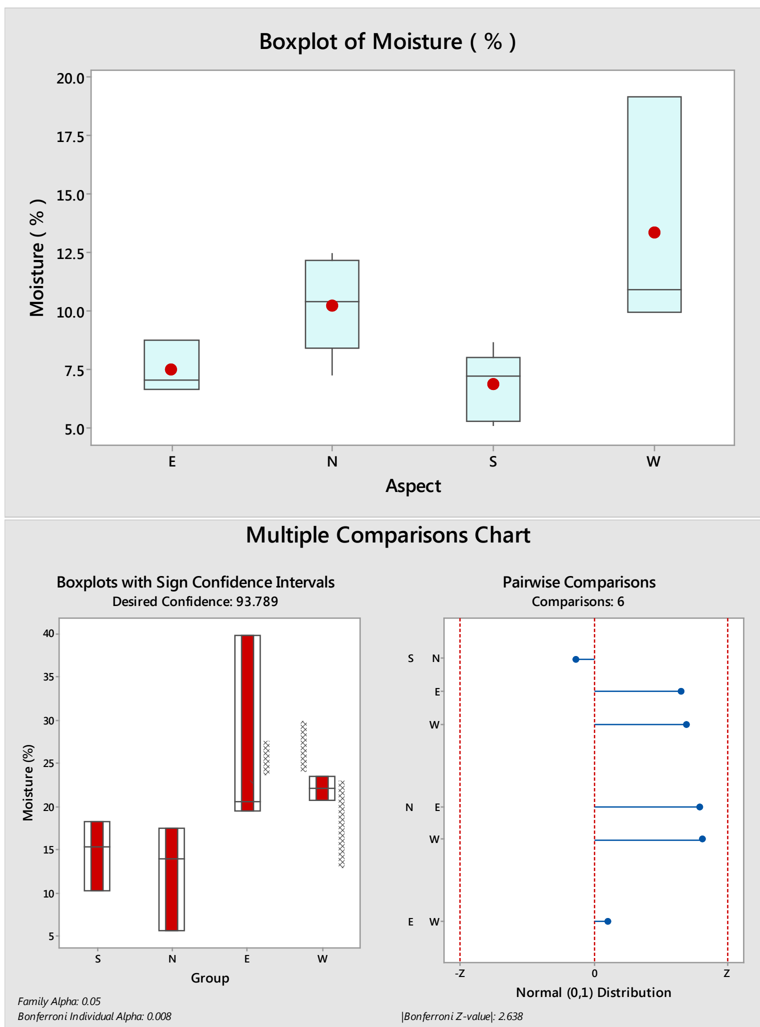


Figure 26. Boxplot of results of parametric analysis of soil moisture by aspect on Colewort Creek Mound 2 (top), and multiple and pairwise comparisons of Drift Creek West (bottom).

5.1.3 Soil Parameters at Anderson Creek and Marietta Slough

The number of samples collected at Anderson Creek and Marietta Slough was insufficient for statistical analysis; the results are presented in plots (Figure 27). The range of temperatures at Marietta Slough was slightly larger than the range at Anderson Creek.

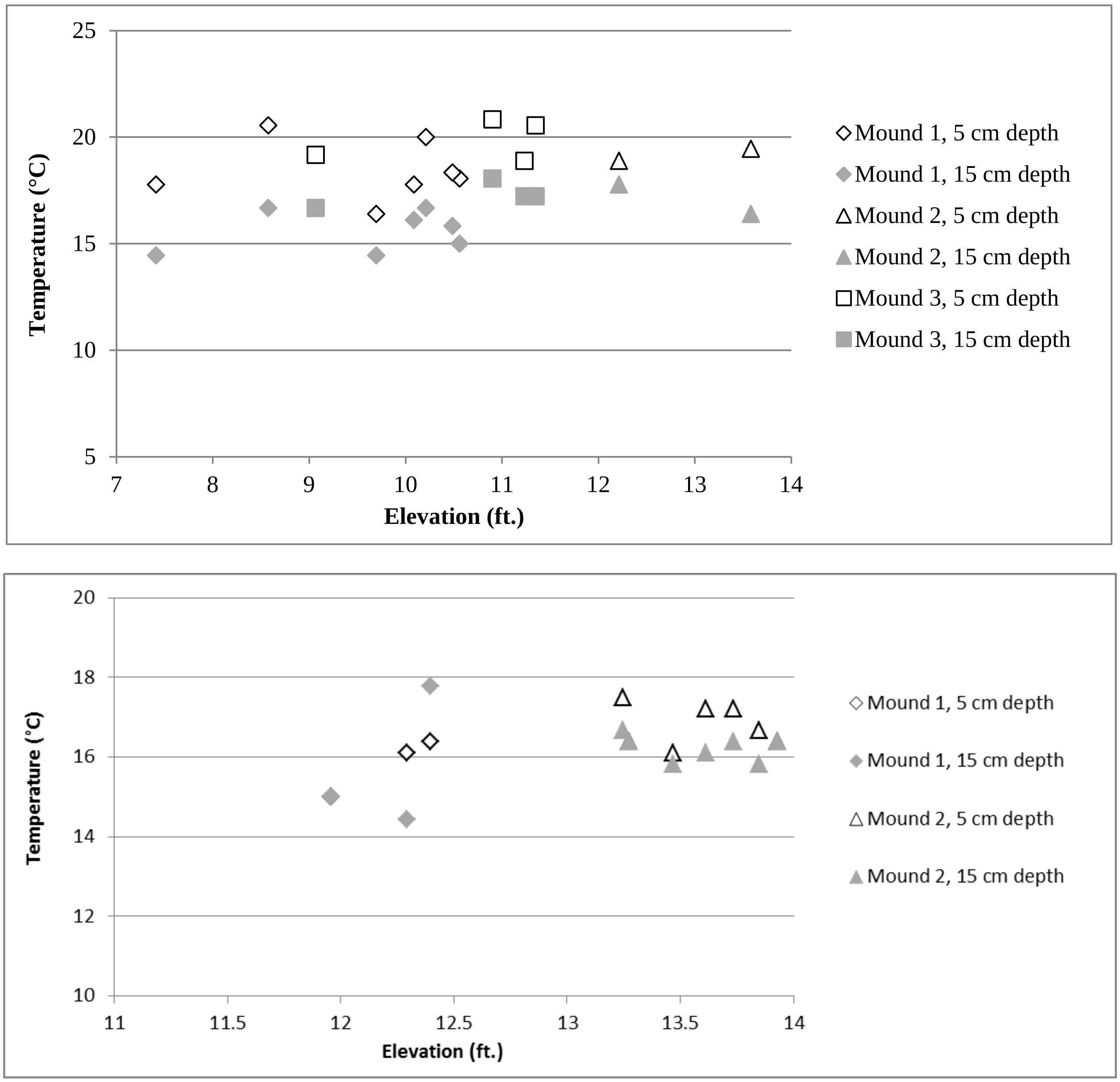


Figure 27. Soil temperature at Anderson Creek (lower panel) and Marietta Slough (upper panel) mounds relative to elevation (ft, NAVD88). At Anderson Creek, points at elevation 11.96 ft, 13.28 ft, and 13.93 ft have the same temperature at both depths.

5.2 Reed Canarygrass

Results include field observations of vegetation and surface and soil conditions, and quantitative data from two older restoration sites: statistical analysis of 1 m^2 plot-scale percent cover data from Devil's Elbow, and spatial data analysis of the change in areal cover of reed canarygrass from Spencer Island.

5.2.1 Field Observations

Differences in reed canarygrass cover between and within sites were visually observed and assessed quantitatively.

Where sufficient tidal inundation has been established either through excavation or levee breaching it appears that native vegetation is successful in out-competing reed canarygrass. Successful examples include Devil's Elbow, Ruby Lake, and Spencer Island. We determined that the lower elevations of reed canarygrass at the Devil's Elbow and Ruby Lake sites were 1.7 m, CRD (1.83 m or 6.0 ft, NAVD88) and 1.45 m, CRD (2.74 m or 9.0 ft, NAVD88), respectively. The lower elevation of reed canarygrass at the Spencer Island site varied across the site from 2.0 to 2.5 m, NAVD88. The range of lower elevations at Spencer Island was perhaps due to the effect of proximity to the main channel of the Snohomish River, where salinity may also have an effect. The modeled WSE and salinity data from the site indicated that 0.1–5 ppt salinity was likely reaching the site about 29 percent of the year (during the dry season July–October), which may also limit the lower elevation range. It is possible that the salinity affects may have increased over time at the site because recent restoration has resulted in more of the site being connected to the lower parts of the river. The lower elevation of reed canarygrass also varies across sites due to differences in the inundation regime. For example, the tidal range at Spencer Island is >3 m and likely precludes reed canarygrass at lower elevations. In the LCRE the lower limit of reed canarygrass is higher at the sites with a greater tidal range; see Section 5.2.2.2 below for a summary of the lower elevations of reed canarygrass in the LCRE.

In addition to elevation and inundation, observations about other control methods include the following:

- Most field sites visited have had woody vegetation established as a primary reed canarygrass control strategy. This appears to be a successful approach, although it is too early in most cases to be certain because woody vegetation is still becoming established. Where older plantings (8 or more years old) have been established, reed canarygrass is being shaded out. Examples include Kandoll Farm and Siuslaw. More recent planting areas appear to be on a positive trajectory, including those at Colewort Creek.
- Examination of plots at the North Fork Siuslaw restoration site generally confirmed findings by Brophy (2014) that the cover of three native plants was beginning to compete with reed canarygrass in at least one of the four plots. These plants included lady fern (*Athyrium filix-femina*), black vetch (*Vicia nigricans*), and cow parsnip (*Heracleum maximum*). These are all higher marsh species that are able to grow taller than reed canarygrass.
- Construction timing and seeding prior to reed canarygrass seed establishment seems to have been successful at Ruby Lake where species such as tufted hairgrass (*Deschampsia cespitosa*) has been established and reed canarygrass invasion has been avoided.
- Single late-season post-emergent herbicide application may have provided initial reduction of reed canarygrass cover but does not appear to provide any significant long-term impact on monocultural populations (Kandoll Farm).

5.2.2 Analysis of Data

5.2.2.1 Statistical Analysis

Results from the evaluation of vegetation plots from the Devil's Elbow site indicate that reed canarygrass is declining at the site and native species are increasing (Figure 28). Cover in the vegetation plots varied spatially, especially with regard to reed canarygrass; some plots had much higher reed canarygrass cover than others (Figure 29). The vegetation cover also varied over time, becoming less similar to the cover estimated in 2005 (Figure 30a). The greatest difference was observed in 2015—11 years after restoration (Figure 30b).

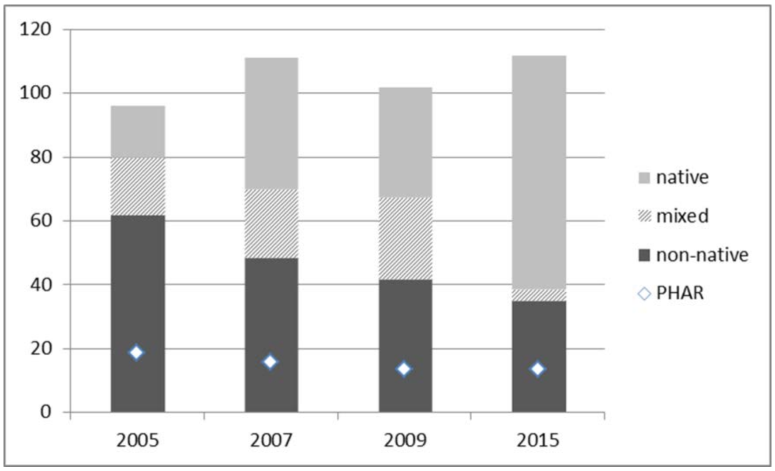
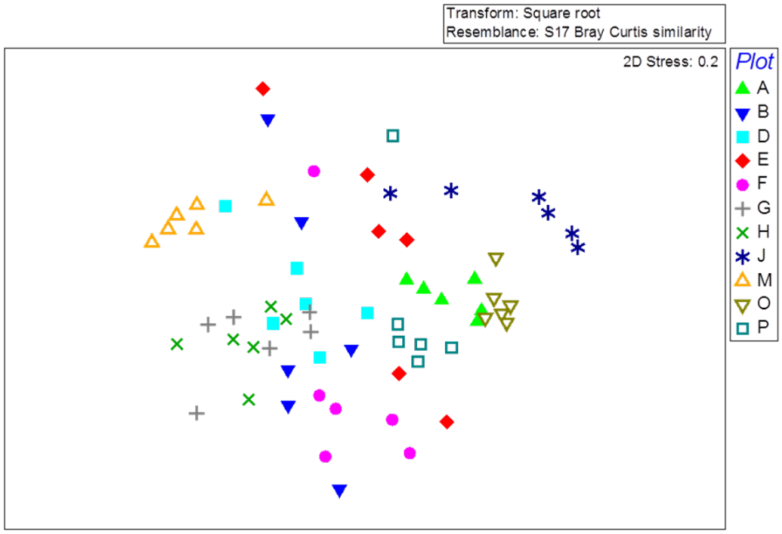


Figure 28. Absolute average percent cover of reed canarygrass (RCG), compared to the total of all native plant species, and the total of all other non-native plant species. The mixed category represents cases in which plants could be identified to genus not species, and thus native or non-native status could not be determined.



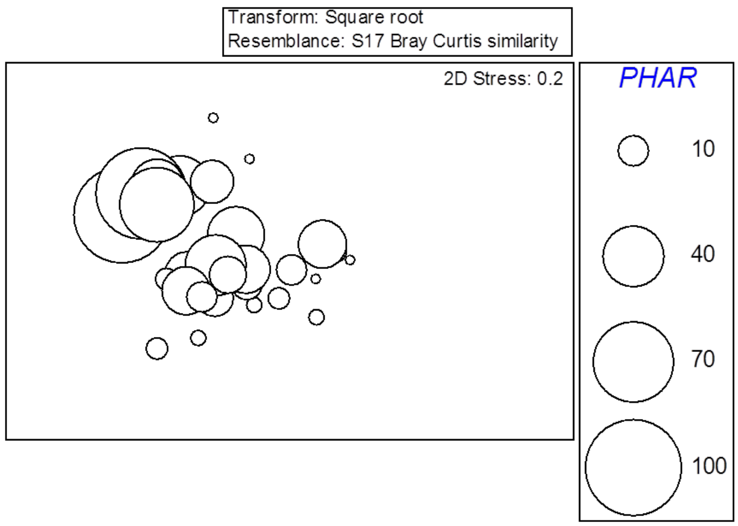


Figure 29. Non-metric multidimensional scaling plot of a Bray-Curtis similarity analysis of plant species cover (top panel) and reed canarygrass cover (RCG; bottom panel) in 11 plots and 6 years of sampling at Devil's Elbow, beginning in 2005 and ending in 2015.

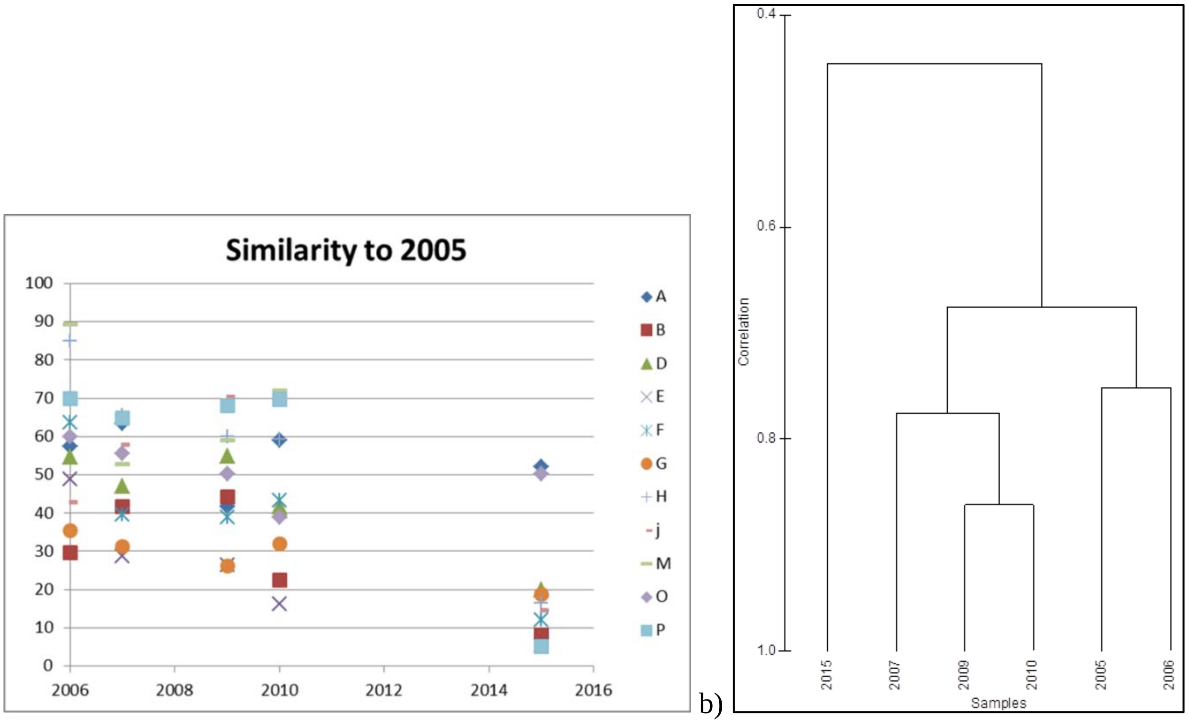


Figure 30. Plot showing the change in the vegetation over time at 11 plots at the Devil's Elbow site sampled in 6 years between 2005 and 2015: a) the similarity of plant species percent cover in all years compared to 2005; and b) a cluster diagram of the second stage (Spearman) correlations across years.

5.2.2.2 Elevation Analysis

The distribution of reed canarygrass elevations and its relationship to the lower elevations of marshes and shrub-dominated wetlands is a tool for restoration planning but it differs along the river (Table 9). Reed canarygrass is not present below rkm 15 and is found at higher elevations in the lower portion of the LCRE below rkm 35. Aside from that, the elevation relative to NAVD88 generally increases moving up river as the overall riverbed elevation increases. Where data were available we included the elevation of the lower limit of emergent marsh vegetation and woody vegetation as a means of bracketing the potential extent of emergent marsh at each river location. Variability in the shrub boundaries is more greater than the other boundaries depending on the species that were present at the reference sites.

Table 9. Lookup table for the lower limit of reed canarygrass (RCG) elevation, marsh elevation, and shrub elevation by 5 km intervals from the mouth of the Columbia River to Bonneville Dam. Elevations are in feet NAVD88.

River Kilometer	5	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80
River Mile	3	6	9	12	16	19	22	25	28	31	34	37	40	43	47	50
Lower Marsh Elevation	5.0	5.0	4.1	3.2		3.2	3.1	3.6			2.9			4.2	3.8	4.4
Lower RCG Elevation	NA	NA	NA	8.1	8.0	6.8	6.8	5.4	5.7	5.8	5.8	6.0	6.2	6.3	6.4	6.6
Lower Shrub Elevation		10.1		9.2			9.1	7.4			7.8	8.1		8.3	8.4	8.9

River Kilometer	85	90	95	100	105	110	115	120	125	130	135	140	145	150	155	160
River Mile	53	56	59	62	65	68	71	75	78	81	84	87	90	93	96	99
Lower Marsh Elevation		5.6		5.9	5.8		5.6	6.2		6.6			7.4	8.0	7.7	
Lower RCG Elevation	6.9	6.9	7.1	7.2	7.4	7.7	8.0	8.1	8.2	8.4	8.7	8.7	8.8	8.9	9.0	9.2
Lower Shrub Elevation		9.2		8.6	8.6			10.0		10.9		14.0	9.8	13.1	10.8	

River Kilometer	165	170	175	180	185	190	195	200	205	210	215	220	225	230
River Mile	103	106	109	112	115	118	121	124	127	130	134	137	140	143
Lower Marsh Elevation						9.6	10.7	10.2		10.4		12.7		12.0
Lower RCG Elevation	9.4	9.7	10.2	10.5	10.8	11.2	11.6	12.5	13.0	13.5	13.9	14.2	14.3	15.1
Lower Shrub Elevation						13.8		13.0	15.3			16.0		17.4

5.3 Channel Networks

This section summarizes the results of our spatial data processing and statistical analysis of island area, wetland area, wetland channel area, wetland channel perimeter, and the number of wetland channel outlets, differentiated between wetlands on islands and the mainland. We tested the null hypotheses of no difference in basic tidal channel network descriptors between reaches, and no difference between wetlands located on the mainland and the islands of any given reach. To the extent warranted by the existing data, we developed linear regression models for wetland channel perimeter, wetland channel area, and the number of wetland channel outlets, all as a function of wetland area. In reporting statistical results in this section, significance is stated if $p < 0.05$.

5.3.1 Spatial Data Processing

We developed data for wetlands, separating the mainland and islands and each of eight hydrogeomorphic reaches, for the following parameters: channel area (m^2), channel perimeter (m), number of channel outlets, wetland area (m^2), and wetland perimeter (m) (Figure 31). Despite the high-quality data sets that recently have been made available, this remained an extremely challenging task because of the variability throughout a tidal river system, which required many levels of discrimination to achieve consistent interpretations. We evaluated channel perimeter rather than length because channel length data were not available in the databases and assessment of the perimeter data revealed that no fraction of perimeter would equal a reasonable assessment of length because of the convoluted nature of some tidal channel networks and the great variability in network plan-form across the LCRE. This rule-based census approach to data development produced a large number of wetlands for subsequent statistical analysis. For mainland wetlands, $n = 164$, with a large range by reach: Reach G, $n = 2$ to Reach B, $n = 60$. For island wetlands, which are only present in Reaches A, B, and C, $n = 142$, also with a large range by reach: Reach A, $n = 8$ to Reach B, $n = 113$.

5.3.2 Descriptive Statistics

In this section, a summary of some basic features of wetland channel networks on islands and the mainland is presented in tabular form for the eight hydrogeomorphic reaches of the LCRE.

5.3.2.1 Mainland Channel Networks

We evaluated nine features of wetland channel networks on the mainland. Five of them were developed directly by spatial data processing in GIS and four were ratios: channel area (m^2), channel perimeter (m), number of channel outlets, wetland area (m^2), wetland perimeter (m), channel area:wetland area, channel perimeter:wetland area (m/m^2), channel outlets:wetland area (outlets/ha), and wetland area:wetland perimeter (m^2/m). All features varied widely with high coefficients of variation (CVs); e.g., mainland wetland area ranged from 1,127 m^2 to 2,640,041 m^2, the number of channel outlets from 0 to 41, and the ratio of channel outlets:wetland area from 0.011 outlet/ha to 9.74 outlets/ha (Table 10).

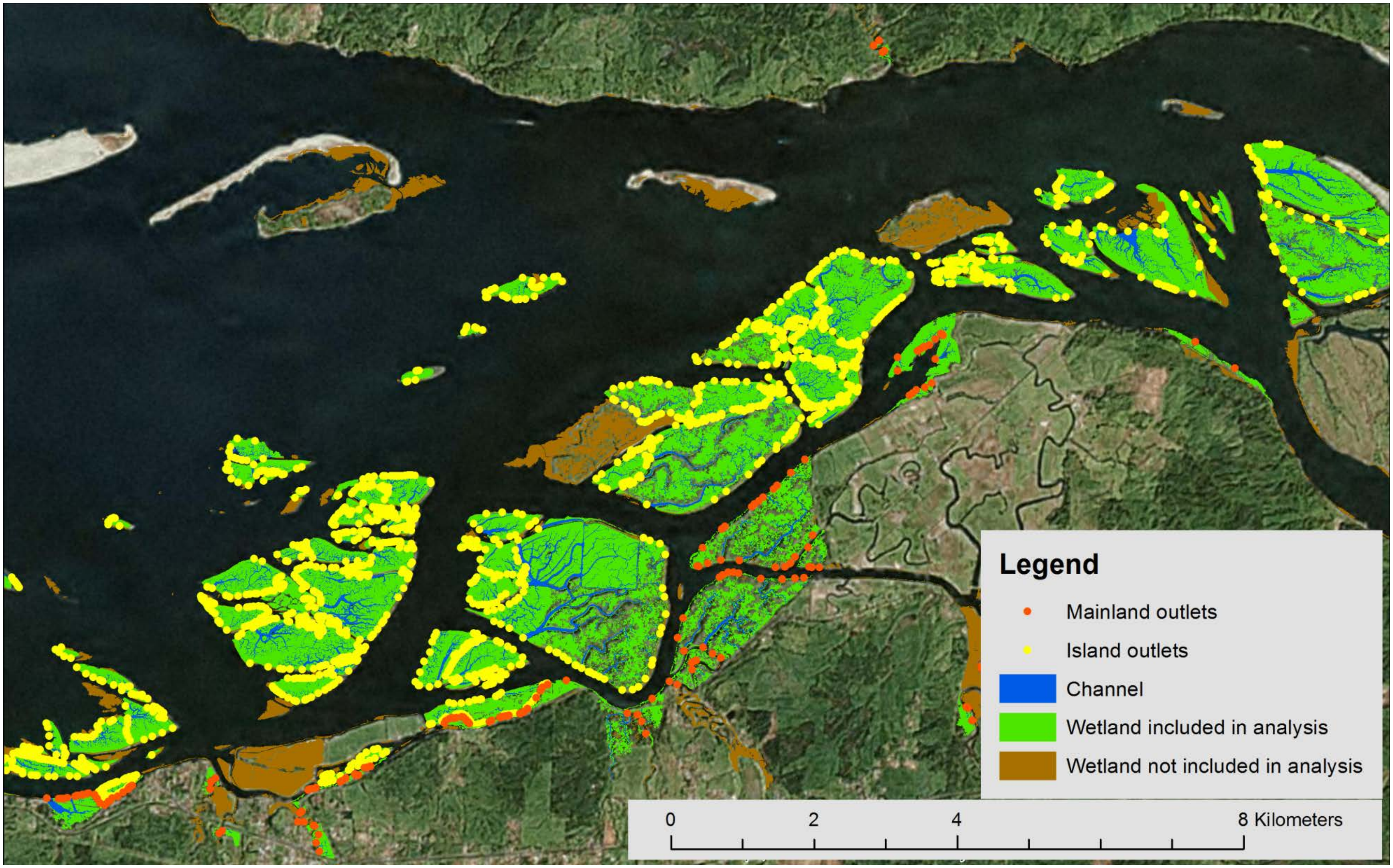


Figure 31. Example of marsh area (green), island channel outlets (yellow dots), and mainland channel outlets (orange dots).

Table 10. Descriptive statistics for mainland wetland channel networks including as a rule the small channels, tidal channels, floodplain channels, and tie channels categories classified in the Landscape Planning Framework, and all other channels identified within wetlands through visual examination of the data.

Variable	Reach	N	Mean	StDev	Minimum	Q1	Median	Q3	Maximum	CV
Channel area (m^2)	A	24	9602	15934	83	643	3498	12214	62207	166%
	B	60	8249	19516	29	272	1578	4878	113517	237%
	C	22	8932	28389	73	105	404	5424	133640	318%
	D	5	1446	2031	38	62	569	3268	4890	140%
	E	19	3233	7627	76	243	476	3333	33812	236%
	F	28	17335	49671	38	181	769	7647	234307	287%
	G	2	11669	13413	2185	*	11669	*	21153	115%
	H	4	17298	24593	765	838	7751	43304	52924	142%
Channel perimeter (m)	A	24	3341	5149	65	240	1677	2939	21006	154%
	B	60	1890	3446	24	133	456	1836	18494	182%
	C	22	2127	6218	43	85	186	1748	29412	292%
	D	5	333	390	30	58	267	640	1002	117%
	E	19	566	809	59	147	249	722	3579	143%
	F	28	2830	7475	24	100	373	1985	38474	264%
	G	2	1076	757	540	*	1076	*	1611	70%
	H	4	2470	2916	340	342	1510	5559	6521	118%
No. of channel outlets	A	24	6.46	9.75	1.00	1.00	2.50	7.75	41.00	151%
	B	60	5.58	7.44	1.00	1.00	2.00	6.75	33.00	133%
	C	22	2.91	2.67	1.00	1.00	1.50	5.00	9.00	92%
	D	5	1.20	0.45	1.00	1.00	1.00	1.50	2.00	37%
	E	19	1.21	0.71	1.00	1.00	1.00	1.00	4.00	59%
	F	28	2.36	3.76	0.00	1.00	1.00	2.00	20.00	160%
	G	2	1.50	0.71	1.00	*	1.50	*	2.00	47%
	H	4	1.50	1.00	1.00	1.00	1.00	2.50	3.00	67%
Wetland Area (m^2)	A	24	100599	178642	1127	4721	34475	105059	825726	178%
	B	60	85793	144028	1206	6762	25981	95318	779141	168%
	C	22	114124	291081	2084	8789	33089	89235	1393183	255%
	D	5	98236	169803	1261	2128	10214	238355	396219	173%
	E	19	28941	33182	1741	6359	20905	33564	137017	115%
	F	28	304151	601299	1411	7572	75173	258363	2640041	198%
	G	2	85459	39747	57354	*	85459	*	113564	47%
	H	4	157897	170273	3429	7487	149861	316345	328439	108%
Wetland Perimeter (m)	A	24	7616	10594	392	1000	4881	7668	41474	139%
	B	60	9159	17742	276	1169	3320	10455	104131	194%
	C	22	6760	9843	717	1399	3268	8819	45907	146%
	D	5	4710	5695	324	538	2082	10196	13919	121%
	E	19	2807	2856	633	1545	2113	3574	13684	102%
	F	28	11949	22148	617	1196	5652	12206	115165	185%
	G	2	4627	804	4059	*	4627	*	5196	17%
	H	4	7013	7235	961	1511	4905	14624	17283	103%

Table 10. (contd)

Variable	Reach	N	Mean	StDev	Minimum	Q1	Median	Q3	Maximum	CV
Channel Area:Wetland Area	A	24	0.166	0.163	0.015	0.057	0.103	0.243	0.629	98%
	B	60	0.074	0.080	0.003	0.024	0.048	0.096	0.391	107%
	C	22	0.070	0.148	0.003	0.009	0.028	0.067	0.708	212%
	D	5	0.052	0.066	0.007	0.010	0.013	0.115	0.161	126%
	E	19	0.102	0.110	0.011	0.012	0.048	0.246	0.330	108%
	F	28	0.089	0.130	0.000	0.005	0.043	0.108	0.513	146%
	G	2	0.112	0.105	0.038	*	0.112	*	0.186	93%
	H	4	0.309	0.311	0.002	0.049	0.249	0.628	0.735	101%
Channel Perimeter: Wetland Area	A	24	0.059	0.050	0.010	0.026	0.040	0.073	0.211	85%
	B	60	0.025	0.019	0.003	0.011	0.020	0.031	0.085	77%
	C	22	0.022	0.034	0.002	0.005	0.014	0.022	0.156	154%
	D	5	0.022	0.028	0.003	0.003	0.010	0.048	0.068	124%
	E	19	0.032	0.037	0.005	0.008	0.016	0.038	0.138	115%
	F	28	0.026	0.049	0.000	0.004	0.013	0.019	0.230	191%
	G	2	0.012	0.003	0.009	*	0.012	*	0.014	29%
	H	4	0.065	0.063	0.001	0.007	0.061	0.127	0.136	98%
Channel Outlets: Wetland Area (ha)	A	24	2.131	2.490	0.218	0.492	0.945	2.947	8.877	117%
	B	60	2.177	2.538	0.027	0.389	1.132	2.912	9.740	117%
	C	22	1.354	2.210	0.065	0.315	0.469	1.139	9.152	163%
	D	5	2.480	3.320	0.050	0.090	0.980	5.630	7.930	134%
	E	19	1.225	1.466	0.145	0.298	0.503	1.573	5.743	120%
	F	26	1.169	1.794	0.011	0.075	0.553	1.424	7.088	153%
	G	2	0.218	0.184	0.088	*	0.218	*	0.349	84%
	H	4	0.891	1.367	0.030	0.050	0.308	2.314	2.916	153%
Wetland Area: Wetland Perimeter	A	24	9.490	5.920	2.200	4.870	7.180	15.300	19.910	62%
	B	60	8.857	5.116	2.169	5.193	7.703	11.037	29.595	58%
	C	22	11.200	6.740	2.380	5.180	12.340	15.000	30.350	60%
	D	5	10.740	10.530	3.890	3.940	4.910	20.450	28.470	98%
	E	19	8.820	4.410	2.750	3.830	9.390	11.530	16.580	50%
	F	28	16.460	12.280	1.860	7.560	13.700	22.860	57.950	75%
	G	2	17.990	5.460	14.130	*	17.990	*	21.860	30%
	H	4	18.800	21.100	3.600	4.200	11.200	41.100	49.400	112%

5.3.2.2 Island Channel Networks

For islands, we evaluated the same features as for mainland wetlands and additionally included island area. Only three reaches were evaluated because the other reaches had no islands, with the exception of G (n = 1). Similar to mainland wetlands, the variability is high, e.g., 1 to 69 channel outlets, wetland area of 0.09 ha to 251.36 ha, and the ratio of channel outlets:wetland area from 0.13 to 17.71 outlets/ha (Table 11).

Table 11. Descriptive statistics for island wetland channel networks including as a rule the small channels, tidal channels, floodplain channels, and tie channels categories classified in the Landscape Planning Framework, and all other channels identified within wetlands through visual examination of the data.

Variable	Reach	N	Mean	StDev	Minimum	Q1	Median	Q3	Maximum	CV
Channel perimeter (m)	A	8	2813	3224	391	408	1630	6324	8091	115%
	B	113	7809	14463	28	338	1589	8728	93287	185%
	C	21	2035	2355	35	203	867	3452	7562	116%
Channel area (m^2)	A	8	8051	12265	413	650	2698	15467	34138	152%
	B	113	28784	65869	33	579	3776	28768	532344	229%
	C	21	7125	10134	52	369	2242	10883	33773	142%
No. Channel Outlets	A	8	8.25	5.34	2	3.25	7.5	12.75	17	65%
	B	113	15.19	15.22	1	3	9	24.5	69	100%
	C	21	9.33	8.22	1	4	6	15.5	27	88%
Island Area (ha)	A	8	5.64	5.1	0.62	2.41	2.83	11.6	13.6	90%
	B	113	22.27	48.02	0.1	1.09	4.43	21.1	346.16	216%
	C	21	13.77	18.23	0.29	1.36	4.5	25.58	71.53	132%
Wetland Area (ha)	A	8	5.08	4.6	0.62	2.37	2.52	9.28	13.57	91%
	B	113	18.95	36.91	0.09	0.98	4.38	20.35	251.36	195%
	C	21	11.99	15.39	0.28	1.31	3.77	21.37	57.24	128%
Channel Perimeter: Wetland Area	A	8	0.07	0.10	0.02	0.02	0.04	0.06	0.30	136%
	B	113	0.04	0.02	0.00	0.03	0.04	0.05	0.15	56%
	C	21	0.02	0.01	0.01	0.01	0.02	0.03	0.07	67%
Channel Area: Wetland Area	A	8	0.23	0.45	0.02	0.03	0.07	0.13	1.34	200%
	B	113	0.12	0.10	0.01	0.06	0.11	0.16	0.60	79%
	C	21	0.06	0.06	0.01	0.02	0.04	0.09	0.25	96%
Channel Perimeter: Island Area	A	8	0.06	0.08	0.02	0.02	0.04	0.06	0.25	126%
	B	113	0.04	0.02	0.00	0.02	0.04	0.05	0.13	55%
	C	21	0.02	0.01	0.01	0.01	0.02	0.02	0.07	71%
Channel Area: Island Area	A	8	0.19	0.37	0.02	0.03	0.07	0.13	1.10	190%
	B	113	0.11	0.09	0.00	0.05	0.10	0.15	0.53	77%
	C	21	0.06	0.06	0.01	0.02	0.03	0.08	0.24	97%
Number of Outlets: Wetland Area (ha)	A	8	2.84	3.52	0.80	1.20	1.49	2.91	11.34	124%
	B	113	3.03	3.22	0.13	0.93	1.88	3.95	17.71	106%
	C	21	2.25	2.00	0.25	0.61	1.63	3.63	7.16	89%
Number of Outlets: Island Area (ha)	A	8	2.72	3.55	0.80	0.97	1.44	2.77	11.31	131%
	B	113	2.80	2.88	0.12	0.82	1.72	3.84	14.07	103%
	C	21	2.14	1.97	0.20	0.54	1.42	3.60	6.93	92%
Wetland Area: Island Area	A	8	0.927	0.087	0.788	0.833	0.974	0.996	0.998	9%
	B	113	0.925	0.086	0.701	0.886	0.970	0.984	1.000	9%
	C	21	0.913	0.073	0.781	0.857	0.940	0.977	1.000	8%

5.3.2.3 Summary of Descriptive Statistics

While our original intention in developing tables summarizing the channel network characteristics for each reach (Table 10, Table 11) was to provide a lookup table type functionality to support new-project planning, the variability indicates that it would be inappropriate to advise the general use of mean or median values of channel network features as a guide for restoration project design on a reach-by-reach basis. Coefficients of variation for the nine main features analyzed were >80% for all reaches (excluding reach G, n = 2) with the following few exceptions.

Mainland wetlands (Table 10) with CV < 80% for a given reach analyzed for a given parameter follow: Reaches D, E, and H for number of channel outlets, where the median number of channel outlets equaled *one* for each of these three reaches; Reach B, channel perimeter:wetland area; and all reaches except Reach D for wetland area:wetland perimeter, a geometric relationship that is assumed to be relatively proportionate.

Island wetlands (Table 11) with CV < 80% for a given reach analyzed for a given parameter follow: Reach A for number of channel outlets; Reaches B and C, channel perimeter:wetland area; Reach B, channel area:wetland area; Reaches B and C, channel perimeter:island area; and Reach B, channel area:island area. The majority of island wetland areas were equivalent to the island areas and this is consistent across the three reaches that had CVs from 8 to 9% (Table 11; Figure 32). Therefore, only analyses associated with ratios divided by the wetland area are going to be considered for direct comparison to the mainland wetland statistical analysis in the following sections. (Note, this result is not surprising because the rule for inclusion of an island in spatial data processing for this study was that >70% of the island consisted of wetland, in order to ensure comparability with the mainland wetland areas delineated for analysis.)

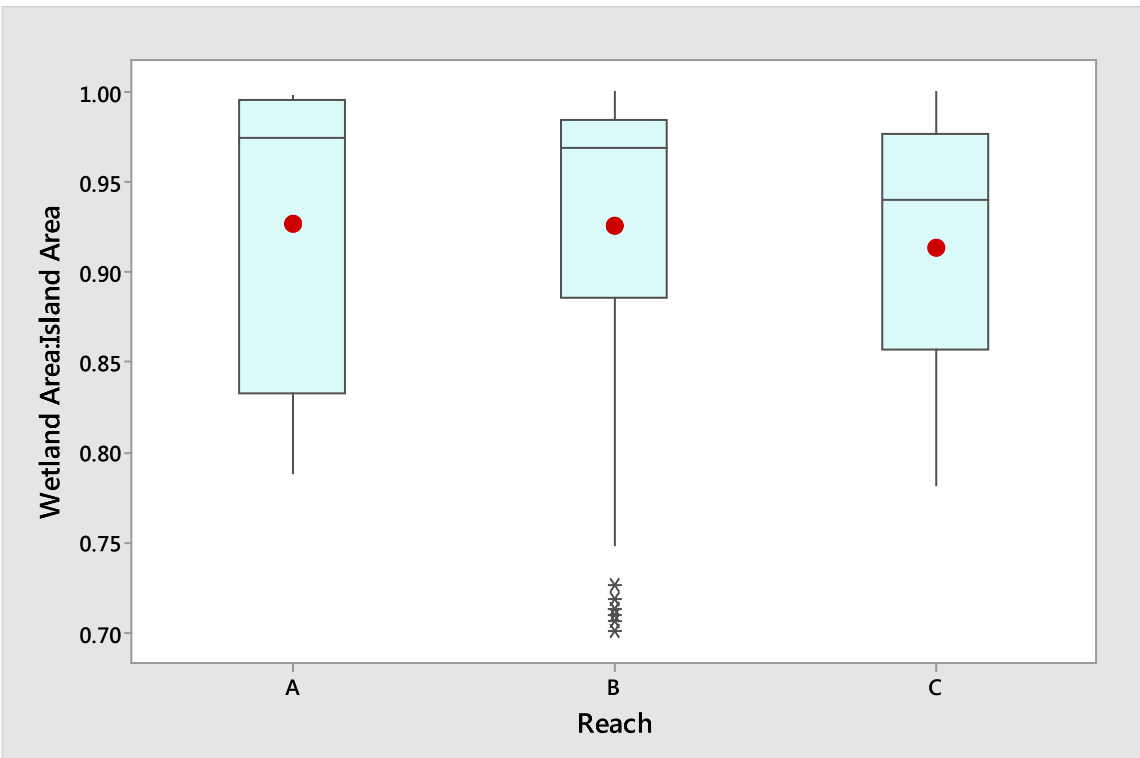


Figure 32. Boxplot of wetland area:island area for Reaches A, B, and C.

5.3.3 Analysis of Differences by Reach

5.3.3.1 Analysis of Mainland Wetlands for Differences by Reach

In Kruskal-Wallace multiple comparisons testing of mainland wetland channel networks for the eight hydrogeomorphic reaches, four parameters differed significantly by reach:

- channel outlets (p = 0.001, adjusted for ties); significantly different pairwise comparisons were Reach E vs. B (p = 0.0001) and E vs. A (p = 0.0003));
- channel area:wetland area (p = 0.008); significantly different pairwise comparisons were Reach A vs. C (p = 0.0002), F vs. A (p = 0.0016);
- channel perimeter:wetland area (p < 0.001); significantly different pairwise comparisons were Reach F vs. A and A. vs. C (p < 0.001), and A vs. B (0.0007); and
- number of outlets:wetland area (p = 0.032); no significantly different group comparisons, nearly F vs B (Figure 33).

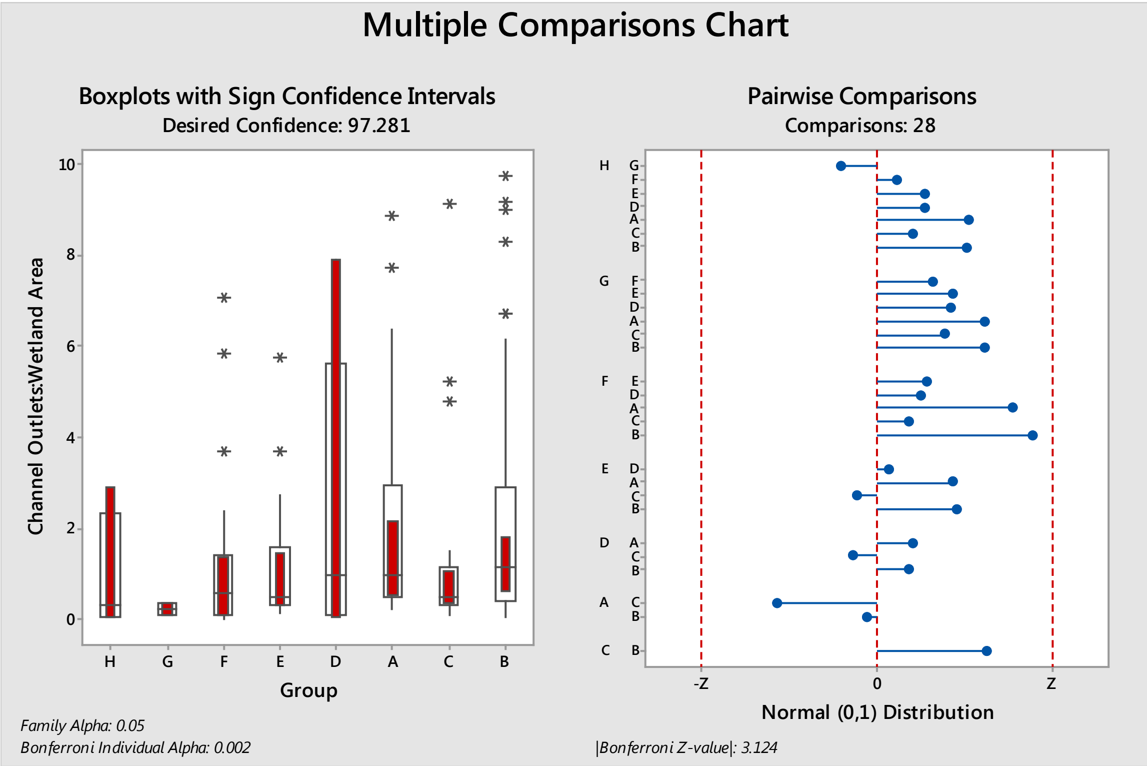


Figure 33. Multiple comparisons chart and pairwise comparisons of mainland channel outlets:wetland area by river reach indicate high variability throughout the LCRE (CVs > 117%, with Reach G excluded because of low sample size).

5.3.3.2 Analysis of Island Wetlands for Differences by Reach

The Kruskal-Wallace multiple comparisons tests among reaches (Reach A, n = 8; Reach B, n = 113; Reach C, n = 21) were significant for only two of the parameters:

- channel perimeter:wetland area (p < 0.001); significantly different pairwise comparison was Reach B vs. C (p < 0.001; Figure 34);
- channel area:wetland area (p = 0.003); statistically different pairwise comparison was Reach B vs. C (p = 0.0009).

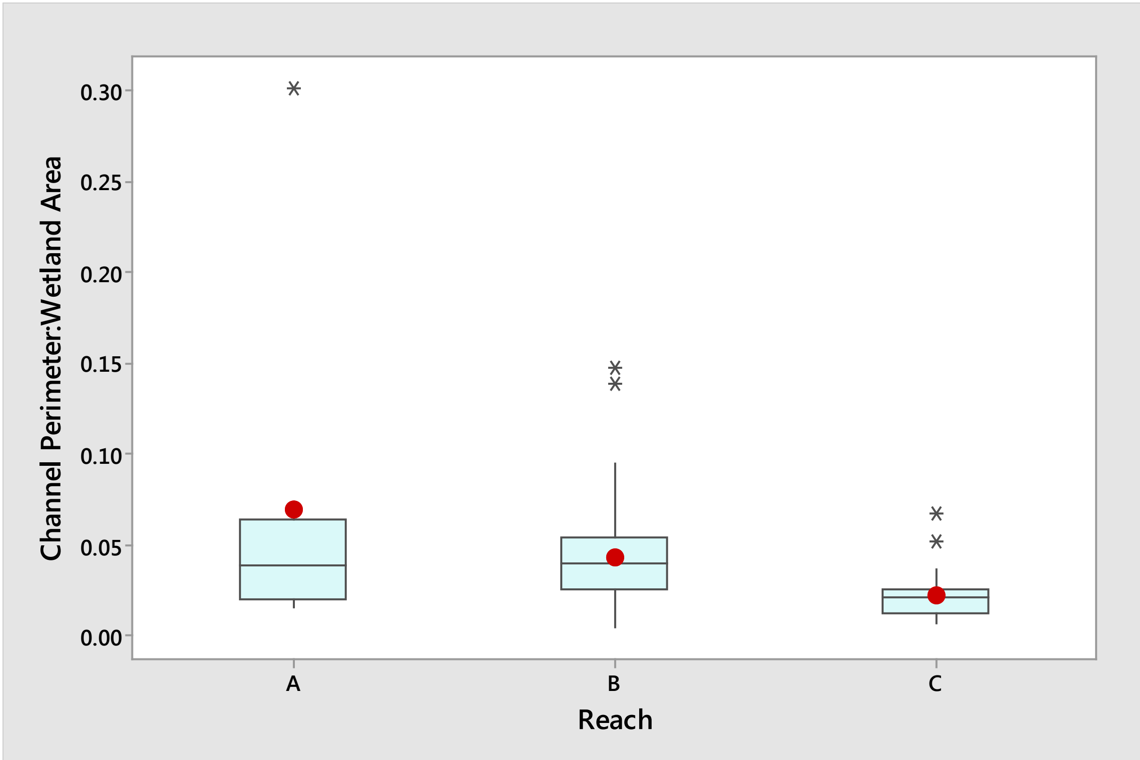


Figure 34. Boxplot of channel perimeter:wetland area for wetlands on islands in Reaches A, B, and C.

5.3.4 Regression Analysis

Here we report the results of 36 linear regression models as a function of wetland area, in total: 3 metrics × 7 reaches for mainland wetlands plus 3 for common slope, and 3 metrics × 3 reaches for island wetlands plus 3 for common slope. In addition, to fully understand the data set and discriminate important factors, we conducted nine regressions (3 metrics × 3 reaches) for the island reaches using island area instead of wetland area, 18 regressions for the island reaches using channel data sets that did and did not include the "small channels" category from the Landscape Planning Framework as a function of island area and wetland area, and 9 for common slopes across reach.

5.3.4.1 Regression Analysis for Mainland Wetlands

Few of the regressions on the mainland wetland area of the channel area, channel perimeter, and number of channel outlets produce good predictive models. The exception is the linear models of channel perimeter as a function of mainland wetland area for Reaches A and B, which are relatively good predictive models ($R^2 > 80\%$; Figure 35). In all cases, except for Reach G (not used in the analysis; n = 2), slopes are significantly different among reaches ($p < 0.04$). The use of a common slope in the model reduces the predictive capability of the models within each reach ($R^2 < 75\%$ for channel area, 78% (except for Reach A which remained at 84%) for channel perimeter, and 64% for number of channel outlets). Based on the nonparametric runs test of the goodness-of-fit to the common slope model as a function of wetland area, the fit for all reaches is not significantly different for channel area, the fit for four reaches significantly deviates from the common slope model for number of channel outlets (A, C, E, F), and the fit for Reach B significantly deviates from the common slope model for channel perimeter.

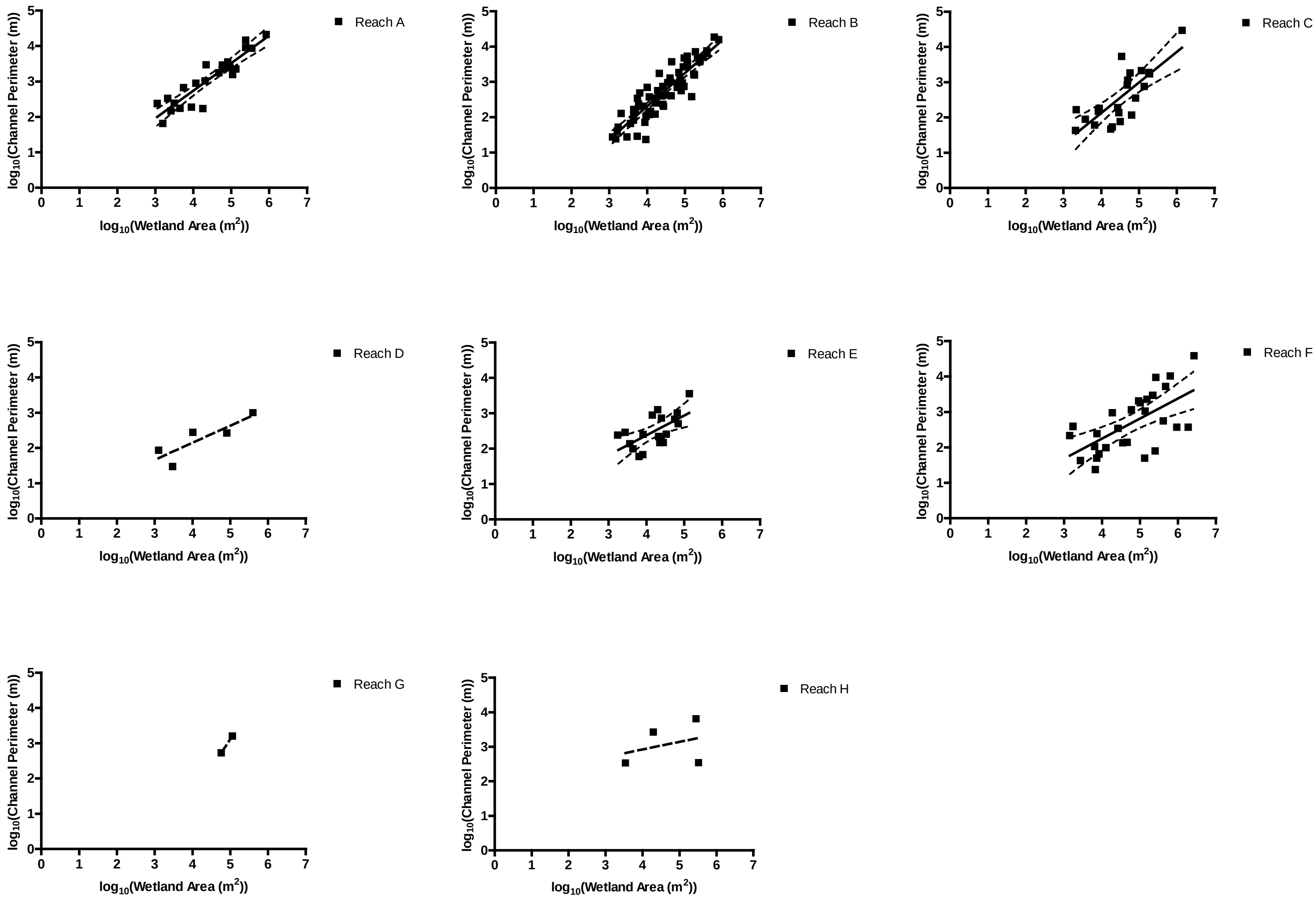


Figure 35. The linear models for channel perimeter as a function of wetland area are relatively good predictive models for Reaches A (R^2 = 84%) and B (R^2 = 81%).

- For *number of channel outlets as a function of wetland area*, none of the linear models are good predictors (all $R^2 < 73\%$) for slopes that were significantly different from zero. The only slopes significantly nonzero are for Reaches A, B, C, and F. The slopes are significantly different ($p = 0.008$) for all reaches except G ($n = 2$), which was not used in the comparison. When a common slope is used in the model, all of the R^2 drop to <64%. Reaches A, C, E, and F significantly deviate ($p < 0.047$) from the common slope model based on the nonparametric runs test for goodness-of-fit.
- For *channel perimeter as a function of wetland area*, the linear models for Reaches A and B are relatively good predictive models ($R^2 > 80\%$); all of the other models are not particularly good predictors (all $R^2 < 75\%$). The best fit linear model for Reach A is $\log_{10}y = -0.38 + 0.78$ ($\log_{10}$wetland area) and for Reach B is $\log_{10}y = -1.46 + 0.94$ ($\log_{10}$wetland area). The only slopes significantly different from zero are for Reaches A, B, C, E, and F. The slopes were significantly different ($p = 0.01$) for all reaches except G ($n = 2$), which was not used in the comparison. When a common slope is used in the model, except for Reach A all of the R^2 values drop to <78%. Reach B significantly deviates ($p = 0.046$) from the common slope model based on the nonparametric runs test for goodness-of-fit.
- For *channel area as a function of wetland area*, none of the linear models are particularly good predictors (all $R^2 < 80\%$). All reaches fit the separate slopes linear model, and all slopes were significantly nonzero except Reaches D and H. The slopes for Reaches A−H (except Reach G; $n = 2$; not used in the comparison) were significantly different ($p = 0.04$). When a common slope is used in the model, all of the R^2 drop to <75%. None of the reaches rejected the common slope model ($p > 0.12$) based on the nonparametric runs test of the goodness-of-fit.

5.3.4.2 Regression Analysis for Island Wetlands

Slopes for channel area, channel perimeter, or number of channel outlets as a function of wetland area were not found to be significantly different between Reaches A, B, and C (Figure 36). This result remained consistent whether or not the "small channel" category (identified in the Landscape Planning Framework) was included in the analysis. Models based on wetland area are similar to those based on island area. For regression on island area and regression on wetland area, models including the "small channel" category were better predictors than those excluding this category; thus the regression model results presented include small channels (as do our mainland wetland model results).

- Slopes for channel perimeter as a function of wetland area are not significantly different among Reaches A, B, and C ($p = 0.32$); the common slope = 1.01. However, the y-intercepts are extremely significantly different ($p < 0.0001$). The global $R^2 = 89\%$.
- Slopes for channel area as a function of wetland area are not significantly different ($p = 0.52$); the common slope = 1.14. However, the y-intercepts are very significantly different ($P < 0.003$). The global $R^2 = 84\%$.
- Slopes for the number of outlets as a function of wetland area are not significantly different ($p = 0.44$); the common slope = 0.53. The y-intercepts are not significantly different ($p = 0.22$), therefore it is possible to calculate one pooled y-intercept for all the data = 0.55476. However, the global $R^2 = 67\%$, so the number of channel outlets does not produce a good predictive model.

We conclude that when using individual region-based data models, Reaches B and C provide a high level of prediction for channel perimeter ($R^2 \geq 85\%$) and Reach B provides a high level of prediction for channel area ($R^2 = 87\%$).

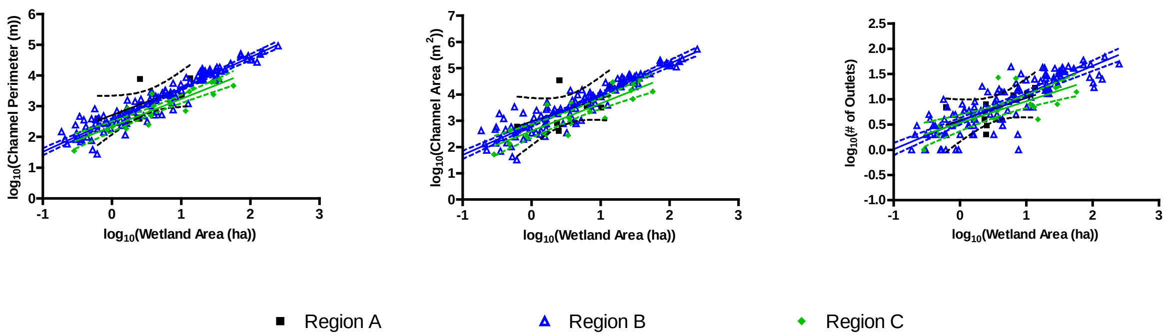


Figure 36. Log-log plots of wetland channel perimeter, channel area, and number of channel outlets on island wetland area with data including small channels.

5.3.5 Comparison between Wetlands on Islands and on the Mainland

We compared channel networks of wetlands on islands and the mainland using the Mann-Whitney test on the median and its confidence interval, for Reaches A, B, and C (the reaches with sufficient islands for analysis), using the channel area, channel perimeter, and the number of outlets, and three ratio-based parameters: channel area:wetland area, channel perimeter:wetland area, and number of channel outlets:wetland area. Results by reach were as follows:

- Significant differences for channel area, channel perimeter, and the number of outlets ($p < 0.001$) and for all three ratio parameters for Reach B (mainland $n = 60$, island $n = 113$); significant at $p < 0.001$ for channel area:wetland area and channel perimeter:wetland area; significant at $p = 0.01$ for number of channel outlets:wetland area);
- Mixed significant differences for Reach C (mainland $n = 22$, island $n = 21$); significant at $p = 0.001$ for channel outlets and $p = 0.02$ for number of channel outlets:wetland area; nearly significant at $p = 0.005$ for channel perimeter and $p = 0.0782$ for channel perimeter:wetland area; not significant for channel area or channel area:wetland area ($p > 0.12$);
- No significant differences between islands and the mainland for Reach A (mainland $n = 24$; island $n = 8$; $p > 0.068$).

6.0 Conclusions and Recommendations

We synthesized the results of the outreach to practitioners, literature review, field observations and analyses to derive conclusions, implications for restoration practice, and recommendations for mound design, reed canarygrass control, and channel network design relative to channel outlets.

6.1 Conclusions

6.1.1 Mounds

All findings from field work in this study must be interpreted in light of the fact that sampling occurred in the summer of 2015 at or near midday and that ambient air temperatures were very high relative to historical averages and trends. Based on these data, we derived the following conclusions.

1. Statistical results strongly suggest that the mounds can stratify in terms of soil moisture.
2. Statistical analysis of temperature was inconclusive, though it appears to be positively correlated with elevation. Mound aspect appeared to be less important to temperature and moisture than hypothesized.
3. Size: Advantages to “big” are less edge and more canopy cover; there are also advantages to a “sea” of small mounds, which may better mimic a swampy hummocky environment, provided mounds are high enough to support woody vegetation. (Restoration designs in the LCRE are often in between those two extremes.) If mounds are large, the relative effects of tidal and fluvial hydrologic drivers in summer need to be understood relative to moisture benefits for plants.
4. Qualitatively observed differences in plant mortality and the vigor of plantings appeared to correspond to differences in soil organic matter and moisture.

6.1.2 Reed Canarygrass

We made the following conclusions regarding environmental conditions and reed canarygrass control.

6.1.2.1 Environmental Conditions

1. Key environmental controls are shade, salinity, and elevation.
2. Elevation is important at the low and high ends of the spectrum: through the hydrologic regime providing enough inundation that RCG cannot grow, and through providing non-inundated substrate on which woody plants can become established.
3. Reed canarygrass is an impediment to the cost-effective pilot-channel excavation method (invasive mat prevents channel evolution in response to flows).
4. Available nutrients may be important to RCG performance (positive correlation with high nutrients).
5. High marsh in freshwater regions is the plant community at the greatest risk, past and present, from reed canarygrass in the LCRE.

6.1.2.2 Control

1. Most available information about control is from non-tidal environments.

2. The only known example of planting prior to breaching in the LCRE, Otter Point, was planted a year ahead and led to success though it also highlighted the possibility that irrigation may be needed in some cases. Both woody and herbaceous species were planted at this site.
3. The relative performance of native plant species in competing with reed canarygrass in tidal environments has not been formally tested in the LCRE, but *Deschampsia cespitosa* (see Ruby Lake) and *Scirpus microcarpus* (see Anderson Creek and other sites) have shown the ability to compete at the same elevations as reed canarygrass. Species that can grow taller than reed canarygrass can also have a competitive advantage, such as lady fern (*Athyrium filix-femina*), black vetch (*Vicia nigricans*), and cow parsnip (*Heracleum maximum*) (see N. Fork Siuslaw). Many other species have the potential to out-compete it when it is reaching its inundation threshold (see Devil's Elbow).
4. Woody vegetation has the potential to compete, over the long term, but native understory is variable. The ability to compete may depend on shade; for example, the growth habit of *Salix lucida* provides little shade compared to shrubby willow species (e.g., S. scouleriana and S. sitchensis). This was observed at Marietta Slough, and for *Fraxinus latifolia* at Ruby Lake. It is consistent with comments from practitioner outreach that the Sauvie Island North unit is an example of pristine canopy cover where the understory is still reed canarygrass and blackberry.
5. Control is most likely to succeed if implemented at a watershed scale because of the distribution of propagules throughout hydrologically connected systems. This is challenging in the context of a hydrologic reconnection program such as CEERP, and must be interpreted as the largest practicable scale, at minimum, the site scale.
6. Small areas of reed canarygrass can be effectively controlled using a combination of manual methods, such as pulling and clipping seed heads, and targeted chemical treatment. This method might be especially useful in restored areas when infestation is slow or in a previously treated area to prevent re-infestation. This is the method used in coastal watersheds on the Olympic Peninsula in Washington.
7. A number of studies recommend applying multiple methods in combination and dense plantings in every available niche including those vacated by reed canarygrass because of control measures. This is consistent with the only success story in the Columbia region that we encountered, although successful site was located on Willamette Valley prairie not in the LCRE.
8. There are elements of success in native plant establishment on Devil's Elbow and other sites where combinations of land elevation and hydrology are allowing native plants to compete.
9. Available methods applicable in the LCRE are mechanical (mowing and discing), hydrologic (inundation), chemical (grass-specific or general), and biological competition (seeding and/or planting).
10. The timing of control method implementation is critical to its success but specific to regional environments (growing season, hydrologic regime, etc.), and little testing has been done for the LCRE or other tidal environments in the Pacific Northwest, including the relative value of pre- and post-restoration control.
11. For chemical control, glyphosate remains a "go-to" product and grass-specific selective products need to be tested in tidal environments.
12. Burning is not a suitable tool in environments where native plants are not fire-adapted and therefore cannot recover and compete.
13. No biological control method is available.

6.1.3 Channel Outlets

The background of much research on channel outlet connectivity for salmon is on deltaic systems of the Puget Sound, particularly the Skagit River (Beamer et al. 2005; Hood 2015a). To support CEERP practitioners, we focused this study on data development specific to the LCRE. We hypothesized that because the Columbia River is not deltaic and the LCRE is characterized by distinctive hydrologic zones (Jay et al. 2015, Jay et al. in revision) with observable differences in island and mainland wetland features, geomorphological features would differ across the floodplain because channel development is fundamentally driven by the requirements of flow conveyance as modified by local geology. Based on the needs articulated by practitioners during the outreach phase of this research, our focus was on channel outlets although we also analyzed other basic descriptors of channel networks that could be derived from the data. It is important to note that wetland channel length could not be derived from existing data, only channel perimeter, which cannot be directly translated into length in a manner that is consistent throughout the LCRE because of the range of plan-form channel network types (e.g., Coleman et al. 2015).

We found that the variability of channel network properties in the LCRE both longitudinally (i.e., between river reaches) and laterally (i.e., between mainland and island wetlands) is substantial as seen in the CVs (Table 10, Table 11) and in many cases statistically significant. Of particular note is that the ratio of number of outlets to wetland area was highly variable throughout mainland wetlands of the LCRE (CVs > 117%, excluding Reach G because of low sample size, Table 10). The ratio (number of outlets:wetland area) also was variable throughout island wetlands of the LCRE (CVs > 89%). Similarly, Rinaldo et al. (2004) observed diversity rather than common patterns in tidal landscapes, which they suggest results from processes that vary with spatial scale as well as competing dynamic processes.

The linear regression of channel area, channel perimeter, and the number of channel outlets as a function of wetland area (island area had the same results) by reach, distinguishing islands from mainland wetlands, produced few good predictive models. In virtually all cases, the use of a common slope (for all reaches) in the model causes R^2 to drop below acceptable values, discouraging prospects for any single regression model using these parameters suitable for the LCRE. There were five exceptional cases in which we were able to develop predictive models. For *mainland wetlands*, the linear models of channel perimeter as a function of wetland area for 1) Reach A and 2) Reach B, which are relatively good predictive models for these reaches ($R^2 > 80\%$). In Kruskal-Wallace multiple comparisons testing of mainland wetland channel networks for the eight hydrogeomorphic reaches, the number of outlets:wetland areas differed significantly by reach ($p = 0.032$) (Figure 33). The predictive models for *island wetlands* are the linear models for channel perimeter as a function of island wetland area for 3) Reach B and 4) Reach C, which provide a high level of prediction for channel perimeter ($R^2 \geq 85\%$), and 5) the linear model of channel area as a function of island wetland area for Reach B, which also provides a high level of prediction for channel area ($R^2 = 87\%$). Thus, provided that islands and mainlands are modeled separately by reach, channel perimeter emerges as a metric that can sometimes be predicted based on wetland area, for mainland wetlands on two lower river reaches (A and B), and for island wetlands on two lower river reaches (Reaches B and C).

With regard to the number of channel outlets as a function of mainland wetland area, none of the linear models are good predictors (all $R^2 < 73\%$) for the slopes that were significantly different from zero (that is, for Reaches A, B, C, and F). Moreover, the slopes are significantly different ($p = 0.008$) for all reaches except G ($n = 2$, not used in the comparison). When a common slope (i.e., all reaches) is used in the model of channel outlets as a function of mainland wetland area, all of the R^2 values drop to <65%. Reaches A, C, E, and F significantly deviate ($p < 0.047$) from the common slope model based on the nonparametric runs test for goodness-of-fit.

6.2 Implications for Practice

6.2.1 Mounds

1. Data analysis reinforces the notion of thinking in terms of relative vertical position when designing planting plans, because volumetric water content (moisture) is negatively correlated with elevation.
2. The practitioner will need to evaluate the importance of statistical results on soil moisture relative to locally important native plants and plant associations, using the hydrologic regime and elevation data as the design basis.
3. Findings about moisture and aspect indicate that considering aspect *per se* is not necessary; light may be a more important feature.
4. Consider the source of mound material, whether it is from the bottom of a slough or the topmost layer of a floodplain, especially regarding organic matter content; if possible place topsoil at the top of mounds to enhance plant vigor and success. Consider the potential for a weedy seed bed, and perhaps implementing an intervening year of control to eradicate the weed seed bed before topsoil is moved to the top of mound and hydrology is reconnected. Additional weed control may be needed in subsequent years.
5. In examination of the reference site and historical conditions to inform restoration project design, consider the presence and type(s) of topographic variability. For instance, quantitative assessment of the size (elevation, width, and length), shape, and density of relatively vertical features on the landscape, and their collective distribution across the landscape, will provide important information to inform analysis of the suitability of such features on the restoration site.
6. Project goals will lead to different mound designs; e.g., for forested wetland goals, shading out RCG could be done by designing many small mounds at very close density to mimic forested wetland microtopography and using spruce and woody plants to achieve shading.

6.2.2 Reed Canarygrass

For current project planning we recommend the following:

1. Combine multiple methods for multiple years to achieve cumulative beneficial effects. Comprehensive site preparation prior to restoration may be more effective and cost efficient than post-restoration control efforts.
2. When possible, consider control at the largest possible scale and, if feasible, at the watershed scale. This is challenging in the context of a hydrologic reconnection program such as CEERP, and must be interpreted as the largest practicable scale, at minimum, the site scale.
3. Plant or seed strong competitors to fill aboveground and belowground niches.
4. Remember that the effects of woody species on light change as plants grow (e.g., *Salix lucida* and *Fraxinus latifolia* do not shade the understory at maturity).
5. Consider the potential loss of high marsh resulting from control methods focused on establishing high and low elevations.
6. Consider removing heavy nutrient sources at least 1 year in advance of construction.

In regard to the policy context, we note that the majority of projects/sponsors do not have funding for post-restoration stewardship or maintenance. Thus, it is practical and less expensive in the long run to control reed canarygrass to the greatest extent possible during the restoration project.

6.2.3 Channel Outlets

6.2.4 Application of the Models and Analyses

The quartiles of the data distribution of the number of channel outlets provide a range that can be considered by engineers during restoration design planning on the mainland (Figure 37a,b) and on islands (Figure 38a,b). Although these do not account for nonlinear effects of scale, they may serve as an indicator of the number of channel outlets that is characteristic in the LCRE. The exact configuration of channels including the number of outlets, channel dimensions, and configuration is site and regionally dependent (Section 6.2.3.4). Because of the wide variability in the data, evidence regarding the historical channel network and number of outlets (Section 6.2.3.3) would likely take precedence in the final design.

We reported acceptable predictive regression models applicable only to specific lower river reaches, as follows:

1. Channel perimeter emerges as a metric that can sometimes be predicted based on wetland area; i.e., for *mainland* wetlands on two lower river reaches (A and B), and for *island* wetlands on two lower river reaches (Reaches B and C);
2. For *island* wetlands, the linear model of channel area as function of island wetland area for Reach B provides a high level of prediction for channel area.

These models could be consulted by practitioners as lines of evidence in addition to those already used routinely, but should not be viewed as prescriptive given the great variability in these metrics even between sites within reaches (Table 10, Table 11).

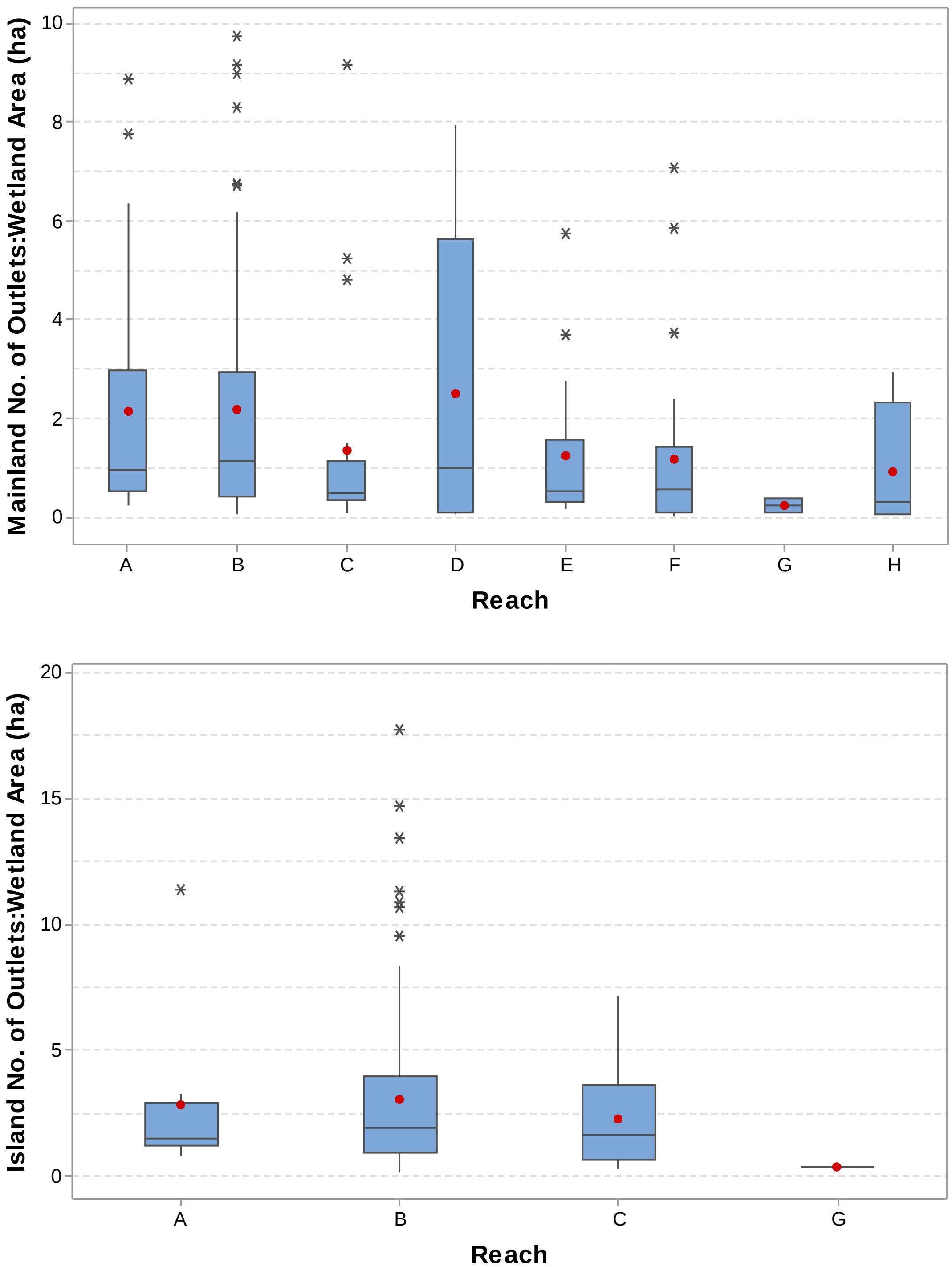


Figure 37. Plots of channel outlets:wetted area for BPA-RDC, box lines = Q1, Q2, and Q3, * = extreme values = outside whiskers, upper whisker = the minimum of the maximum observation or 1.5 times the interquartile range (Q3-Q1) added to the Q3, and lower whisker = the maximum of the minimum observation or 1.5 times the interquartile range subtracted from the Q.

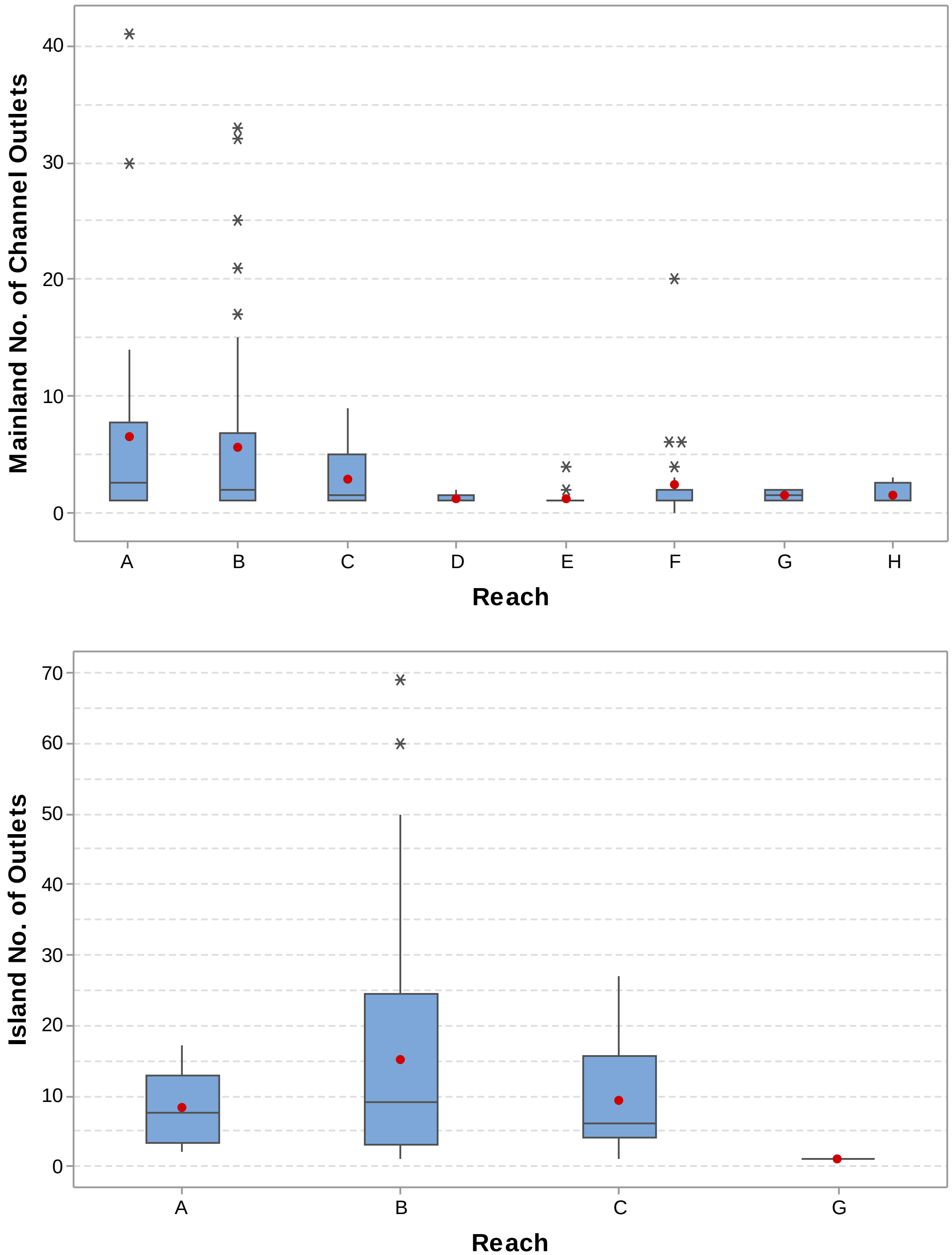


Figure 38. Plots of number of channel outlets for BPA-RDC, box lines = Q1, Q2, and Q3, * = extreme values = outside whiskers, upper whisker = the minimum of the maximum observation or 1.5 times the interquartile range (Q3-Q1) added to the Q3, and lower whisker = the maximum of the minimum observation or 1.5 times the interquartile range subtracted from the Q.

6.2.4.1 Application of Previously Published Models

Previously published models are available for channel-network–related elements of project design in the LCRE (e.g., Diefenderfer et al. 2008, 2013; ESA PWA, Ltd. and PC Trask and Associates, Inc. 2011; Borde et al. 2012). However, we did not evaluate these in this study because the models do not include the number of channel outlets, a primary focus for restoration practitioners. On the basis of our data analysis, some cautions are in order in regard to the application of previously published models of channel outlets as a function of wetland area for wetlands of the LCRE (Hood 2015b). The results of 16 linear regressions we performed on these parameters differ considerably from results reported by Hood (2015b); i.e., we found that the number of channel outlets as a function of wetland area does not produce a good predictive model for island or mainland wetlands of any of the eight hydrogeomorphic reaches nor is a common slope model for the LCRE an acceptable interpretation of the data. Some differences in methods between our study and Hood's (2015b) are evident, which may help to explain the differences in results. The analyses differed with respect to sample size, geographic extent, delineation by river reach, and discrimination between main-stem and island wetlands. Our analysis used a rule-based census approach to spatial data development resulting in a sample size of n = 306 reference wetlands on islands and mainlands located in seven of the eight river reaches.

6.2.4.2 Historical Channel Network-Based Design

The interviews we conducted at the outset of this study found that, universally, practitioners in the CEERP seek to restore site-specific historical channel networks where they can be discerned from available information. They use historical maps, historical photos, LiDAR, and field survey information to detect the presence of channel networks. They also use information from reference sites as analogues when needed if historical channels cannot be defined or if they cannot be restored for practical reasons. Many practical considerations weigh into channel network design, particularly local infrastructure, land uses, and stakeholder concerns such as flooding.

Through analysis of the comprehensive spatial data sets developed through the CEERP to date, we have demonstrated the variability of wetland channel perimeter, channel area,

and the number of channel outlets throughout the LCRE, and the correspondingly limited ability to develop predictive regression models from existing data, with the few exceptions identified above. It seems to us, that the approach used by practitioners—i.e., developing a "reference model" (Clewell and Aronson 2013) from historical information and reference sites—is not inferior to the use of a regression model. Also, in many cases, island marsh geomorphology is inherently different than mainland sites, so reference information for one should only be applied to the other with care.

6.2.4.3 Landscape Setting

Fundamentally, channels develop to convey flow, and the needs for this function differ based on elements of the landscape setting including the position relative to upstream and downstream influences, elevation relative to the hydrologic regime, and percent wetland perimeter exposed to main-stem river or tributary hydrology (Figure 37). Thus, in addition to the tidal-fluvial gradient in hydrologic regime (Jay et al. 2015) and variability in geologic characteristics (Cannon 2015), the landscape setting of restoration projects is important to the design of channel networks. It would be a mistake to calculate the number of potential channel outlets based on wetland perimeter without considering the effective reduction in perimeter corresponding to the landscape setting, e.g., features such as the proximity of upland slopes and the location of tributary, blind slough, off-channel, and main-stem river waterways relative to the wetland area of interest (Figure 37).

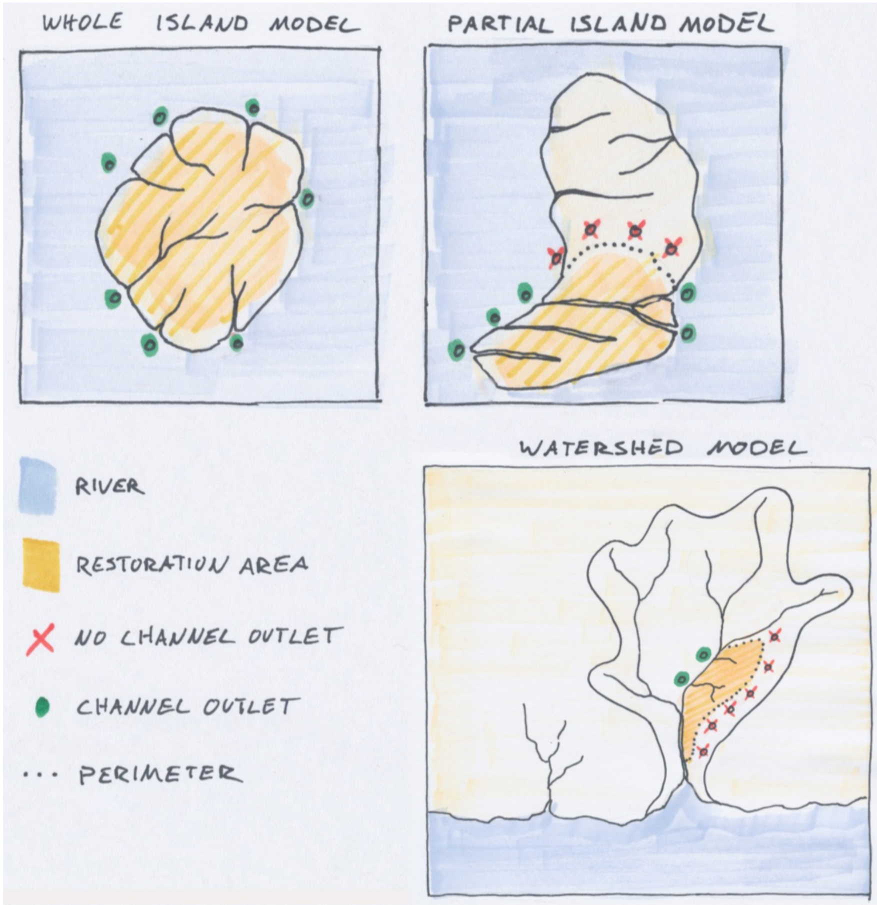


Figure 39. Illustration of the geomorphic and hydrologic setting and potential channel outlets of restoration sites on tidally influenced islands in the main-stem river versus tidal floodplains of mainland tributaries to the river.

6.3 Recommendations for Future Study

In this section, we offer summary recommendations for potential future research to support design challenges in the CEERP, regarding topographic variability, reed canarygrass control, channel networks, and habitat connectivity.

6.3.1 Topographic Variability

Three remaining uncertainties stand out in regard to mounds: planting success and the establishment of a viable native plant community with multiple habitat benefits under variable tidal-fluvial hydrologic regimes (i.e., magnitude, frequency, duration of flooding); the size, shape, and configuration of mounds; and the utility of mounds in different ecosystem settings (e.g., restored marsh, shrub-dominated wetland, and surge plain forested wetland).

In the course of outreach to LCRE, outer coast, and Puget Sound practitioners, we received feedback regarding planting plans for mounds. However, the scope of work in fiscal year 2015 limited our primary analysis to the soil moisture and temperature characteristics of mounds in summer, with ancillary data on air temperature and soil organic matter. Research was constrained in particular by the lack of baseline planting data, on a per-mound basis. Additional research that would be informative to restoration practitioners would include real-world examples from the LCRE. *We recommend that in a few site-specific examples, baseline planting data be collected along with environmental conditions such as soil moisture and temperature, and tracked over time.* Such a focus is indicated by information from the literature, which on the one hand shows that planting densely can reduce the probability of development of functional habitat characteristics such as boughs, hollows, and natural tree recruitment (Vesk et al. 2008), yet also shows the relative benefit of dense willow plantings for reed canarygrass control (Kim et al. 2006). If early dense plantings are required to control reed canarygrass, should thinning be implemented at an early seral stage in order to promote the development of forested wetland habitat niches? *We recommend evaluation of the statistical results on soil moisture herein, relative to locally important native plants and plant associations, to produce a list of general planting recommendations for the different vertical positions on mounds as a tool for practitioners. We recommend workshop discussion of potential development of a material management decision framework for practitioners, which describes potential uses, ecological objectives, and design considerations for material generated from tidal wetland restoration work.*

Secondly, provocative contrasts in the potential size, shape, and configuration of mounds in the LCRE emerged. For example, could a sea of very small mounds, of a size comparable to the microtopography of a reference forested wetland in the LCRE, produce increased habitat benefits in terms of inundation, fish habitat availability, and/or the development of plant communities and secondary production of prey resources? Are the relatively large mounds currently being designed on the LCRE overly isolated from the water table and could they require irrigation for plant establishment? Do they contain sufficient organic matter to support the plantings funded through restoration plans? Will they ultimately compact (as other Pacific Northwest examples have shown over a decade) and how will the hydrology change in this case, such that it is comparable to the microtopography focus in the literature? How do river reach and WSE affect mound ecology? *We recommend developing a work plan to further investigate mound design for the LCRE, including planting design, mound morphology, and ecosystem setting. We anticipate this effort would include developing a conceptual model of the ecosystem function of mounds, and identifying and characterizing the types of features that occur naturally in the LCRE, e.g., bar and scroll, natural levee, alluvial fan, and tree fall, and their association with types of hydrology, geomorphology, and plant communities as a reference condition.*

6.3.2 Reed Canarygrass Control

To improve long-term project planning we recommend the following:

1. Study the efficacy of methods for 1) integrating control in a restoration project, and 2) controlling reed canarygrass plants that have become established after restoration. Outcome: cost-benefit analysis of control methods/timing.
2. Integrate mechanical control, chemical control, and seeding in a blocked field study, e.g., including early and late-spring spraying, discing, seeding, grass-specific spraying, and planting of forbs. Outcome: LCRE reed canarygrass management protocol.
3. Verify whether findings on the competitiveness of reed canarygrass in the Midwest apply in the LCRE through nutrient-enrichment studies in LCRE field settings. Outcome: recommendation on site preparation time to discourage establishment of a reed canarygrass monoculture.

6.3.3 Channel Networks and Habitat Connectivity

The CEERP takes an ecosystem approach to restoration of salmon habitat in the LCRE. Accordingly, it is important that guidelines about what constitutes quality habitat are available to project planners and engineers. Guidance for the CEERP is available from development of the survival benefit unit metric by the ERTG, which judged relative fish density derived from classes of restoration actions such as lowering or breaching dikes to be greater than effects of actions involving tide gates (ERTG 2011). The views of the ERTG regarding which *features* are important are also clear from examining the project scoring criteria:

> the top score for potential benefit for habitat capacity/quality is given for maximum natural *habitat complexity*; well-developed *natural disturbance regime* and *ecosystem functions*; extensive *channel and edge network* and *large wood*; much *prey resource production and export*; no *invasive species or nuisance predators*; water quality/temperature quality excellent; site relatively large (>100 acres); …
>
> the top score for potential benefit for habitat access/opportunity is given for *high connectivity* of site for most species, populations and life history types coming down river *at most water level stages*; located in a *main-stem area or a priority reach*; *unencumbered access* to site [*emphasis added*] (ERTG 2010).

In summary, the ERTG scoring criteria relevant to the restoration design challenge module for channel networks are generally for an extensive channel network located near the main stem with unencumbered connectivity at most water level stages. These criteria translate into clear guidance for landscape position and water levels (ERTG 2013). However, the ERTG criteria were not developed to provide specific guidance or quantification for channel network features such as those considered herein, i.e., channel area/wetland area, number of channel outlets/wetland area, and channel perimeter/wetland area (sometimes referred to as "channel edge density"). (We were unable to consider the density of confluences within wetlands because of limitations in the available data sets.) Nor were the ERTG criteria designed to provide specific information regarding other features of plan-form morphometry of the network, e.g., channel order, bifurcation, length, and sinuosity (Coats et al. 1995) or channel dimensions (e.g., width:depth ratio, cross-sectional area, longitudinal slope, hydraulic geometry) (Zeff 1999). The potential influence that removing larger sections of dikes rather than relatively small channel breaches may have on surface water and groundwater dynamics, channel dimensions, and fish movements is also not specifically described.

The quantitative design guidance available to date for these features in the LCRE, developed through applied geomorphology methods, has been limited to specific reaches. ESA PWA, Ltd. and PC Trask and Associates, Inc. (2011) developed guidelines based on field data collection at five island emergent marsh sites in Reaches C and D: regressions for channel area as a function of tidal prism, and maximum channel depth below mean higher high water as a function of drainage area. Diefenderfer (2007) and Diefenderfer et al. (2008) developed guidelines based on field data collection at three mainland forested wetlands in the vicinity of Grays Bay in Reach B: relationships for channel cross-sectional area at the outlet and total length of channels as a function of catchment area (watershed area), and channel cross-sectional area at the outlet as a function of the total length of channels. These reports all noted the importance of considering the difference between the channel dimensions calculated based on the tidal prism of the site at the time of breaching, and the ultimate tidal prism of the site as a function of sedimentary processes, channel evolution, and the establishment and succession of vegetation.

The results of our regression analyses of channel network features as a function of wetland area in the eight reaches, which separated islands from mainlands, highlight the limitations of extrapolating hydraulic geometry models such as these from islands to the mainland or vice versa. We agree with the authors of ESA PWA, Ltd. and PC Trask and Associates, Inc. (2011), who wrote “It should be noted that there can be a significant range of uncertainty in these predictions and where possible they should be calibrated with data on similar marshes in the vicinity of the restoration site.” The variability of channel network features within reaches must be kept in mind (Table 10, Table 11).

The analyses herein, taken together with information developed from field data collection specific to certain reaches by ESA PWA, Ltd. and PC Trask and Associates, Inc. (2011), Diefenderfer (2007), and Diefenderfer et al. (2008), lead us to believe that it is likely that reasonable models for channel network features as a function of wetland area can be developed. These models would likely need to include vegetation type (Borde et al. 2011) and inundation (Coleman et al. 2015). Given the four predictive regression models developed herein, channel perimeter should be explored further as a dependent metric; i.e., if a planner knew only the size of the wetland area at the start of the project, it would be beneficial to have a “rule of thumb” for total wetland channel perimeter as a starting point for the design. We have learned that in many cases, the historical plan-form channel network cannot be duplicated exactly because of limitations such as local infrastructure and stakeholder concerns, and in such instances a model would be useful. A fundamental question is whether it is possible to design a model that is better able to predict required adaptations to climate change than the historically present channel network? *We recommend that such models be investigated on a reach-specific basis, separating island and mainland wetlands, with emphasis on reaches where a large number of restoration projects are likely to occur.*

It may also be valuable to develop a case study of a LCRE wetland restoration project to compare the relative channel network design outcomes of various approaches. In our outreach, practitioners expressed that through project design reviews by the ERTG they had received estimates of being a factor of two to four times low in their estimates of channel outlets, so serially examining increases up through five times the historical channel network may have heuristic benefit. *We recommend that various channel network design approaches beaddressed in a workshop involving restoration practitioners, and focusing on one or more example restoration sites.*

The ultimate reason given for an emphasis on channel outlets is habitat connectivity for salmon (Hood 2015b). Connectivity is clearly an important value for habitat restored in the CEERP (ERTG 2010). Indeed, the ERTG and interim cumulative effects assessment of the CEERP recognize the importance of connectivity in both direct access to habitat and indirect effects of wetland habitat restoration through the export of prey and macrodetritus (Diefenderfer et al., in press; ERTG 2010; NMFS 2014). Connectivity also plays a role in channel evolution, which is important because a number of practitioners mentioned using a pilot-channel method to initiate channels at the time of implementation, with the expectation that the channel network will expand based on local hydrodynamics and sedimentary processes. Moreover, the Biological Opinion (NMFS 2008) Reasonable and Prudent Alternative 59 included a connectivity index : “The Action Agencies will monitor and evaluate selected ecological attributes of the estuary, which include the following or equivalent…develop an index of habitat connectivity and apply it to each of the eight reaches of the study area…” Such an index was subsequently prototyped by the Corps (Diefenderfer et al. 2012). The function of the index to track progress on CEERP’s efforts to increase habitat connectivity is directly relevant to the channel networks restoration design challenge. *We recommend that the Corps quantified habitat connectivity index be implemented.*

Finally, most of the monitored indicators of channel networks that we identified in the initial examination of the challenge module were not investigated because of limitations in scope and the decision to focus on the indicator of greatest current interest as voiced by the Columbia practitioner interviews: channel outlets. Moreover, the literature specific to design of channel networks is sparse, and abstracting principles from more general literature would be a substantial undertaking. Nonetheless, many of these indicators are of continuing interest and uncertainty, e.g., channel network density, the effectiveness of pilot channels (particularly in reed-canarygrass–dominated areas), and others. Additionally, the historical approach that is used by practitioners involves examining aerial photos and maps of wetland channel networks from periods prior to the current hydrologic regime of the Columbia, yet accounting for differences between historical condition and present flow-conveyance requirements is a complex problem because of the variability in hydrodynamics throughout the floodplain. *Therefore we recommend that further research into channel network design uncertainties be conducted to inform designs, including an examination of the literature on regulated rivers for trends in floodplain channel network response.*

6.3.4 Outreach

Our overarching recommendation is to invite feedback from the estuary sponsors in regard to engagement with the findings of this research. We would like to ask practitioners which elements of this report would be useful as stand-alone documents available on the web (e.g., Table 9). We suggest that practitioners consider whether a workshop focused on specific restoration projects as case studies of these three challenge modules would be beneficial. We think it might be especially beneficial to include projects currently in the design phase in a workshop[1] to examine how the findings of this research may be applied and whether we can test some of the remaining uncertainties on the ground through variation of specific design elements.

[1] This workshop was conducted on February 19, 2016 in Portland, Oregon. It will be documented in the 2016 annual report for BPA Project No. 2002-077-00 due on August 31, 2016.

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