Comparing historical losses of forested, scrub-shrub, and emergent tidal wetlands on the Oregon coast, USA: A paradigm shift for estuary restoration and conservation

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Sitka spruce-dominated tidal forested wetland ("tidal swamp") in the Nehalem River Estuary, Oregon. Historically, tidal forested wetlands made up over half of all tidal wetlands in Oregon, but 95% of these tidal forests have been lost. Photograph © Laura Brophy.

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Data availability: Geospatial data from this study are available from the author upon request. A web application for viewing the data is found at http://arcg.is/1LSSeT. This report can be downloaded from the following link:
https://appliedeco.org/report/brophy_2019_oregon_tidal_swamp_and_marsh_losses_final_dec2019/

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Glossary and abbreviations

NOTE: The definitions of wetland types provided here are informal and specific to the purposes of this report. For formal definitions of wetland types, see the CMECS classification system (FGDC 2012).

CMECS: The Coastal and Marine Ecological Classification Standard (FGDC 2012)

Estuary: a partially enclosed body of water or wetland that periodically receives freshwater and seawater inputs and extends from its connection to the ocean to the limit of tidal influence, defined by salinity gradients or tidal inundation; includes the "freshwater tidal zone" in which water levels fluctuate with the tides, but salinity is < 0.5. This definition is drawn from Pritchard (1967) and Wolanski (2007).

Historical tidal wetlands (also "historical tidal marsh," "historical tidal swamp," etc.): tidal wetlands present prior to European settlement of the Oregon coast (in the 1800s). Many historical tidal wetlands have been lost due to diking or other factors, but some historical tidal wetlands remain today.

Non-diked: Lacking a dike

OCMP: Oregon Coastal Management Program

Outer coast (of Oregon): the Oregon coast south of the Columbia River, extending to the California border

PMEP: Pacific Marine and Estuarine Fish Habitat Partnership

Tidal forested wetland: A tidal wetland with more than 10% cover of trees. This is one type of "tidal swamp;" the other type is scrub-shrub tidal wetland. In Oregon and the Pacific Northwest, tidal forested wetlands may be brackish or fresh. Also called "tidal forest" or "tidal forest/woodland."

Tidal emergent wetland: Equivalent to "tidal marsh." A tidal wetland with vegetation dominated by herbaceous plants such as grasses, sedges, rushes, and broadleaved herbaceous plants. In Oregon and the Pacific Northwest, tidal emergent wetlands can be saline, brackish, or fresh.

Tidal marsh: Equivalent to "tidal emergent wetland" (see above)

Tidal scrub-shrub wetland: A tidal wetland dominated by shrubs, with less than 10% cover of trees. This is one type of "tidal swamp;" the other type is tidal forested wetland. In Oregon and the Pacific Northwest, scrub-shrub tidal wetlands can be brackish or fresh.

Tidal swamp: A tidal wetland with vegetation dominated by woody plants (either shrubs or trees). In Oregon and the Pacific Northwest, tidal swamps can be brackish or fresh.

Tidal wetland: A wetland inundated by the tides. The tidal wetland types included in this study are emergent (tidal marsh), scrub-shrub (dominated by shrubs), and forested (dominated by trees).

Executive summary

<u>This study evaluated historical extent (prior to European settlement), current extent, and losses for each of the three major tidal wetland types (emergent, scrub-shrub, and forested) on the Oregon coast.</u> The first study of its kind on the Oregon coast, it produced results vital to conservation and restoration planning, since these wetland types are often targets for restoration and each type supplies unique ecosystem services. The study included the coast's 15 largest estuaries; they contain 96.5% of the coast's historical tidal wetland area, so results are representative of the coast in general.

Results show that prior to European settlement, the coast contained 15,399 ha of historical emergent, scrub-shrub and tidal forested wetlands, 34% higher than the previous estimate (11,498 ha) by Good (2000). **<u>Historically, forested and scrub-shrub tidal wetlands (collectively called "tidal swamp") formed a majority (57.8%) of the coast's tidal wetland area, with forested wetlands predominating (54.4%). Emergent tidal wetlands ("tidal marsh") occupied a smaller area (42.2%).</u>**

Diking caused the loss of 57.9% of historical tidal wetlands (8917 ha), and an additional 21.9% (3373 ha) of historical tidal wetlands were converted from one vegetation type to another (primarily from forested to emergent). However, losses were not equal across habitat classes. **<u>Together, diking and vegetation conversion resulted in the loss of 95.0% of historical tidal forested wetlands and 95.9% of historical scrub-shrub tidal wetlands, compared to 58.9% of historical tidal marsh.</u>** Currently, only 9.7% of remaining, non-diked tidal wetlands are forested and 8.2% scrub-shrub, and these remnants are fragmented and small (mostly under 10 ha). Among the larger remaining contiguous areas are the Hoquarten Slough wetlands in the Tillamook Bay estuary and the Coal Creek wetlands in the Nehalem River estuary.

Two factors offset some of the losses of historical tidal marsh: 1) substantial gain (1770 ha) of new tidal marsh in former mudflats ("marsh advance") due to sediment accretion and low relative sea level rise (SLR); and 2) tidal wetland restoration (over 700 ha). We did not find evidence of widespread erosion or drowning of tidal wetlands. The marsh advance suggests Oregon's tidal wetlands may be more resilient to SLR than some other coastal regions of the U.S., but they may still be vulnerable to rapid SLR.

These findings represent a major step forward in understanding the history of the Oregon coast. No previous study measured the historical prevalence or losses of tidal forested wetlands on the entire coast, so the potential ecological significance of this habitat type's near-eradication has been largely unrecognized. Recent research has emphasized the importance of habitat diversity in supporting species of concern. For example, diverse habitats contribute to salmonid genetic diversity, thus supporting population sustainability and resilience. **<u>This study shows that tidal forested wetlands, a major component of the historical landscapes in which salmonids evolved, have been nearly eradicated.</u>**

<u>This study highlights the urgency of protecting Oregon's remaining tidal forested wetlands, and restoring them where possible.</u> Appendix 11 highlights key considerations for tidal swamp restoration, and emphasizes the need for further field monitoring and research to support these efforts.

This study serves as a pilot test: its methods could be applied in other regions, such as the remainder of the U.S. West Coast. To do so, further development of input data (particularly mapping of historical vegetation and tidally disconnected areas) is needed. Extending this analysis would advance estuarine resource management, and would assist land managers in prioritizing conservation and restoration actions to support species of concern and provide other valued ecosystem services.

Background

Tidal wetlands are vital habitat for many wildlife species—including salmon listed under the Endangered Species Act of 1973 (16 U.S.C. §1531 et seq.)—and provide a broad range of critical ecosystem services that benefit humans and other species in Oregon. However, tidal wetland losses have not yet been accurately quantified in a consistent, comprehensive way for the coast of Oregon. New tools that became available in 2014–2019, including updated, elevation-based digital maps of current estuarine habitats (OCMP 2014a, b; Brophy et al. 2019), provided long-needed base layers for analyzing wetland losses. This study addressed the urgent need for quantitative, accurate data on losses of tidal wetlands, including differentiation of losses for the three habitat classes that are the focus of most tidal wetland restoration and conservation actions in Oregon (emergent, scrub-shrub, and forested tidal wetlands).

Habitat loss due to human activities (e.g. diking, tide gates, restrictive culverts, and fill) does not occur evenly across all tidal wetland types. For example, studies in the Siuslaw and Tillamook estuaries showed that a much higher proportion of "tidal swamp" (forested and shrub tidal wetland) was lost, compared to tidal marsh (emergent tidal wetland) (Brophy 2005a, Ewald and Brophy 2012). From a conservation standpoint, the loss was significant, because tidal swamps once constituted a high proportion (60-70%) of all tidal wetlands in these two estuaries – thus raising the priority of tidal swamp protection and restoration. Vulnerability to climate change may also differ by habitat class, increasing the importance of understanding differential habitat loss more broadly. High past losses would increase the urgency of restoration and increase the need for strategic planning to protect existing and restored tidal swamps into the future.

Although data are sparse, existing studies suggest that Pacific Northwest tidal swamps provide unique habitat functions and ecosystem services. For juvenile salmonids, habitat functions provided by tidal swamps include low tide refuge (including beaver ponds) (Miller and Sadro 2003), deep sheltering tidal channels and abundant large woody debris (Diefenderfer and Montgomery 2008), opportunities for osmotic adjustment, and prey production (Davis et al. 2019). Other functions specific to tidal swamps include multi-layered wildlife habitat (due to the presence of herb, shrub and tree canopy layers), and very high levels of soil carbon storage (Kauffman et al., in preparation).

This study quantified the historical area, current area, and loss of each major habitat class of tidal wetlands (emergent, shrub and forested) for the 15 largest estuaries of the Oregon coast. Prior to this study, no comprehensive estimates of tidal wetland loss by habitat class were available for the Oregon coast. Only three studies (Brophy 2005a, 2012; Ewald and Brophy 2012) quantified tidal wetland loss by vegetation class within individual estuaries of Oregon's outer coast, and those analyses used older data sources rather than the new, elevation-based estuarine habitat maps recently completed for Oregon and the U.S. West Coast (Lanier et al. 2014, Brophy et al. 2019). However, losses of tidal swamp versus marsh have been evaluated for the Lower Columbia River estuary (Thomas 1983; Christy and Putera 1992; Graves et al. 1995; Marcoe and Pilson 2017), and this information has been central to restoration planning in this large Pacific Northwest estuary (LCEP 2012).

Although the Pacific Marine and Estuarine Fish Habitat Partnership (PMEP) analyzed tidal wetland losses for the U.S. West Coast (Brophy et al. 2019, PMEP 2018a), the PMEP analysis did not break down losses by habitat class. Determination of loss by habitat class requires historical vegetation data, and those data are not yet available for all West Coast estuaries. In addition, PMEP's analysis used an indirect assessment method; that is, diked/disconnected areas were not directly identified. Instead, PMEP's analysis used the National Wetland Inventory (NWI) to identify current tidal wetland areas. All areas within the historical estuary extent but not classified by the NWI as tidal wetlands were classified as "lost." This indirect approach produced results that are useful for understanding wetland losses at the broad, landscape scale, but has inherent, recognized limitations, as described in the resulting publication (Brophy et al. 2019). These limitations include the fact that the NWI fails to classify many upriver tidal forested wetlands as tidal, instead classifying them as palustrine forested wetlands—thus resulting in these wetlands' being considered "lost" in the indirect assessment, whereas in fact, they are important remnant tidal swamps. The current study, by contrast, used direct mapping of tidally disconnected areas, resulting in more accurate assessment of losses.

This study's results—quantitative, accurate data on tidal wetland losses for the three major habitat classes—provide important guidance for restoration and conservation actions in Oregon estuaries. The study also serves as a pilot test for extension of this analysis to other regions, such as the remainder of the U.S. West Coast. Many private individuals, non-governmental entities (NGOs), and governmental entities have expressed a need for such data for the West Coast. This study's methods could be applied to this broader area, but to do so, further development of input data (particularly, comprehensive mapping of historical vegetation and direct mapping of tidally disconnected areas) is needed.

Geographic scope

This study analyzed tidal wetland loss for the 15 largest estuaries of Oregon's outer coast: Alsea Bay, Beaver Creek, Coos Bay, Coquille River, Necanicum River, Nehalem River, Nestucca Bay, Netarts Bay, Salmon River, Sand Lake, Siletz Bay, Siuslaw River, Tillamook Bay, Umpqua River, and Yaquina Bay (Figure 1). These 15 estuaries make up 96.5% of the total historical tidal wetland area on the outer Oregon coast (Brophy et al. 2019), so they adequately characterize overall tidal wetland losses for the study area. Smaller estuaries, which total only 3.5% of the historical tidal wetland area, could not be evaluated using this study's methods (see "**Data limitations**" below). The Columbia River estuary was not included, because data already exist for tidal wetland loss by habitat class within that estuary.

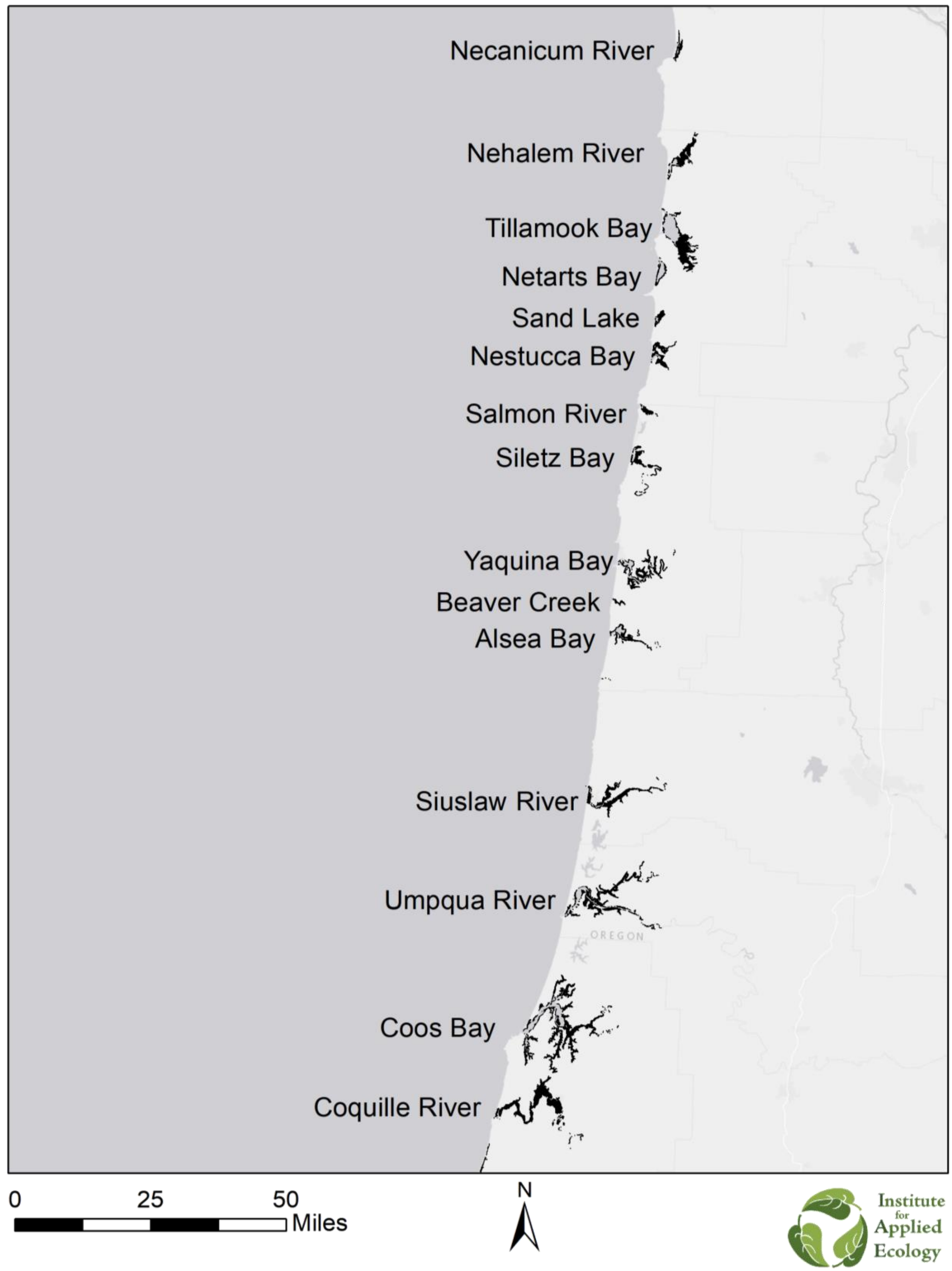

Figure 1. Oregon coast estuaries included in this study

Methods

In the methods below, "CMECS" refers to the Coastal and Marine Ecosystem Classification Standard, a national standard for classification of marine and estuarine habitats (FGDC 2012).

The two major types of wetland change quantified in this analysis were:

1. **Diking:** Diked areas are disconnected from tidal flows.
2. **Vegetation conversion:** These areas have undergone a change in habitat class (vegetation type). Vegetation conversion can happen with or without diking.

Various combinations of these two factors—diking and vegetation conversion—correspond to broad categories of estuarine change, listed in "**Major categories of change in tidal wetland area**" below.

To map the wetland areas affected by these two factors, this study quantified the historical area, current area, and loss of each tidal wetland habitat class. Four types of data were used for the analysis: historical estuary extent, wetland losses (diked areas), historical vegetation class, and current vegetation class.

Historical estuary extent was obtained from the Oregon Coastal Management Program's (OCMP's) 2014 estuary habitat maps, specifically digital maps of the CMECS Aquatic Setting, V0.4.1 (hereafter, "CMECS Aquatic") (OCMP 2014a, Lanier et al. 2014). These data were subsequently incorporated into PMEP's "West Coast USA Current and Historical Estuary Extent" geospatial dataset (hereafter, "Estuary Extent"), V1.0 (PMEP 2018b, Brophy et al. 2019). The proportion of the total historical tidal wetland area on the Oregon coast that was represented by the 15 study estuaries was determined from PMEP's digital maps of the CMECS Biotic Component, V1.1 (hereafter, "CMECS Biotic") (PMEP 2018c, Brophy et al. 2019), by comparing the total vegetated area (emergent, shrub and forested classes) within the historical estuary extent for the 15 study estuaries versus the full set of 44 estuaries mapped by both OCMP and PMEP.

Current tidal wetland area was defined as any vegetated area (emergent, scrub-shrub or forested) within the historical estuary extent that has not been disconnected from tidal influence – that is, non-diked areas (see next paragraph).

Diking (i.e. "wetland loss") was determined using the diking status attribute (anthropogenic impact modifier AI07) in PMEP's CMECS Biotic maps (PMEP 2018c, Brophy et al. 2019) and OCMP's CMECS Aquatic maps (OCMP 2014a, Lanier et al. 2014). Areas attributed as diked (i.e., areas with modifier AI07) were considered "lost" due to disconnection from tidal flows. Conversely, areas without modifier AI07 (non-diked areas) were considered "retained," i.e. current tidal wetlands. The diking status data were edited to improve accuracy, using expert input from the author and others as well as PMEP's restored areas database (Sherman et al. 2019). However, it is important to note that some tidally disconnected or tidally muted areas may not be recognized as "lost" in the mapping. These could include areas behind restrictive culverts, areas behind tide gates that are not associated with dikes, and areas affected by filled lands, roadways, and railroad embankments.

Historical vegetation class (emergent, scrub-shrub, or forested) was determined using digital maps of historical vegetation from the Oregon Biodiversity Information Center (Hawes et al. 2018) and supplemented with additional data where the maps did not extend to the inland (upslope) estuary boundary.

Current vegetation class (emergent, scrub-shrub, or forested) was obtained from PMEP's CMECS Biotic maps (PMEP 2018c, Brophy et al. 2019), which had been transferred directly from OCMP's earlier work (OCMP 2014b, Lanier et al. 2014), except that the map extent was adjusted to match PMEP's Estuary Extent (PMEP 2018b, Brophy et al. 2019).

The geoprocessing steps used to map and tabulate the areas affected by diking and vegetation conversion are listed below. For a more detailed listing, see Appendix 6.

1. Assembled input data and additional data to assist interpretation and classification of current and historical tidal wetlands; clipped and reprojected data to a common boundary and coordinate system (Oregon Lambert, WKID 2992).
2. Updated the Oregon coast historical vegetation data (Hawes et al. 2008) to incorporate data from Coast Survey charts (T sheets), improving accuracy near the mouths of several estuaries. This work was conducted by John Christy; results were published in Hawes et al. (2018) and described in Christy (2018).
3. Identified additional tidal wetland areas beyond the geographic extent of Hawes et al. (2018), and attributed those areas with major vegetation class (emergent = EM, scrub-shrub = SS, and forested = FO). This work was conducted by John Christy.
4. Merged (geoprocessing tool: "union") the updated historical vegetation data (Hawes et al. 2018) with Christy's additional areas (previous step) to form a unified historical vegetation layer.
5. Developed correspondence tables relating current and historical vegetation classifications to the three vegetation classes for this study (EM, SS, and FO) (Appendices 8 and 9).
6. Used the above correspondence tables to attribute all features in the historical vegetation layer and current vegetation layer (CMECS Biotic) with vegetation class.
7. Created a final analysis layer by merging (geoprocessing tool: "union") the unified historical vegetation layer, PMEP's CMECS Biotic, OCMP's CMECS Aquatic, and PMEP's Estuary Extent.
8. Attributed all areas with the diking modifier (AI07, "Anthropogenic Impact: Impounded/ Diverted") as "diked." This modifier was present within Oregon Coastal Management Program's CMECS Aquatic data and PMEP's CMECS Biotic data. All areas without the diking modifier were classified as non-diked.
9. Created a subset of the data limited to the coast's 15 largest estuaries (listed in Geographic Scope above), representing 96.5% of historical tidal wetland area. Smaller estuaries were omitted because they had no diked areas and/or because the scale of the historical vegetation data was inadequate for further analysis.
10. Using PMEP's draft restored areas dataset (Sherman et al. 2019), revised the diking status attribute where needed for restoration sites.
11. Made further corrections to diking status for major areas that were incorrectly attributed in the source data, based on local knowledge of field conditions and interpretation of aerial photographs and LIDAR digital elevation models (DEMs).
12. Developed a feature symbolization to represent major categories of diking status and vegetation change, and incorporated the symbolization into the final shapefile attribute table.
13. Saved the final products to shapefile "OR_tidal_wetland_loss_by_hab_class_20191020."
14. Prepared maps of diking and vegetation conversion for all study estuaries, using the above feature symbolization. Maps are provided in Appendix 1 of this report.
15. Prepared additional maps to visualize historical prevalence and losses of tidal swamp. Maps are provided in Appendix 2 of this report.
16. Exported attribute table from final shapefile and prepared tabular summaries of results within and across estuaries, using pivot tables in Microsoft Excel.

Non-vegetated areas and other wetland classes: Although this study analyzed loss only for the three major tidal wetland habitat classes (emergent, scrub-shrub and forested), changes to and from non-vegetated areas were also of interest. Such changes could indicate wetland advance (e.g., formation of new emergent marsh on former tide flats), or wetland loss by erosion or drowning. Therefore, our classification included categories to allow analysis of these non-vegetated areas, to the extent possible given the data limitations. For historical vegetation, a "non-vegetated" category (shapefile attribute HISTVEG_CL = NONVEG) was used for bare ground. For current vegetation, the CMECS Biotic mapping did not classify non-vegetated areas but instead assigned them a value of 9.9.9.9 for the attribute CMECS BC CODE; therefore, these areas were attributed as "unclassified" (shapefile attribute CUR_VEG_CL = NA) in this study's products. The current vegetation data source (CMECS Biotic) (but not the historical vegetation data) mapped an aquatic bed class; those areas were attributed as CUR_VEG_CL = AB, but they were not further analyzed. Within the historical estuary extent, both the historical vegetation data and the CMECS Biotic data had some areas that were not mapped (blank); these were attributed as "not mapped/unknown " (shapefile attribute HISTVEG_CL = UNK or CUR_VEG_CL = UNK).

Historical and current vegetation classes are listed in the tables below and are contained within the product shapefile attribute table (fields listed in Appendix 7). Appendices 8 and 9 contain tables showing the source data classifications and their correspondence to the major vegetation classes used in this study (emergent, scrub-shrub, forested, and other classes used in the analysis of vegetation change).

Results

Historical tidal wetland area by habitat class

The total historical tidal wetland area (emergent, scrub-shrub and forested) for the 15 study estuaries was 15,399 ha (Tables 1 and 2, Figure 2). These 15 estuaries contain 96.5% of the Oregon coast's historical tidal wetland area (emergent, scrub-shrub and forested), which totals 15,957 ha for the 44 estuaries mapped by PMEP (Brophy et al. 2019, PMEP 2018c). Therefore, the results of this study effectively characterize the outer coast of Oregon, and the rest of this report refers to the outer Oregon coast, or more briefly, "the coast," rather than the 15 study estuaries.

Tidal forested wetlands comprised over half (54.4%) of the coast's total historical tidal wetland area (Table 2, Figure 2). Tidal scrub-shrub wetlands made up only 3.4% of historical tidal wetland area. Collectively, tidal swamps (forested plus scrub-shrub) occupied 57.8% of the historical tidal wetland area. The remaining area (42.2%) consisted of the tidal marsh that is now most familiar to estuary observers due to its current prevalence.

Tidal forested wetlands were historically widespread, occupying over 50% of historical tidal wetland area in 8 of 15 estuaries and over 30% in 11 of 15 estuaries (Table 1). Only two estuaries (Salmon River and Sand Lake) had low historical prevalence of tidal forested wetlands (14.5% and 7.7% respectively). Maps in Appendix 2 show the historical prevalence of forested and scrub-shrub tidal wetlands, and visually demonstrate the very high losses of these wetland types.

Major categories of tidal wetland change

Changes to historical tidal wetlands fell into the following eight major categories, which are attributed in the shapefile as "MAP_SYMB" and mapped in Appendix 1. The query for each category is provided in Appendix 10, making it possible for users to recreate or modify the map symbolization categories.

1. Diked: These are disconnected from tidal flows and are considered lost. They usually have emergent vegetation now, because of agricultural land uses. Historically, they may have been emergent, scrub-shrub, or forested tidal wetlands, so in addition to diking, many have undergone vegetation conversion. Areas behind dikes may or may not be wetlands; however, field experience suggests most of these are now seasonal wetlands.

2. Non-diked, remained emergent: These areas were historically tidal emergent wetlands ("tidal marsh"), and they remain in the same category today.

3. Non-diked, forested or shrub changed to emergent: These areas were historically tidal forested or tidal scrub-shrub wetlands; today they are tidal marsh (tidal emergent wetlands) due to removal of trees and shrubs. Some of these areas were logged but not used for agriculture; others were logged and converted to agriculture (mostly grazed), but not diked. The majority of these were originally tidal forested wetlands (as opposed to scrub-shrub). For details, see "**Disproportionate loss of tidal swamps**" and "**Conversions from tidal swamp to tidal marsh**" below.

4. Non-diked, marsh advance: These are areas that were non-vegetated (mudflat, aquatic bed, or open water) prior to European settlement, but have since become vegetated tidal marshes. This conversion from non-vegetated surfaces to tidal marsh is also called "marsh advance" or "marsh progradation." For details, see "**Tidal marsh advance and sea level rise**" below.

5. Non-diked, remained forested: These areas were historically tidal forested wetlands ("forested tidal swamp") and they remain in the same category today. For details, see "**Tidal swamp remnants**" below.

6. Non-diked, remained shrub: These areas were historically tidal scrub-shrub wetlands, and they are still in the same category today.

7. Non-diked, other vegetated (mostly currently forested/shrub): These areas are small compared to the major categories above; they are non-diked but have undergone other types of vegetation conversions, such as non-vegetated to scrub-shrub (and vice versa), non-vegetated to forested (and vice versa), emergent to forested, emergent to scrub-shrub.

8. Non-diked, non-vegetated or unclassified (mostly water, mudflat, etc.): These non-diked areas are mostly non-vegetated areas such as water and mudflats (historically and currently), which are unclassified in OCMP's and PMEP's CMECS Biotic maps (CM_BC_CODE = 9.9.9.9). This category also includes areas that are currently aquatic beds, and areas not mapped in either historical or current vegetation maps (no data).

Tidal wetland loss by habitat class

Overall, 57.9% (8917 ha) of historical tidal wetlands were lost due to diking, and an additional 21.9% (3371 ha) of historical tidal wetlands were lost through conversion to another vegetation class (mostly from forested to emergent) (Table 3).

Losses were not distributed equally across wetland types. Losses were highest for tidal forested wetlands (95.0% loss, 7964 ha), whereas tidal marsh losses totaled 58.9% (3827 ha) (Table 3, Figure 2). A high proportion of tidal scrub-shrub wetlands were lost (95.9%), but this constituted a smaller area (497 ha) than the other two classes.

Diking affected a higher proportion of historical tidal swamps (68.3% and 61.3% for forested and scrub-shrub, respectively) compared to tidal marshes (44.3%). Maps in Appendix 1 and tables in Appendices 4 and 5 show diking and vegetation conversion for each estuary.

Although 44.3% of Oregon's historical tidal marsh is currently diked (Table 3), this loss has been offset by 1770 ha of new marsh formed on formerly non-vegetated surfaces such as mudflats ("marsh advance", Table 4 and Appendix 1 maps). The net loss of tidal marsh was also reduced by vegetation conversion: 1174 ha of historical tidal forests were converted to emergent tidal wetlands (Table 4; Appendix 1 maps). When marsh advance and vegetation conversions are considered, there has been only a 10% net reduction in tidal marsh area for the Oregon coast compared to historical conditions (Table 5). By contrast, only 136 ha transitioned from historical tidal marsh to current tidal forested wetland (Table 4), so there was a very high net loss (91.8%) for tidal forested wetlands (Table 5). Scrub-shrub wetlands saw a small net gain in area (12.4%, 64 ha) compared to historical conditions (Table 5), but this habitat class still makes up only a small proportion (8.2%) of the coast's tidal wetlands (Table 2).

This study's analysis accounts for tidal wetland restoration efforts, which have totaled more than 700 ha on the Oregon coast (Sherman et al. 2019). Such areas were historically tidal wetlands, then were diked for agricultural uses -- but due to restoration, they are once again tidal wetlands today. In other words, tidal wetland restoration has resulted in lower losses from diking than would otherwise have been found in this study. However, many tidal wetland restoration sites have undergone vegetation conversions (see "**Conversions from tidal swamp to tidal marsh**" below); such areas may be included in the area of tidal wetland loss due to vegetation conversion (Table 3).

Table 1. Historical area of each major tidal wetland vegetation class by estuary, and percent of historical tidal wetland area consisting of tidal forested wetlands and "tidal swamp" (forested plus scrub-shrub tidal wetlands).

	Historical tidal wetland area (ha)				Percent of historical tidal wetland area	
Estuary	**Tidal marsh (EM)**	**Tidal scrub-shrub wetland (SS)**	**Tidal forested wetland (FO)**	**All tidal wetlands (EM+SS+FO)**	**% tidal forested wetland (FO)**	**% tidal swamp (FO+SS)**
Alsea Bay	259	31	156	445	35.0	41.9
Beaver Creek	26		64	90	71.1	71.1
Coos Bay	1790	245	779	2815	27.7	36.4
Coquille River	565		2989	3554	84.1	84.1
Necanicum River	20		108	127	84.6	84.6
Nehalem River	367	28	609	1004	60.6	63.4
Nestucca Bay	293	16	347	656	52.9	55.3
Netarts Bay	68	0	54	122	43.9	44.3
Salmon River	228	3	36	266	13.5	14.5
Sand Lake	212		18	230	7.7	7.7
Siletz Bay	300	33	101	434	23.3	30.8
Siuslaw River	262	89	740	1090	67.9	76.0
Tillamook Bay	694	4	1178	1876	62.8	63.0
Umpqua River	787	32	828	1647	50.3	52.2
Yaquina Bay	631	37	374	1042	35.9	39.5
Grand Total	6501	518	8380	15399	54.4	57.8

Table 2. Historical and current area and percent of tidal wetlands in each major vegetation class for the Oregon coast.

	Historical tidal wetlands		Current tidal wetlands	
Vegetation class	**Area (ha)**	**% of historical area**	**Area (ha)**	**% of current area**
Emergent ("tidal marsh") (EM)	6501	42.2	5820	82.1
Scrub-shrub (SS)	518	3.4	582	8.2
Forested (FO)	8380	54.4	690	9.8
Scrub-shrub plus forested ("tidal swamp")	8897	57.8	1271	17.9
Total (EM + SS + FO)	**15399**	**100.0**	**7092**	**100.0**

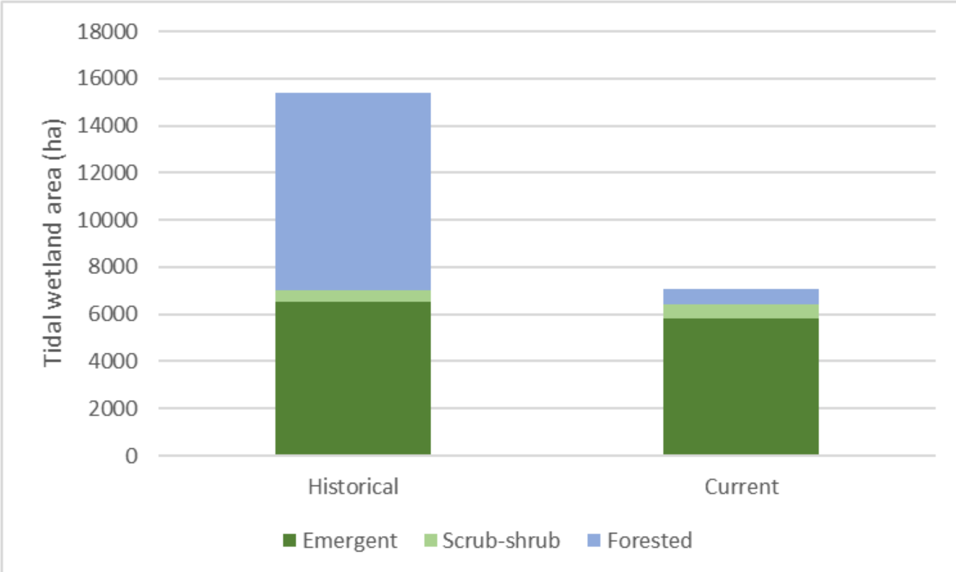

Figure 2. Historical and current tidal wetland area for the Oregon coast (emergent, scrub-shrub, and forested tidal wetlands only), and composition by wetland type

Table 3. Losses of historical tidal wetlands (area and percentage) for the Oregon coast, by historical wetland vegetation class and type of loss. These figures do not include new wetlands formed since the historical period (see Table 5 for that summary).

	Loss due to diking		**Loss due to vegetation conversion**		**Total loss**	
Historical vegetation class	**Area (ha)**	**% lost**	**Area (ha)**	**% lost**	**Area (ha)**	**% lost**
Emergent ("tidal marsh", EM)	2880	44.3	947	14.6	3827	58.9
Scrub-shrub (SS)	317	61.3	179	34.7	497	95.9
Forested (FO)	5720	68.3	2245	26.8	7964	95.0
Total (EM + SS + FO)	**8917**	**57.9**	**3371**	**21.9**	**n/a***	**n/a***

* Total loss is not summed across classes due to interconversions from one class to another.

Table 4. Area of diked former tidal wetlands ("Diked area") and current tidal wetlands ("Non-diked area") for the Oregon coast, by historical and current vegetation class. Key values are in bold and are footnoted. See Appendix 4 for guidance on interpreting this table.

	Diked area (ha)							Non-diked area (ha)							
	Current vegetation class [a]							Current vegetation class							Historical total
Historical vegetation class	Emergent (EM)	Scrub-shrub (SS)	Forested (FO)	Aquatic bed (AB)	Un-classified (NA)	Not mapped (UNK)	**Diked total**	Emergent (EM)	Scrub-shrub (SS)	Forested (FO)	Aquatic bed (AB)	Un-classified (NA)	Not mapped (UNK)	**Non-diked total**	
Emergent ("tidal marsh") (EM)	2,436	82	64	6	91	201	2,880	2,674	149	136	17	503	143	3,621	6,501
Scrub-shrub (SS)	273	15	17	0	9	3	317	137	21	11		24	8	201	518
Forested (FO)	**4,982**[b]	239	195	10	130	164	5,720	**1,174**[c]	244	415	20	711	96	2,660	8,380
Non-vegetated (NONVEG)	268	8	9	14	62	39	400	**1,770**[d]	139	88	1,143	16,512	181	19,834	20,234
Not mapped (UNK)	8	7	2		1	23	41	64	29	40	2	811	44	989	1,030
Total	7,968	350	287	31	293	430	9,359	5,820	582	690	1,182	18,561	471	27,305	36,663
Sum of historical EM, SS and FO that is now diked →							8,917	Sum of historical EM, SS and FO (diked & non-diked) →							**15,399**[e]
								Sum of current EM, SS and FO →						7,092	

[a] Areas behind dikes may or may not be wetlands; however, field experience suggests the vast majority are seasonal wetlands

[b] 4982 ha = area of former tidal forested wetlands converted to diked emergent lands (mostly pastures)

[c] 1174 ha = area of former tidal forested wetlands converted to tidal emergent wetlands

[d] 1770 ha = area of formerly unvegetated mudflat or water converted to tidal marsh via sediment accretion ("marsh advance" or "marsh progradation")

[e] 15399 ha = total historical area of EM, SS and FO wetlands on the outer coast

Table 5. Historical and current area and percentage of tidal wetlands for the Oregon coast, by vegetation class. "Net % loss" at right accounts for newly vegetated areas (marsh advance) and areas converted from one type to another (predominantly forested to emergent); a negative value of "net % loss" indicates gain in area.

	Historical		Current		
Vegetation class	**Area (ha)**	**% of total historical area**	**Area (ha)**	**% of total current area**	**Net % loss, historical to current (negative value indicates gain)**
Emergent ("tidal marsh", EM)	6501	42.2	5820	82.1	10.5
Scrub-shrub (SS)	518	3.4	582	8.2	-12.4
Forested (FO)	8380	54.4	690	9.8	91.8
SS + FO ("tidal swamp")	8897	57.8	1271	17.9	85.7
Total (EM + SS + FO)	**15399**	**100.0**	**7092**	**100.0**	**53.9**

Discussion

Total historical tidal wetland area

The data sources for this study (OCMP 2014a, PMEP 2018b) mapped the historical extent of tidal wetlands on Oregon's outer coast, but the associated publications (Lanier et al. 2014, Brophy et al. 2019) did not compare the results to previous estimates for this geographic region. This study found that the Oregon coast's total historical tidal wetland area (15,399 ha) is 34% higher than the only previous estimate that included tidal swamp as well as tidal marsh (11,498 ha) (Good 2000). Thus, the new maps substantially expand our understanding of the historical "footprint" of Oregon's tidal wetlands. This improved understanding is largely due to the new elevation-based mapping methods described by Brophy et al. (2019) – methods that were first developed at OCMP (Lanier et al. 2014) and which became possible only in the past 5 years, with the availability of high-resolution LIDAR-based elevation data. Our improved understanding of historical estuary extent is also based on full recognition of forested and scrub-shrub tidal wetlands as part of our coastal estuaries. Forested and scrub-shrub tidal swamps have often been omitted from past studies of Oregon coast estuaries, as described below.

Historical prevalence and importance of tidal swamps

This study shows that on the Oregon coast prior to European settlement, tidal forested wetlands were more extensive than tidal marsh -- a paradigm shift for understanding historical change and thus for estuarine conservation and restoration planning in Oregon and by extrapolation, for the Pacific Northwest. Awareness of tidal forested wetlands on Oregon's outer coast has been very low; for example, the Oregon Estuary Plan Book (Cortright et al. 1987), a central resource for land use planning on the coast over the past 30 years, completely omitted tidal forested wetlands from its estuarine habitat classification and mapping. In their foundational study of Oregon and Washington vegetation, Franklin and Dyrness (1973) described "tideland spruce" as scattered Sitka spruce found on "borders of tidal flats and channels," and described scattered Sitka spruce in scrub-shrub wetlands of the Columbia River, but did not mention the once-extensive Sitka spruce-dominated forested tidal swamps of Oregon's outer coast (probably because few examples were left at the time of their study). Only three of Oregon's outer coast estuaries have existing geospatial data quantifying the historical extent and losses of tidal swamps: the Siuslaw (Brophy 2005b), Necanicum (Brophy 2012) and Tillamook (Ewald and Brophy 2012). Awareness of the existence of tidal forested wetlands and their losses has been much higher in the Columbia River estuary (Thomas 1983, Christy and Putera 1992, Diefenderfer and Montgomery 2008, Diefenderfer et al. 2008, Marcoe and Pilson 2017), leading to prioritization of these ecosystems for restoration (LCEP 2012). However, this study is the first to document the historical prevalence and near eradication of tidal swamps on Oregon's outer coast. Our hope is that these findings will raise awareness and elevate the priority for conservation and restoration of tidal forested wetlands on the outer Oregon coast and elsewhere in the Pacific Northwest.

Most tidal wetland studies in Oregon focus on tidal marsh, yet the functions of the nearly-eradicated tidal swamps are largely unknown, and may have been critical to evolution of estuary-dependent organisms. Recent studies indicate tidal swamps may offer important foraging habitat for juvenile salmonids (Davis et al. 2019, Woo et al. 2019), and they are certainly important elements of a once-diverse landscape array of tidal wetland habitats that support salmonid resilience (Woo et al. 2019). Other tidal swamp functions may become particularly valuable under future climate change conditions, such as and soil carbon sequestration (Kauffman et al., in preparation), shading and cooling of subsurface and surface water flows by dense woody canopies, and support for system engineers such as beaver that may contribute to coastal climate change resilience (Diefenderfer and Montgomery 2008).

Disproportionate loss of tidal swamps

The results demonstrate the very uneven loss of wetlands across the three major habitat classes – and the importance of restoring forested and scrub-shrub tidal swamps. Over 95% of historical forested and scrub-shrub tidal wetlands on the Oregon coast have been lost to diking or logging, and this loss is highly significant, because these tidal swamps historically constituted the majority of all tidal wetlands on the coast. Not all of these wetlands are currently diked; some of the losses are due to vegetation conversion (primarily from forested to emergent). See "**Conversions from tidal swamp to tidal marsh**" below for details.

The disproportionate loss of forested and scrub-shrub tidal wetlands probably explains why many people equate tidal wetlands with "salt marsh" on the Oregon coast: tidal marsh is almost all that's left of the historical landscape array of tidal wetland types. The causes of tidal swamp loss on Oregon's coast included logging for spruce lumber during World War I (Williams 1999), conversion to agriculture (as shown in this study), and in some cases, filling for urban and residential development (Good 2000).

Tidal swamp remnants

The few remnants of tidal forested wetlands on the Oregon coast are small in area; only a handful of tidal forested wetlands over 10 hectares remain. The larger remaining contiguous areas are in the Tillamook Bay estuary (especially the Hoquarten Slough wetlands) and the Nehalem River estuary (Coal Creek wetlands and those at the confluence of the mainstem and the North Fork Nehalem River). Some, but not all, of these areas are in conservation status. Some remnants of tidal swamp are present in nearly every estuary, and though these small remnants may seem unimportant, maintaining at least a few examples of a historical landscape array of habitat classes has been recognized as an important landscape conservation strategy. For example, a diverse landscape array of habitats supports genetic diversity in salmon populations, improving salmonid resilience to environmental stresses such as climate change (Jones et al. 2014, Flitcroft et al. 2016, Woo et al. 2019). Protection of all remaining tidal swamps should be considered a top priority for conservation, and tidal swamp restoration (where appropriate) should also be a top priority (see Appendix 11, "**Restoring tidal swamps: a priority for research and practice**").

Conversions from tidal swamp to tidal marsh

Conversion of historical tidal forested wetlands to tidal marsh has been widespread on the Oregon coast, totaling 1174 ha (Table 4; Appendix 1 maps). We analyzed these areas to assess the potential condition of these wetlands. The bulk of the converted area (64.7%) consisted of small polygons or "slivers" less than 5 ha; this may be due to disparate scales of input data (see "**Scale issues**" below). Of the larger contiguous areas, most had previously been diked but had been deliberately restored via dike breaching or dike removal; however, the restoration (at least initially) resulted in tidal marsh rather than tidal forested wetland. This is typically due to subsidence, which results in conditions too wet and/or saline for establishment of the historical woody vegetation type (Turner 2004; Appendix 11). Ideally, restoration re-establishes natural processes; but land use and diking impacts such as subsidence, soil compaction, and ditching may affect wetland characteristics and functions at these sites far into the future. Depending on salinity, accretion rates, sea level rise, and other factors, these converted former tidal swamps may or may not ultimately recover their historical forested or scrub-shrub vegetation.

Some areas converted from forested to emergent tidal wetland were never diked, but were logged and have not recovered their woody dominants. Even non-diked lands were often grazed by livestock in the past, and such agricultural uses probably affected soil conditions, for example causing compaction and subsidence. These areas are subject to many of the same issues listed in the previous paragraph.

Regardless of the reasons for vegetation conversion, areas converted from tidal forested wetlands to emergent tidal wetlands have lost many of the characteristics and functions unique to tidal forested wetlands, particularly those related to large wood production, carbon sequestration, channel complexity, and fish and wildlife habitat. Therefore, even though the conversion of forested to emergent tidal wetlands has reduced the apparent net loss of tidal marsh, this conversion is not a mitigating factor for tidal wetland loss; instead, the likely result is net loss of functions.

Tidal marsh advance and sea level rise

Tidal wetland losses through drowning and erosion are common in other U.S. coastal regions and worldwide, and have often been linked to anthropogenic factors such as sea level rise and watershed alterations (Barbier et al. 2011, Ganju 2019). However, for the Oregon coast, during the time period considered in this study (since European settlement), formation of new marsh appears to have been much more common than loss to erosion or drowning. Across the entire coast, we found that 1770 ha of new marsh has formed on formerly non-vegetated surfaces such as mudflats (Table 1; Appendix 1 maps). This formation of new marsh, also called "marsh advance" or "marsh progradation," has been documented in Oregon (Dicken 1961, Johannessen 1964) and elsewhere in the Pacific Northwest (Hood 2010; Hood et al. 2016; Diefenderfer, Cullinan et al. 2018). Marsh advance on the Oregon coast is in part a product of the coast's high sediment supply, steep watersheds, and largely intact sediment delivery systems (i.e. free-flowing, non-dammed rivers) (Komar 1997, Thom and Borde 1998, Wheatcroft and Sommerfield 2005), as well as generalized land surface uplift resulting in low relative sea level rise in the past (NRC 2012). Sediment pulses associated with forest fires and logging may also have contributed to marsh advance (Dicken 1961, Paulson 1997, Pearson 2002). However, channel network characteristics, soil characteristics, and vegetation can be strikingly different in newly accreted tidal wetlands compared to older "mature" high marsh (Dicken 1961, Jefferson 1975), so the ecosystem functions and services provided by newly accreted tidal marsh are unlikely to replicate those of the mature high marshes that were diked to form agricultural lands. In addition, even though marsh advance may partially offset marsh loss from diking, marsh advance also represents a loss of important mudflat/aquatic bed habitats and the associated ecosystem services (Dissanayake et al. 2018).

If present, erosion or drowning of tidal marsh would have been detected in this study by locating areas that converted from tidal marsh or tidal swamp to open water or unvegetated mudflats. Although some areas did undergo such conversions (Table 4), there was little evidence that the conversions indicated wetland drowning or erosion. Among the largest of these conversions were historical tidal marshes that had subsided due to diking and were subsequently restored, converting to mud flats due to their low elevation. The remaining converted areas were mostly narrow features on the fringes of tidal water bodies, and their conversion appeared related to scale discrepancies (see "**Scale issues**" above) and/or channel migration. By contrast, much larger contiguous areas converted from water or mudflat to emergent marsh, indicating marsh advance rather than drowning or erosion. These findings support the conclusion of Peck (2017) that Oregon estuaries have maintained their elevations relative to past sea level rise, and therefore may be relatively resilient to future sea level rise, provided the rate of rise does not exceed the available sedimentation rates.

Comparisons to other loss estimates

The overall loss from diking determined in this study (57.9% across all three major habitat classes) is slightly higher than the recent estimate of 53.3% wetland loss for Oregon from PMEP's indirect assessment of tidal wetland loss (Brophy et al. 2019). The locations of loss in this study differ somewhat from the locations identified in the PMEP study, due to the different methods used for this study's direct assessment, versus PMEP's indirect assessment. The current study is more accurate because it uses a direct source of information on diking (the "impounded/diverted" modifier in OCMP's CMECS maps), whereas the PMEP study calculated losses indirectly, using the NWI as the source for current tidal wetlands (Brophy et al. 2019). In addition, the current study (but not PMEP's) measured loss due to vegetation conversions, an important analyses for conservation and restoration planning. The current analysis also included three estuaries which were not included in PMEP's indirect assessment of tidal wetland loss: Necanicum River, Sand Lake, and Beaver Creek.

No previous assessments of tidal wetland loss for the Oregon coast have quantified losses separately for each major habitat class. However, recent and earlier assessments in the Lower Columbia River estuary (LCRE) have done so (Thomas 1983, Marcoe and Pilson 2017). Thomas (1983) documented 76.8% loss of tidal swamps and 43.1% loss of tidal marshes in the LCRE. Swamp losses were especially high in the brackish zone: Thomas reported 96% and 100% loss of spruce tidal swamps from Youngs Bay and Baker Bay respectively, "virtually eliminating" these brackish swamps from the LCRE. Marcoe and Pilson

(2017), reported similar losses for tidal swamps and tidal marshes in the LCRE (68.8% and 67.9% respectively). However, Marcoe and Pilson classified wetlands as tidal only if their elevation was below MHHW, whereas our project defines tidal wetlands as those occurring below annual high tide, reducing comparability of the analyses. MHHW is typically the lower, not upper, boundary for high tidal marsh and tidal swamps on Oregon's outer coast; therefore, MHHW was found to be unsuitable as an upper boundary for tidal wetlands on the U.S. West Coast (Brophy 2019).

Earlier tidal wetland loss estimates for the Oregon coast did not separately estimate losses for different habitat classes. In fact, tidal swamps were seldom evaluated in tidal wetland studies of the 1980s and 1990s, probably because there were (and are) so few remaining. However, earlier studies did include losses due to filled lands, which could not be addressed in the current study (see "**Data limitations"** below). For example, Boulé and Bierly (1987) assessed tidal marsh losses for the outer Oregon coast, and found that 3372 ha were diked or filled, representing 45.9% of the historical tidal marsh area of 7350 ha – a similar estimate to this study's value of 44.3% loss of tidal marsh. Good (2000) did include tidal swamps in his loss assessment, although he did not evaluate their losses separately from tidal marsh. He found a somewhat higher loss than the current study (71.7% for the outer coast), perhaps due in part to the inclusion of filled lands (which were lumped with diked lands). However, Good's estimate of total area historical tidal wetland area (11,498 ha) was lower than this study's estimated historical area (15,399 ha), as described in "**Total historical tidal wetland area**" above.

Only three studies (Brophy 2005a, 2012; Ewald and Brophy 2012) have previously quantified losses of historical tidal wetlands by vegetation class within individual estuaries of Oregon's outer coast. Losses were similar in those earlier studies and the current study. For the Tillamook Bay estuary, Ewald and Brophy (2012) reported 91.1% loss of tidal swamps and 84.7% loss of tidal marshes; the current study showed those losses as 92.3% and 69.9% respectively (Appendix 5). For the Siuslaw River estuary, Brophy (2005) reported a 97% loss of tidal forested wetlands and 40% loss of tidal marsh; the current study found those losses to be 96.0% and 28.5% respectively. In the Necanicum, Brophy (2012) reported 80% loss of tidal forested wetlands and 94% loss of tidal marshes; the current study found those losses to be 84.1% and 85.1% respectively. The lower estimates of tidal marsh loss in the current study were due in part to tidal marsh restoration projects completed since the earlier studies.

Data limitations

This analysis inherits the limitations of the input layers. For example, to locate the upslope boundary of tidal wetlands and estuaries, the OCMP and PMEP maps use an elevation-based method that combines land surface elevation data (from LIDAR) with extreme water level models from NOAA (Lanier et al. 2014, Brophy et al. 2019). The method identifies areas potentially subject to tidal inundation – that is, areas within current tide range. However, in many coastal cities, some former tidal wetlands were filled and developed, elevating these areas above current tide range. Because they are now higher than annual high tide levels, these areas are not captured in the OCMP and PMEP elevation-based estuarine habitat maps; they are clearly lost, but cannot be quantified using this study's input data. Therefore, actual wetland losses are probably higher than determined in this study.

During development of OCMP's digital maps of estuarine habitats, diked areas were reviewed for accuracy and found to be accurate enough for landscape-scale assessment, but the maps do not include all areas where tidal flows are altered. In particular, the attribution of diked areas may omit areas disconnected from tidal influence by non-dike features such as restrictive culverts, filled areas, and other barriers to channelized and non-channelized flow. Such alterations can affect large areas, particularly upriver where natural levee features may be combined with small restrictive culverts to limit tidal inundation, allowing agricultural use of former tidal wetlands. Since these muted or hydrologically disconnected areas are not attributed as diked in the OCMP data, wetland losses are probably higher than determined in this study. For example, Brophy and So (2005) found that diking and other major alterations in the Umpqua River estuary affected 62% of historical tidal wetland area, but an additional 19% was affected by "minor alterations" such as restrictive culverts and partial fill. In the Tillamook Bay estuary, Ewald and Brophy (2012) found that 66% of former tidal wetlands were diked and fully disconnected, but an additional 10% had muted tidal exchange. Muting of tidal exchange affects all tidal wetland functions, particularly those affected by frequency and duration of inundation such as channel development, carbon sequestration, groundwater dynamics, and plant community development. Diefenderfer, Johnson et al. (2016) compared tidal wetland restoration approaches and found that tide gate replacement projects, which are characterized by muted tidal exchange, did not generally show evidence of benefits to fish or ecosystems. By contrast, they found that tide gate and dike removal projects (which fully restore tidal flows) showed stronger evidence of benefits.

Because this study used OCMP's spatial data on diked areas to evaluate wetland losses, estuaries with no areas mapped as diked could not be evaluated. Most small estuaries on the Oregon coast (e.g. Ecola, Yachats, Elk, Sixes, Hunter, Chetco, Pistol, Winchuck) have no mapped diked areas in this study's data sources; this is also true for one medium-sized estuary (Rogue River). Although in principle, it might be possible to evaluate vegetation change in these estuaries, in practice this does not work well due to the scale of the input data. Specifically, the relatively coarse-resolution historical vegetation data often fail to align with physical features of small estuaries, such as channels and floodplains, resulting in artifacts in the analysis. Despite the omission of these smaller estuaries from the current study, these estuaries have certainly experienced tidal wetland losses. Local analyses and field investigation are needed to identify and characterize the losses in these estuaries. Examples of such local studies include Ricks Myers (2015) for the Hunter, Pistol, Chetco and Winchuck estuaries, and Brophy (2003) for the Elk and Sixes.

The following estuaries had river channels and very small fringing wetland areas that extended above the historical vegetation maps (even after the additions described in step 3 of Methods above): Alsea, Coos, Coquille, Nehalem, Siletz, Siuslaw, and Umpqua. These minor areas therefore had no data for historical vegetation class. Because these areas consisted almost entirely of river channels, the data gaps have almost no effect on the results of this analysis.

Scale issues

Some of the identified vegetation conversions may be an artifact of the disparate scales of the study's input data. The coarser-resolution historical vegetation data generally mapped forests up to the edge of the tidal channel, whereas the more detailed current vegetation data often maps a narrow fringe of emergent marsh (or maps no tidal wetlands at all) adjacent to the channel. These scale discrepancies are manifested primarily in narrower arms of the estuaries, such as upriver areas.

To determine whether these scale discrepancies might have affected our broad conclusions, we analyzed the historical percentage of tidal forested wetlands within diked areas, which are generally large blocks of tidal wetland rather than narrow fringing wetlands. (Narrow fringing wetlands were not often diked because they were too small for agricultural use or development.) We found that historically (prior to diking), diked areas had an even higher proportion of forested wetlands than the overall study area (64.1% forested, versus 54.4% for the entire study area). This finding supports the broad conclusions of this study (i.e. the historical prevalence of tidal forested wetlands on the Oregon coast).

Recommended uses

The products of this study are recommended for use in landscape-scale conservation and restoration planning, such as prioritization of sites for action planning. The products are not intended for regulatory or legal uses or for site-specific conservation or restoration design; such activities require field collection of data to verify and measure site characteristics and conditions. As described above, this study's data products may contain inaccuracies due to limitations of the input data sources.

Maps produced by this study (Appendices 1 and 2) show the current and historical locations of forested and shrub tidal swamps. Conservation of current tidal swamps is urgent and can proceed immediately; potential mechanisms include land conservation agreements with willing landowners (e.g. conservation easements) and purchase from willing landowners by land trusts. Restoration of tidal swamps is also urgently needed, but locations for tidal swamp restoration need to be chosen carefully. Subsidence and related factors may present challenges to restoration of tidal swamp in some of its historical locations. Selection of appropriate locations for tidal swamp restoration requires careful analysis of the landscape, as well as monitoring of physical conditions at current least-disturbed tidal swamp reference sites and potential restoration sites (see Appendix 11, "**Restoring tidal swamp: A priority for research and practice**").

Products of this study

1) This report, available online at the link below:
https://appliedeco.org/report/brophy_2019_oregon_tidal_swamp_and_marsh_losses_final_dec2019/

2) The following geospatial dataset, available from the author on request:

Vector GIS dataset (shapefile, "OR_tidal_wetland_loss_by_hab_class_20191020.shp") showing areas of tidal wetland loss (diking), vegetation conversion, and wetland advance (wetland gain) for emergent, scrub-shrub, and forested tidal wetland classes. Attributes of the shapefile features are listed in Appendix 7.

Three symbolizations (layer files) are provided with the GIS dataset:

1) Symbolization for Appendix 1 maps of diking and vegetation conversion: "OR_tidal_wetland_loss_by_hab_class_20191020.lyr"

2) Color vision variant symbolization of the Appendix 1 maps: "OR_tidal_wetland_loss_by_hab_class_20191020_color_variant.lyr." This symbolization uses a combination of colors and hatching to provide better resolution for people with color vision variants such as deuteranopia, protanopia and tritanopia.

3) Symbolization for Appendix 2 maps of historical vs. current tidal swamp: "OR_tidal_wetland_loss_by_hab_class_20191020_swamp_maps.lyr."

3) Thanks to the Pacific States Marine Fisheries Commission and the Pacific Marine and Estuarine Fish Habitat Partnership, a web application is available for viewing the data at http://arcg.is/1LSSeT.

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Appendix 1. Maps of diking and vegetation conversion

Purpose: These maps are provided to illustrate the major changes in tidal wetland habitats in Oregon coast estuaries. The legend lists the major categories of change, which are shown in the colors listed below.

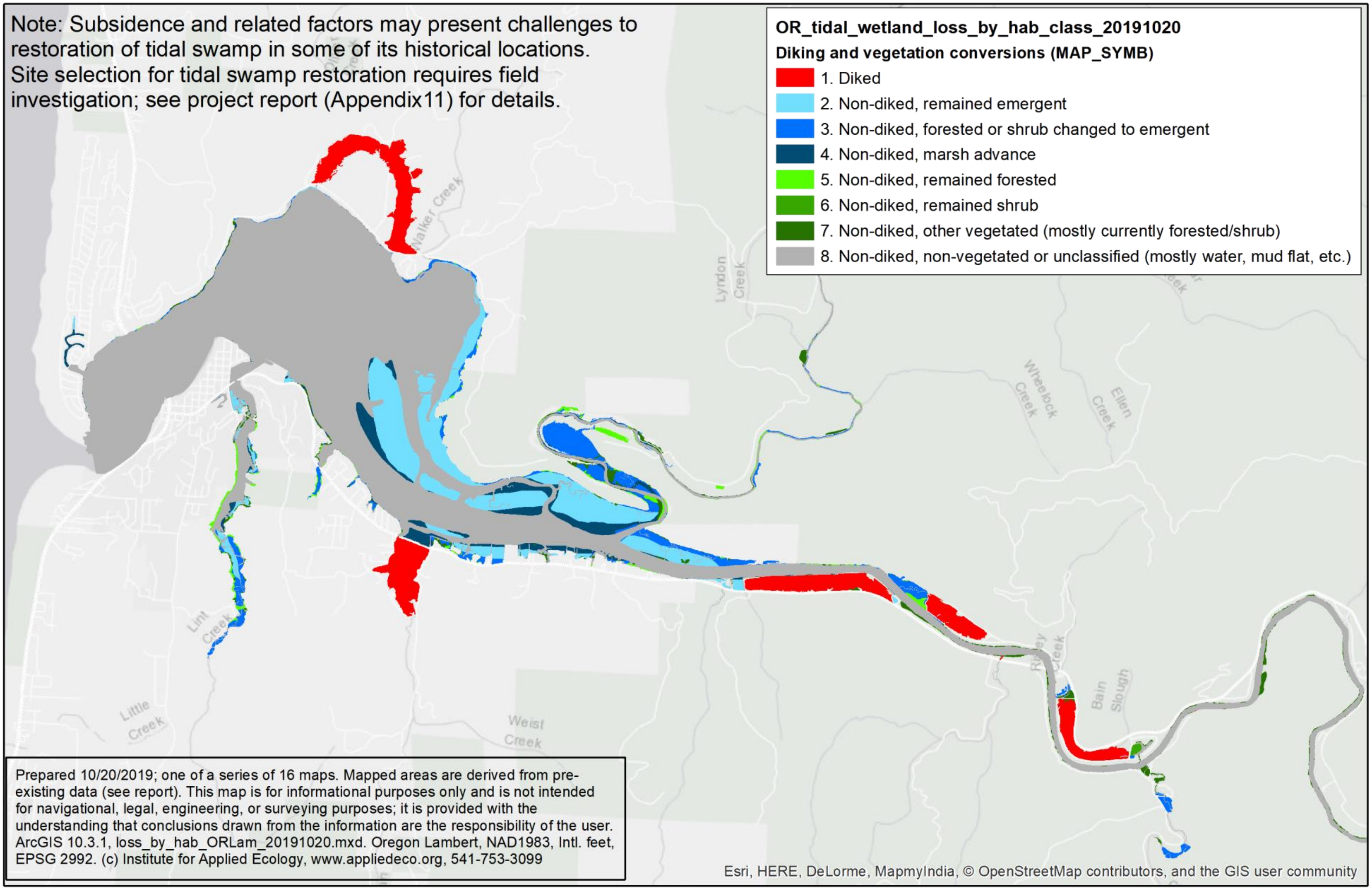
Color symbolization:

- **Red** indicates diked areas (former tidal wetlands that have been lost due to diking). These are all the same shade of red, regardless of their historical wetland type.
- **Blue** represents current, non-diked tidal marsh (tidal emergent wetlands); shades of blue indicate their former (historical) wetland types.
- **Green** represents current, non-diked tidal swamp (either forested or scrub-shrub); shades of green indicate their former (historical) wetland types.
- **Gray** represents other classifications, mostly open water and mudflats.

The queries used to generate the eight legend categories are provided in Appendix 10.

Can tidal swamps be restored in their historical locations? As noted on each map, wetland subsidence and related factors may present challenges to restoration of tidal swamp in some of its historical locations. Selection of appropriate locations for tidal swamp restoration requires careful analysis of the landscape, as well as field investigation of physical conditions at the potential restoration site compared to least-disturbed tidal swamp reference sites. See Appendix 11 for further discussion of these issues and approaches to tidal swamp restoration.

Alsea Bay estuary: Diking and vegetation conversions in tidal wetlands



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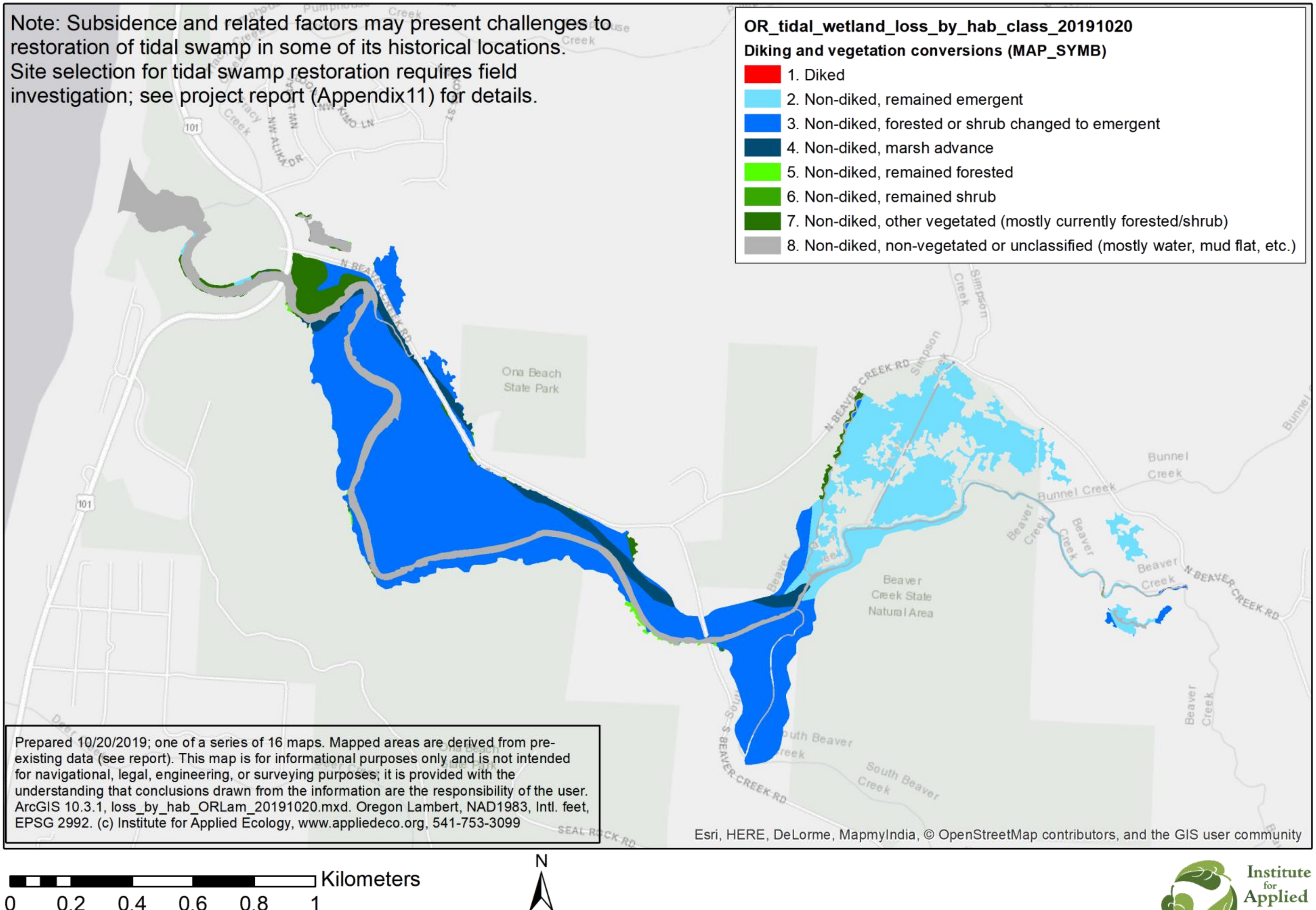
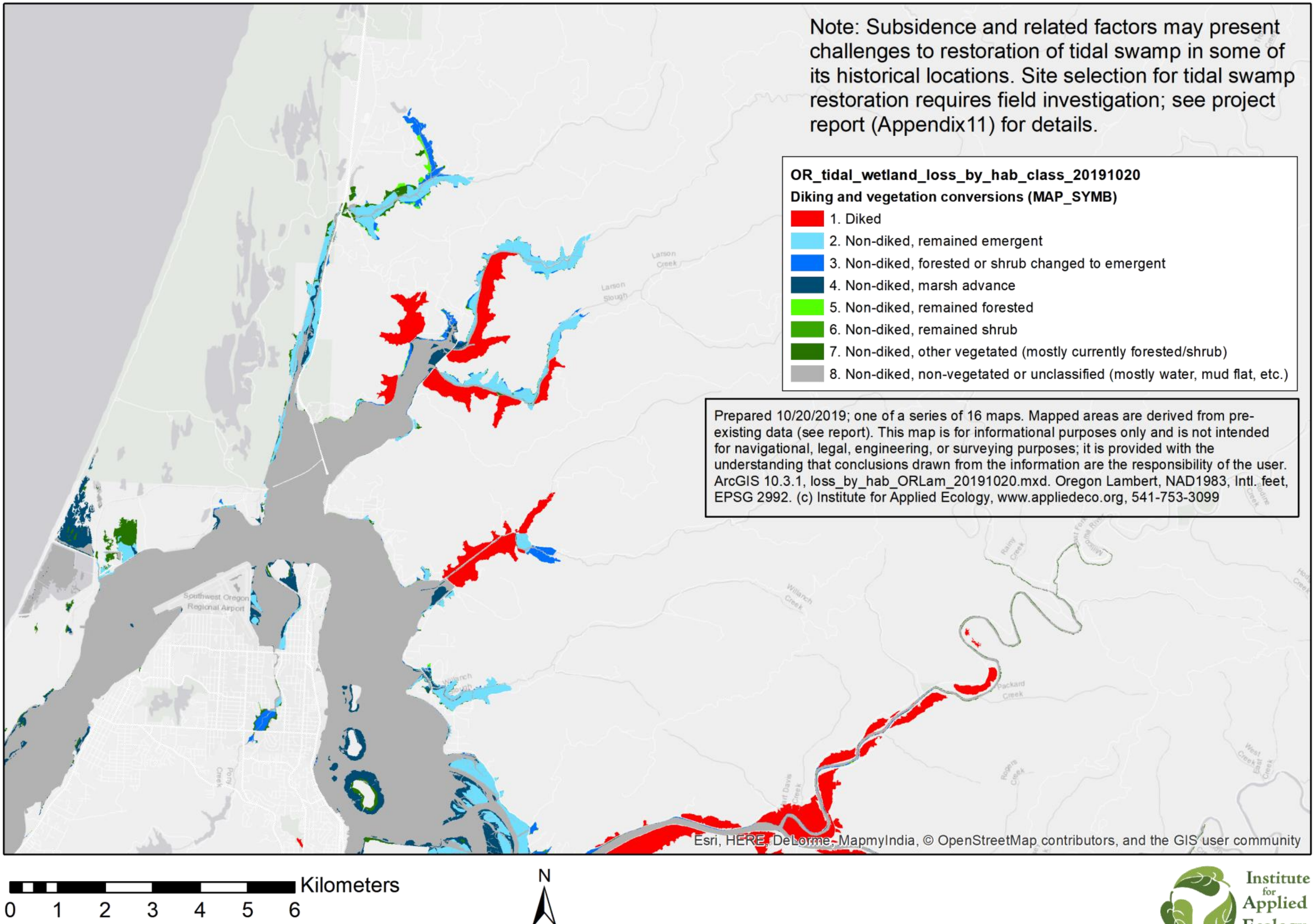
Institute for Applied Ecology

Beaver Creek estuary: Diking and vegetation conversions in tidal wetlands



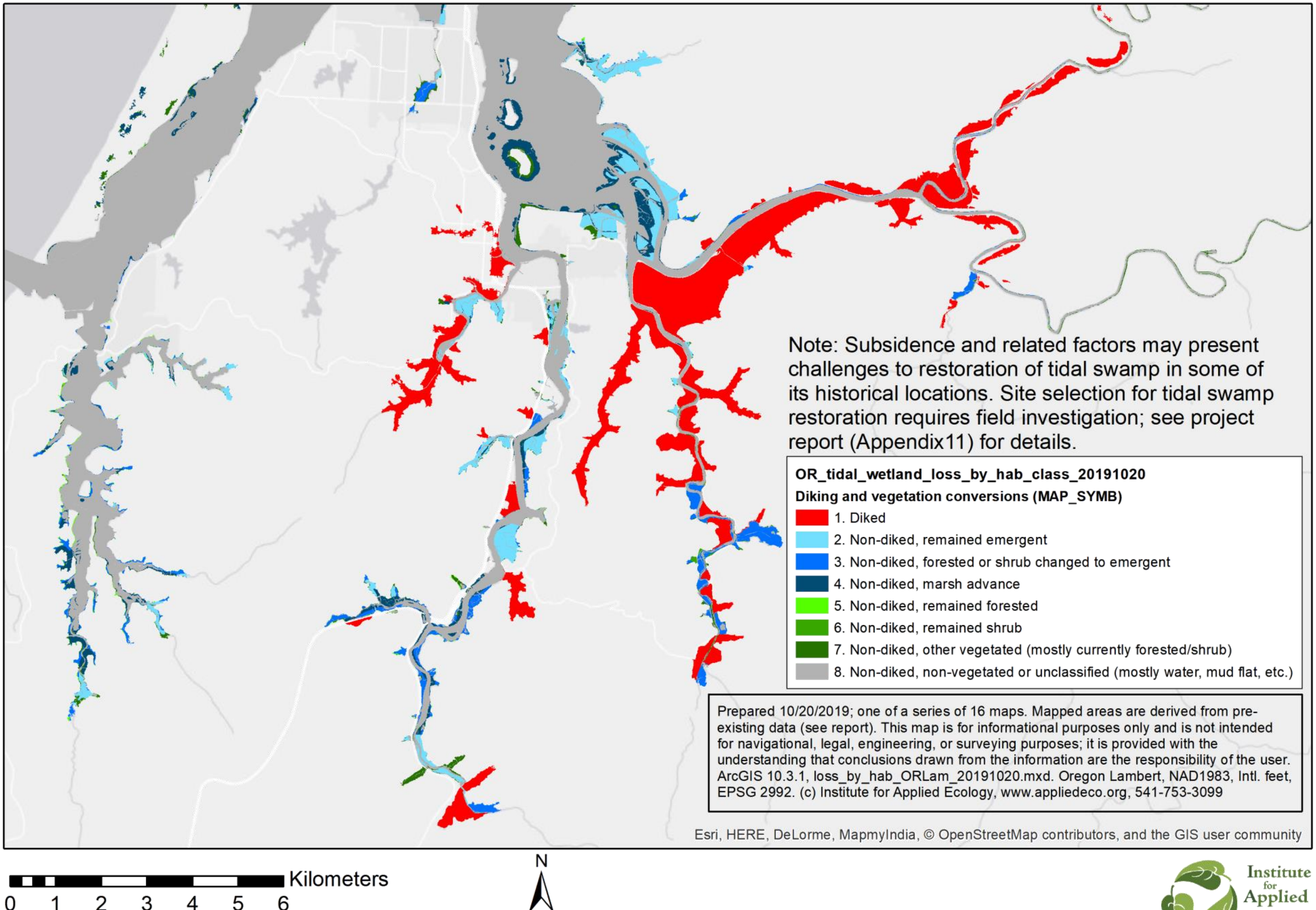
Institute for Applied Ecology

Coos Bay estuary, north half: Diking and vegetation conversions in tidal wetlands



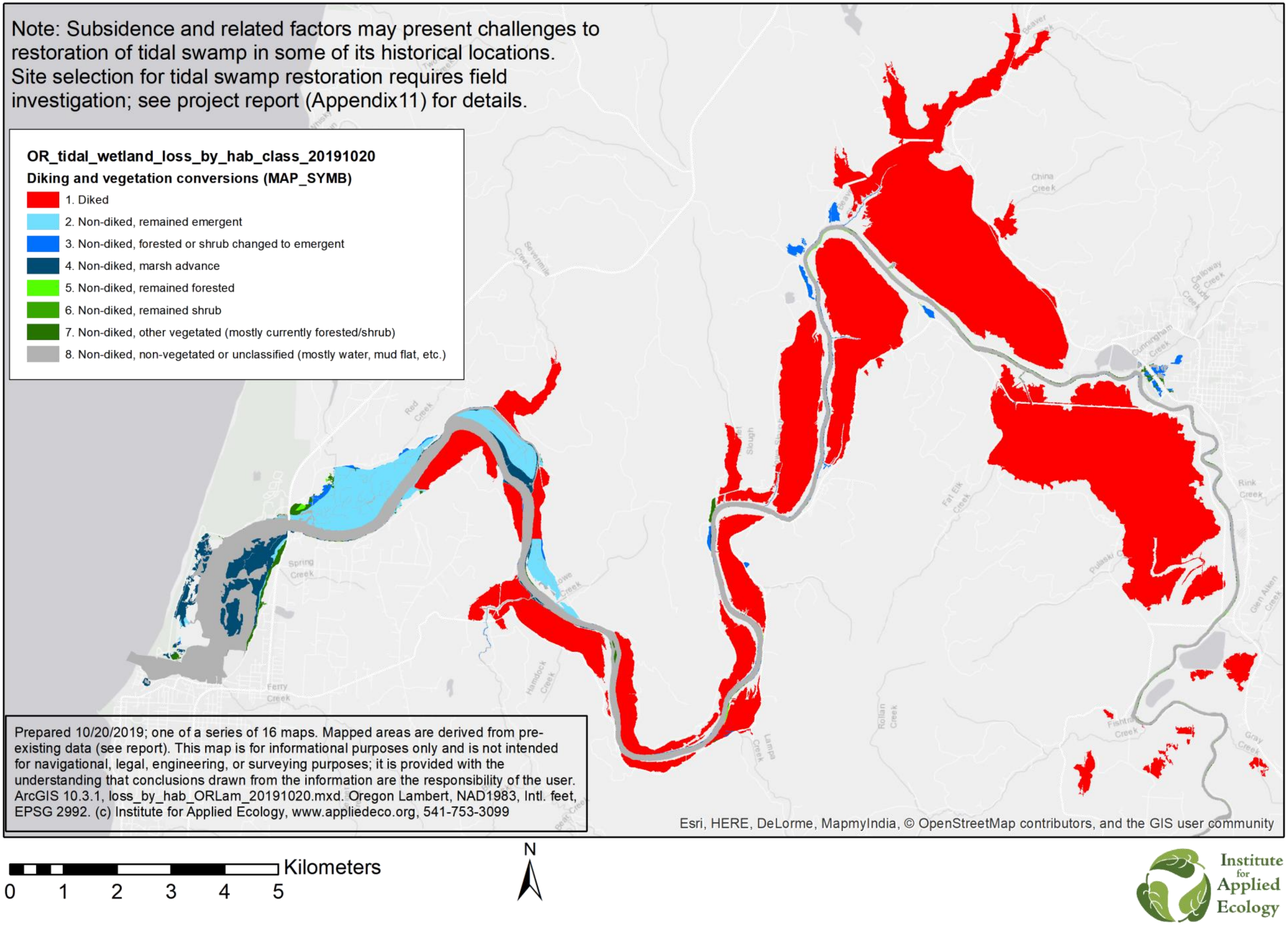
Institute for Applied Ecology

Coos Bay estuary, south half: Diking and vegetation conversions in tidal wetlands

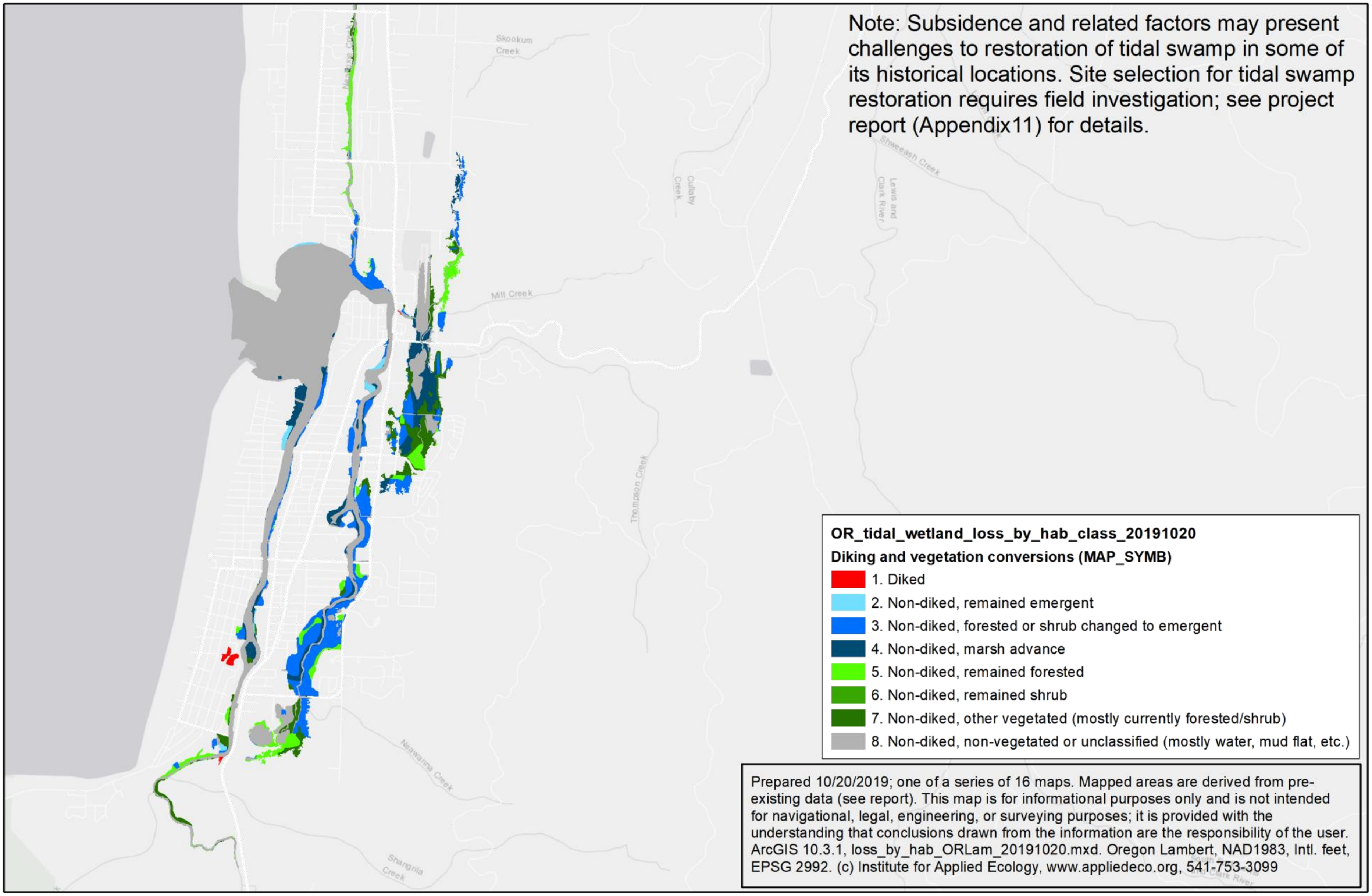


Institute for Applied Ecology

Coquille River estuary: Diking and vegetation conversions in tidal wetlands



Necanicum River estuary: Diking and vegetation conversions in tidal wetlands



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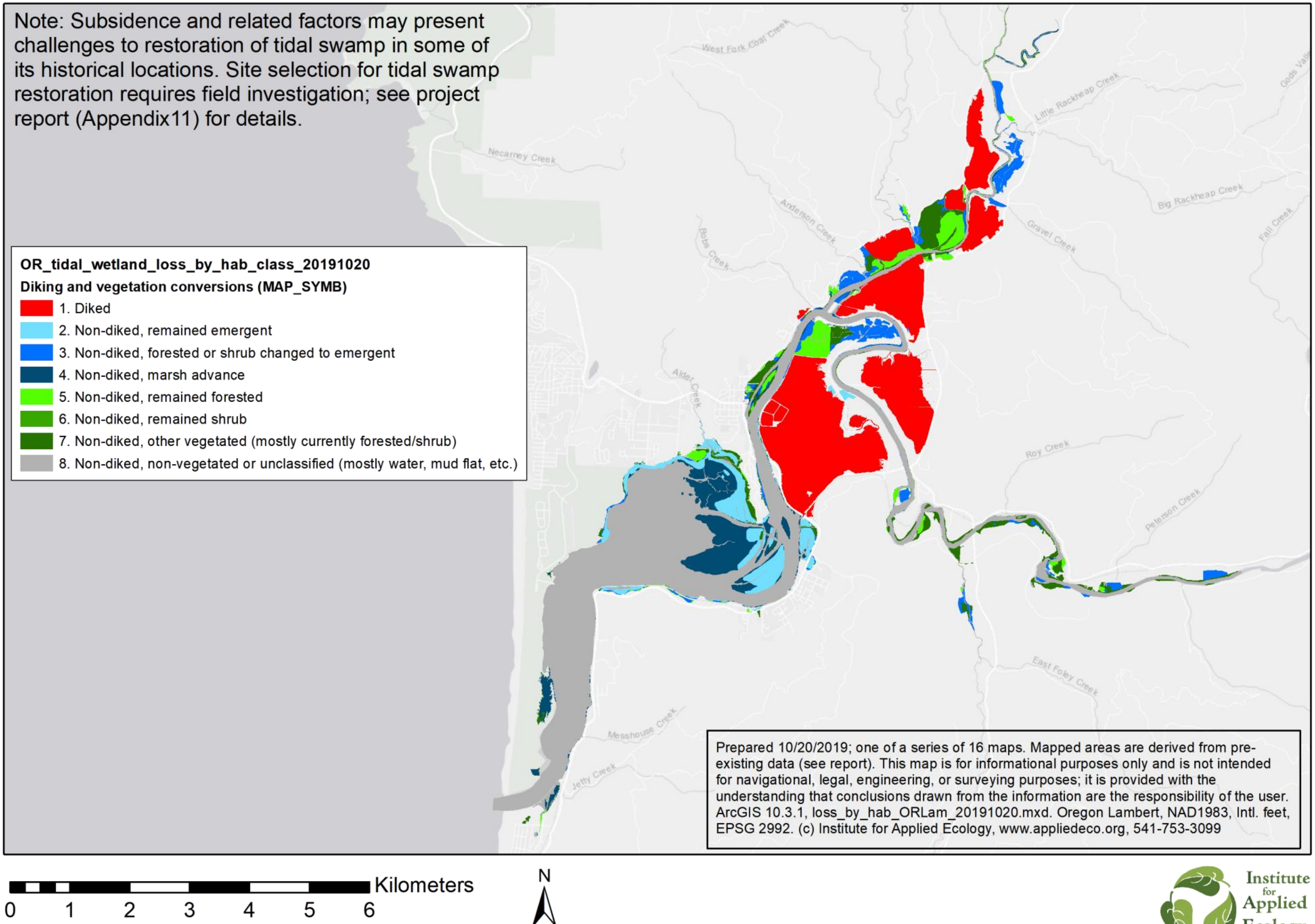
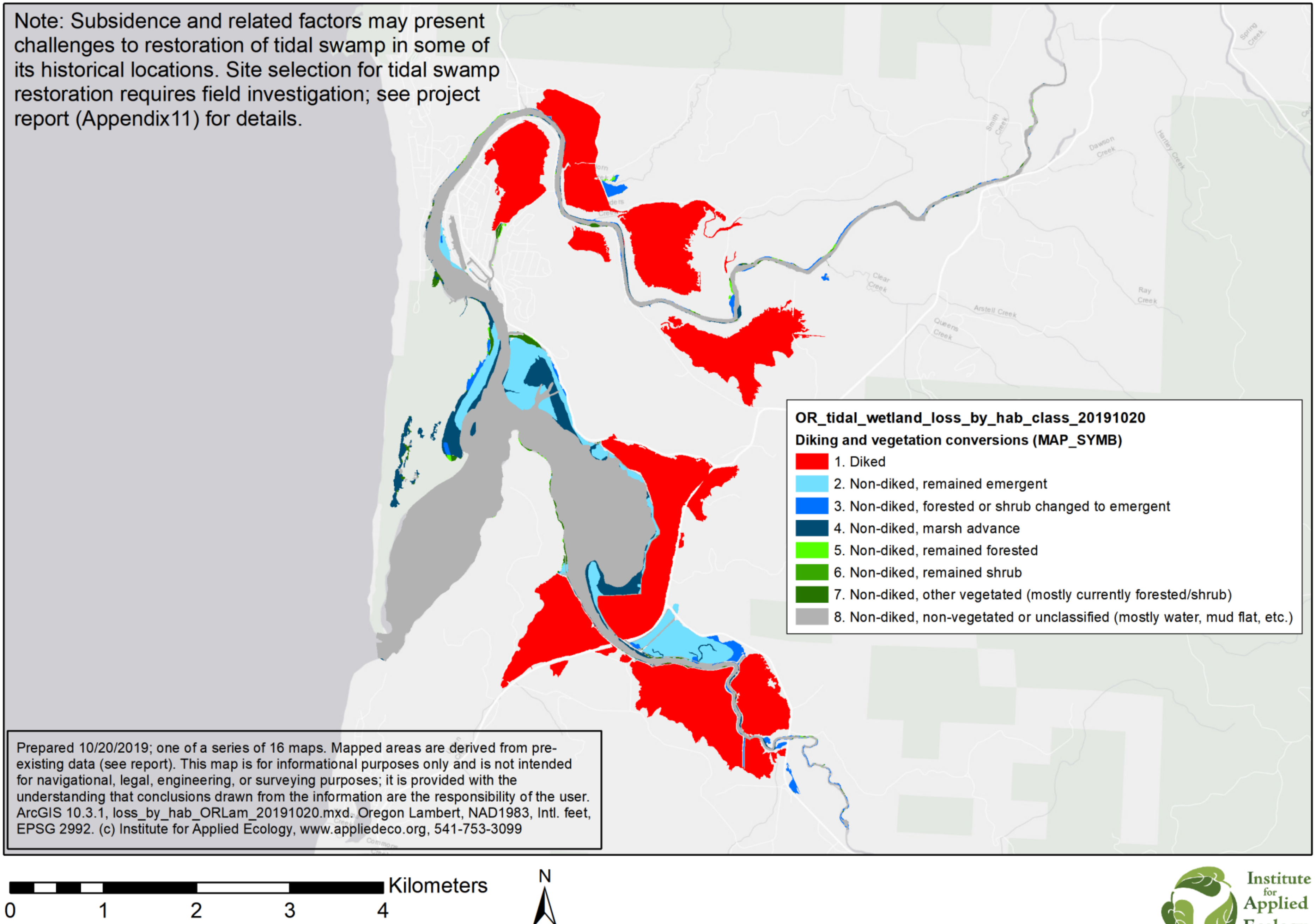
Institute for Applied Ecology

Nehalem River estuary: Diking and vegetation conversions in tidal wetlands



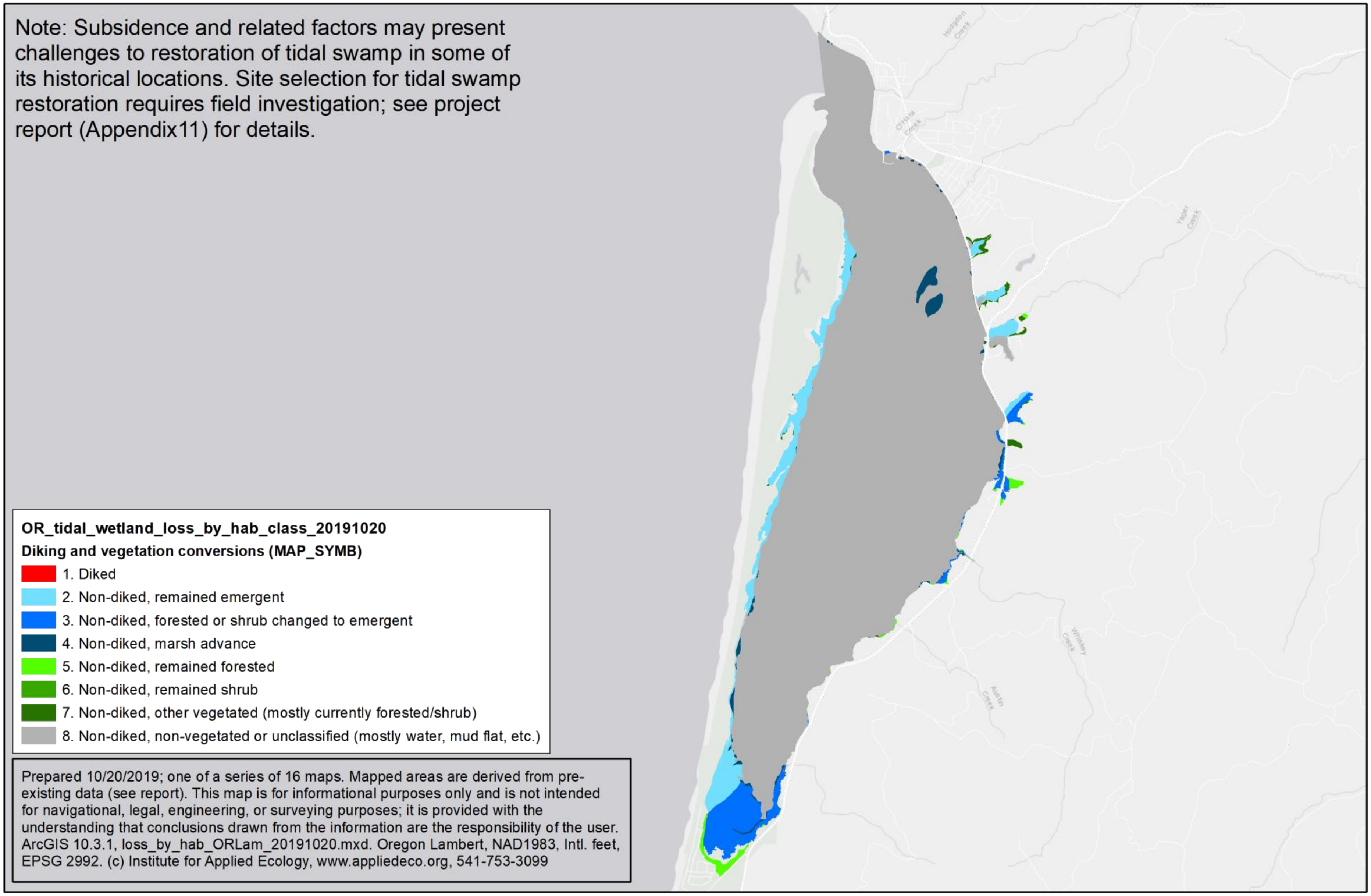
Institute for Applied Ecology

Nestucca Bay estuary: Diking and vegetation conversions in tidal wetlands



Institute for Applied Ecology

Netarts Bay estuary: Diking and vegetation conversions in tidal wetlands



0 1 2 3 4 Kilometers

N

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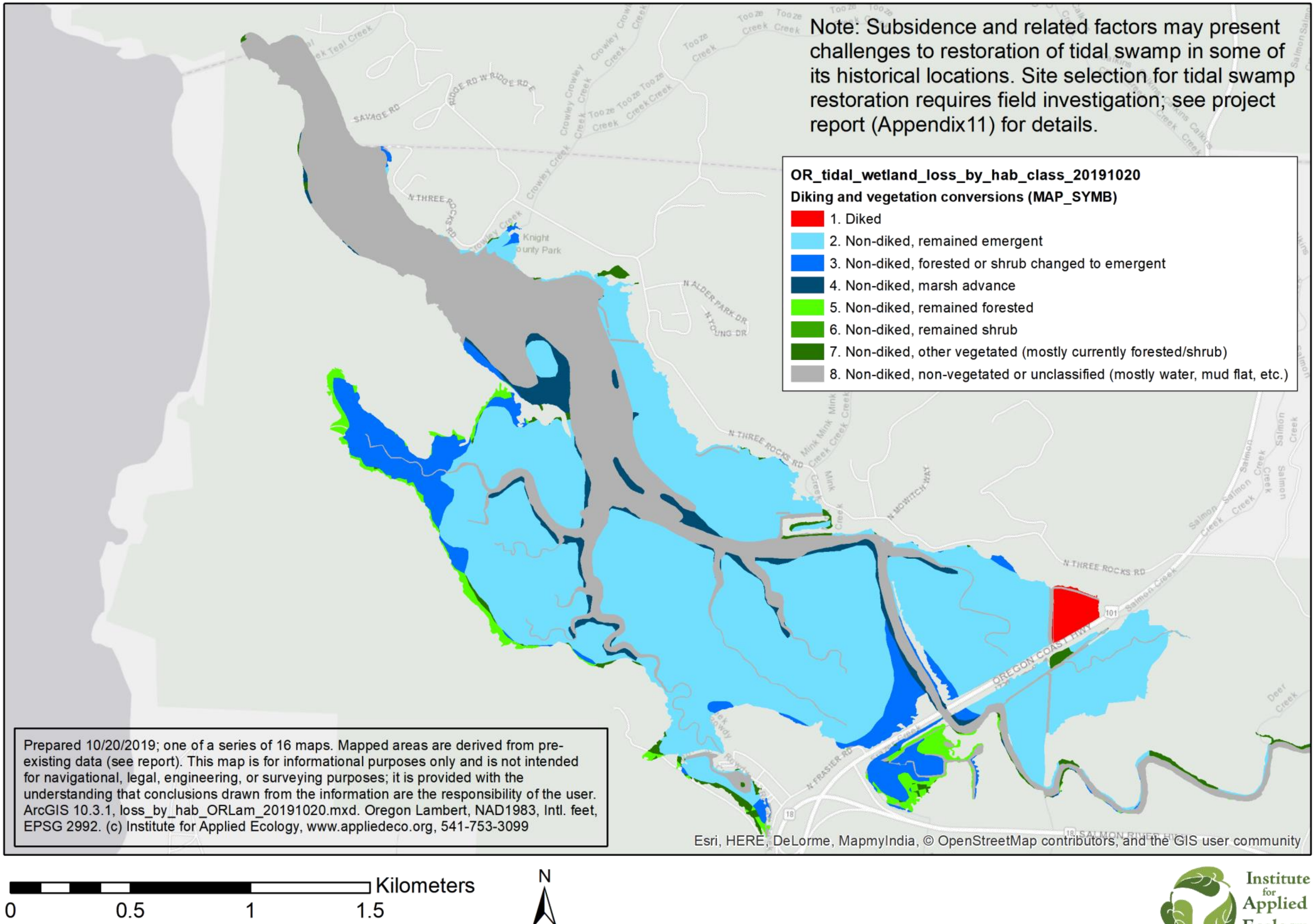
Salmon River estuary: Diking and vegetation conversions in tidal wetlands



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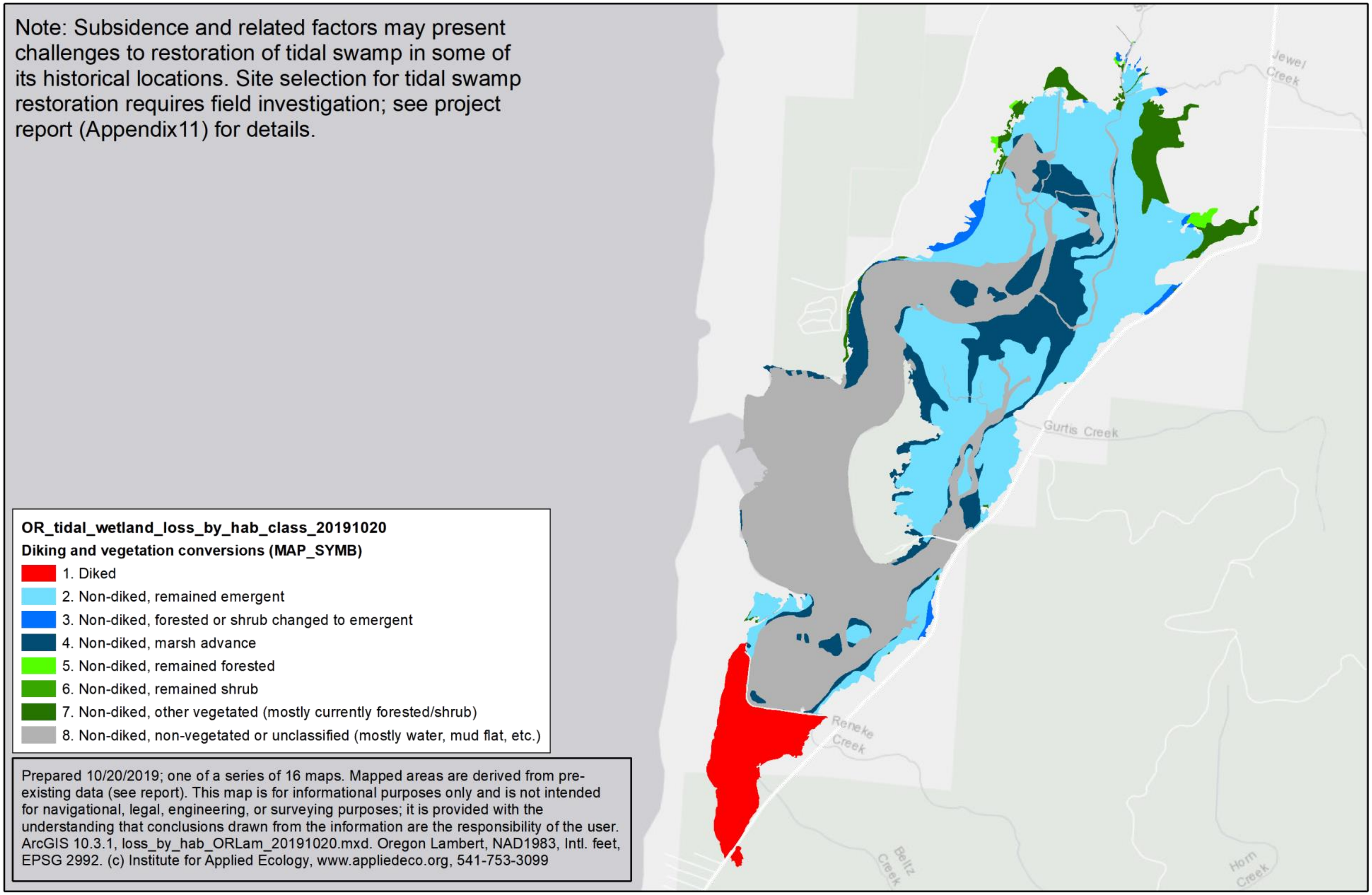
Sand Lake estuary: Diking and vegetation conversions in tidal wetlands



Kilometers 0 1 2

N

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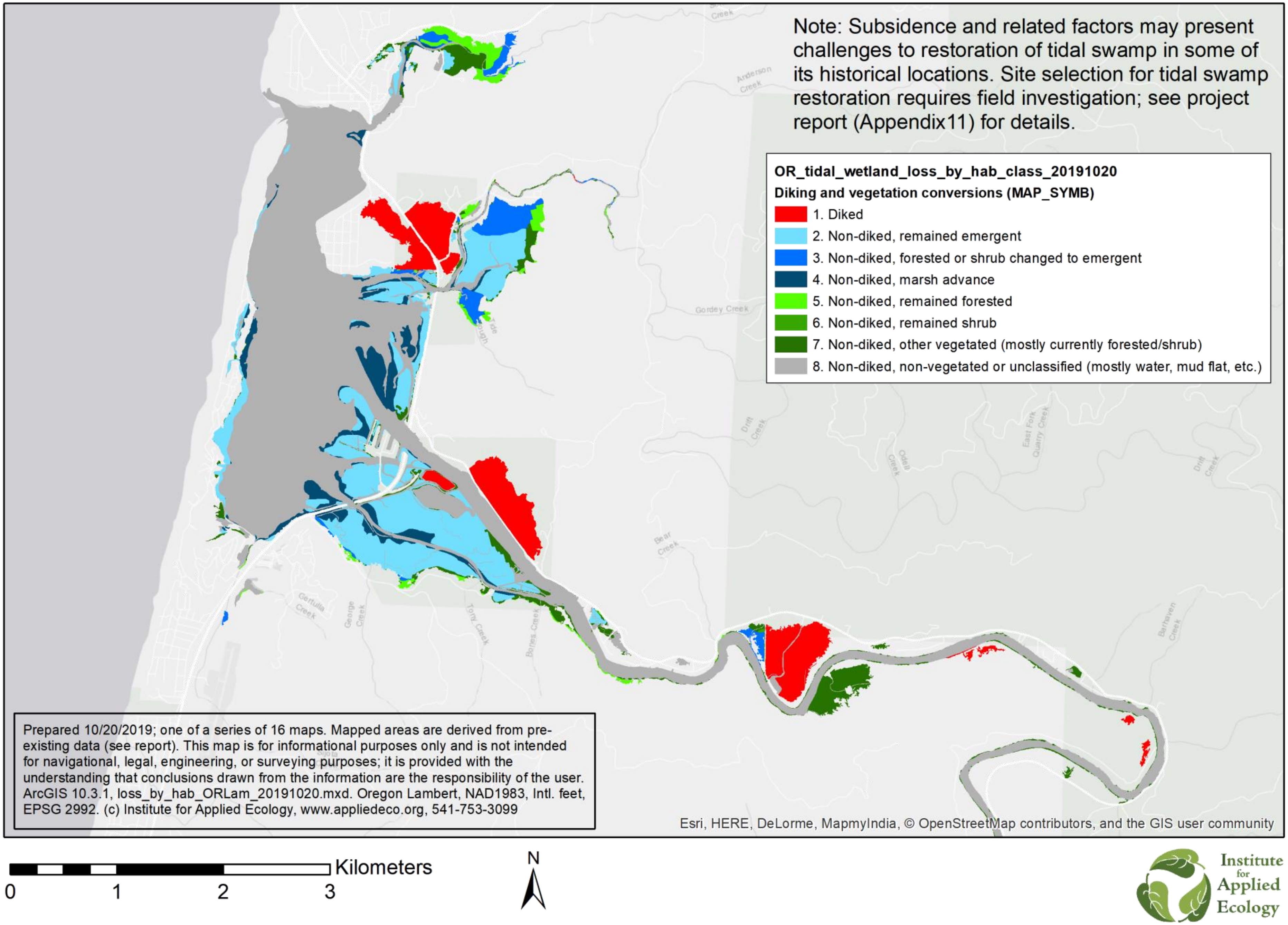
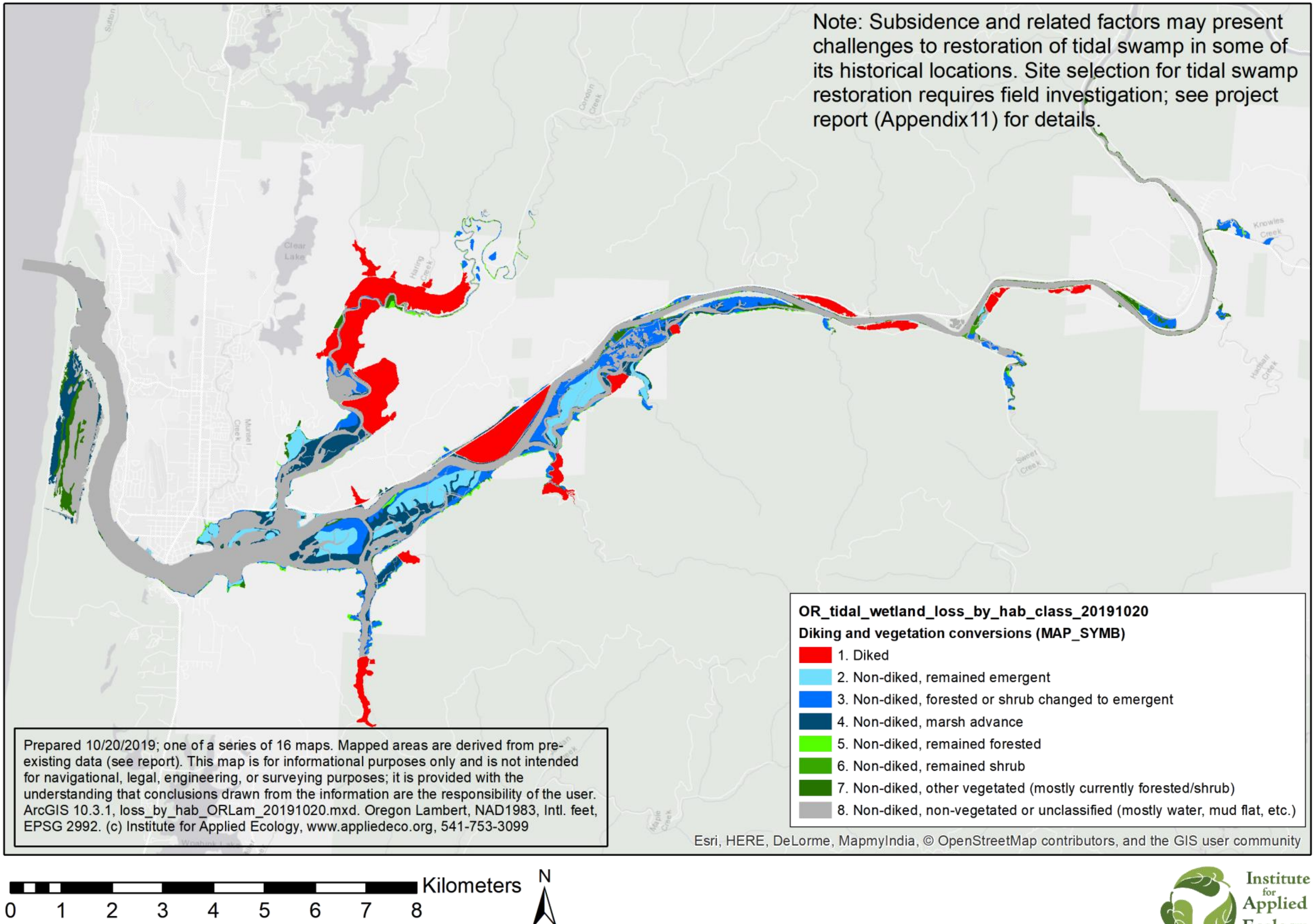
Siletz Bay estuary: Diking and vegetation conversions in tidal wetlands



Siuslaw River estuary: Diking and vegetation conversions in tidal wetlands



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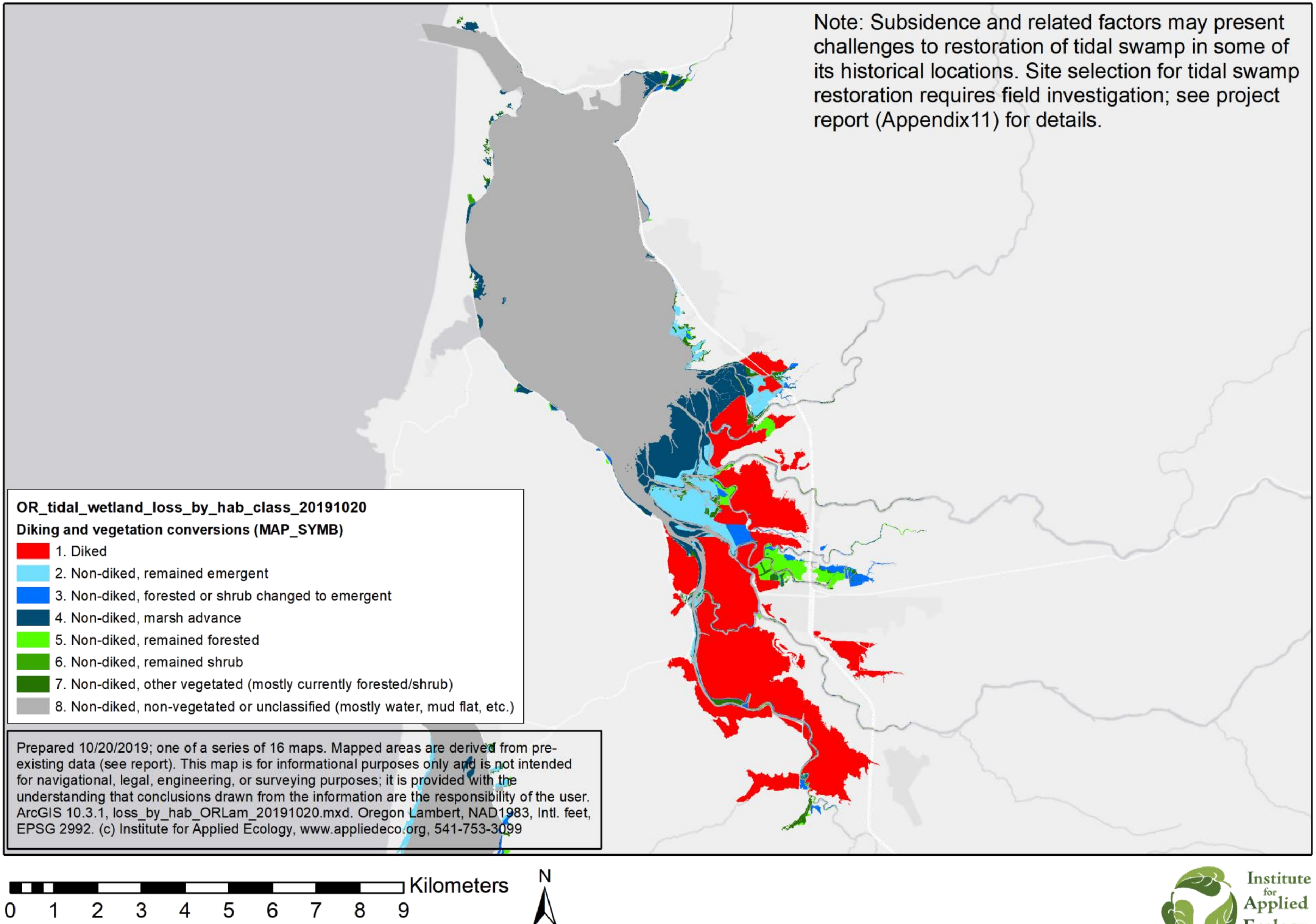
Tillamook Bay estuary: Diking and vegetation conversions in tidal wetlands



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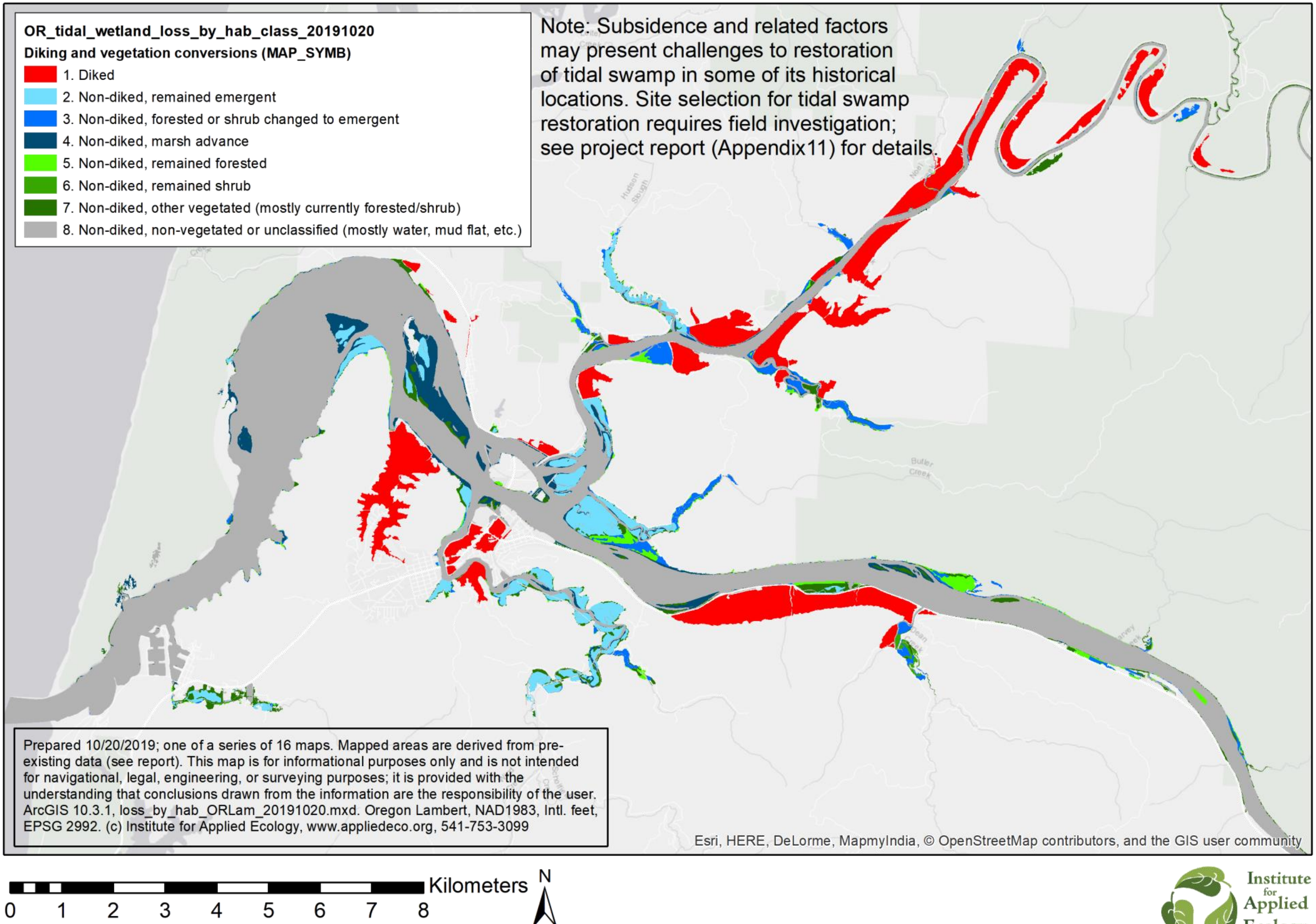
Umpqua River estuary: Diking and vegetation conversions in tidal wetlands



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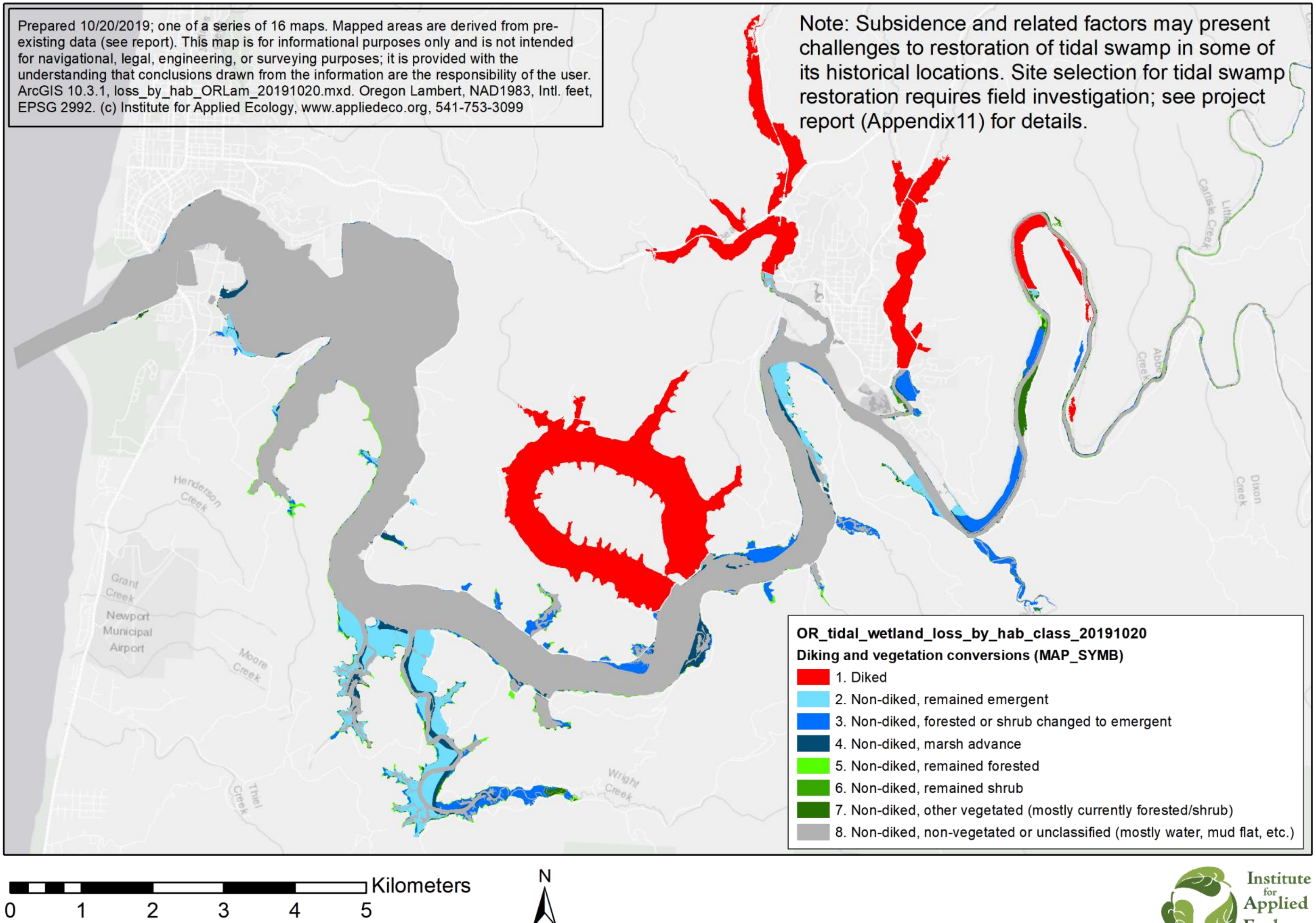
Yaquina Bay estuary: Diking and vegetation conversions in tidal wetlands



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Appendix 2. Maps of tidal swamp loss

Purpose: These maps are provided to better illustrate the historical prevalence of tidal swamps (forested and scrub-shrub tidal wetlands) in Oregon coast estuaries, and the high losses of these tidal swamps. Maps are presented for those estuaries that historically had a substantial area of tidal swamp (>300 ha): The Coos, Coquille, Nehalem, Nestucca, Siuslaw, Tillamook, Umpqua, and Yaquina.

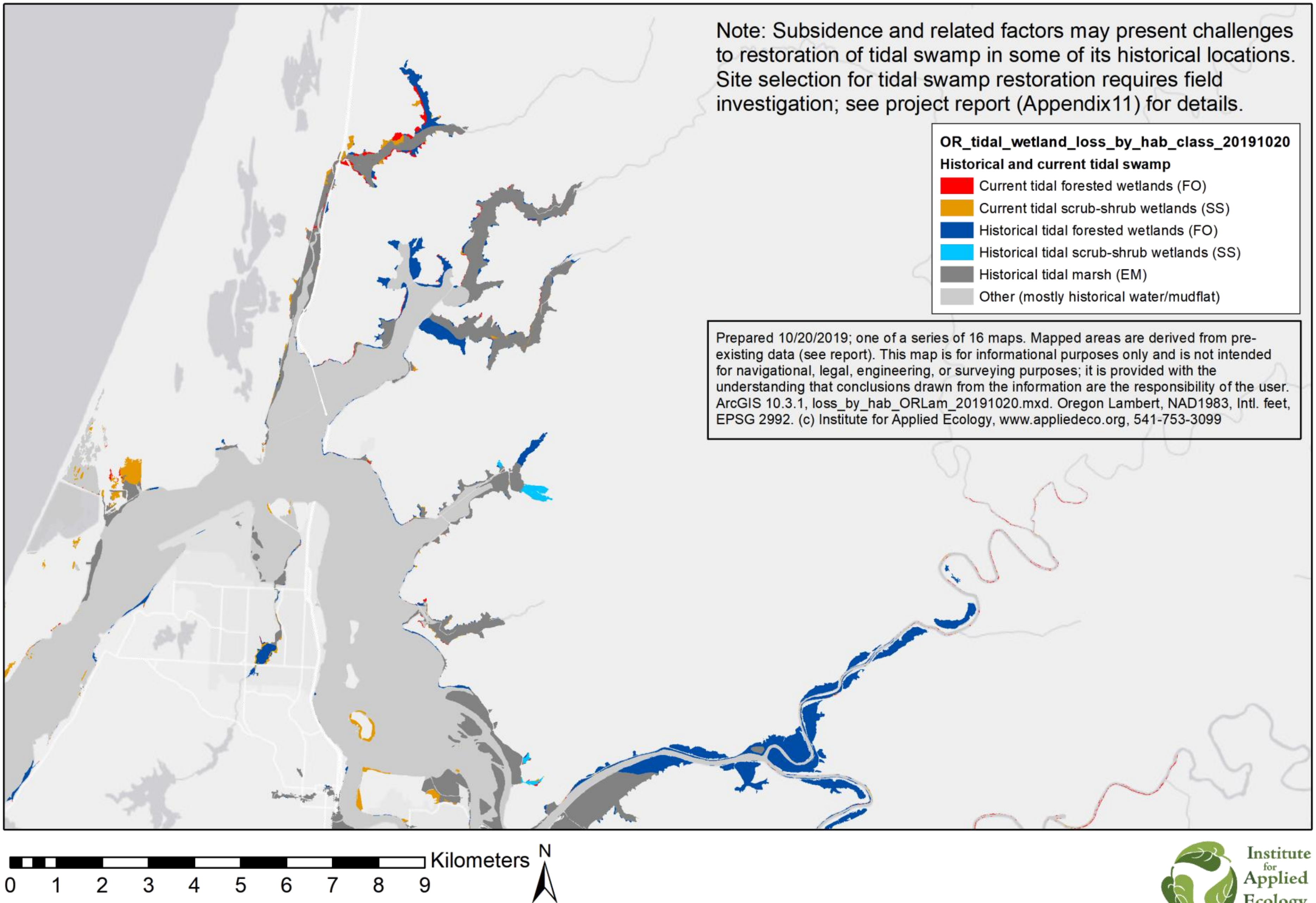
Color symbolization: The colors used in the Appendix 2 maps differ from those in Appendix 1: current tidal swamps are shown in red (to stand out), and lost historical tidal swamps are shown in blue.

The maps show that very little tidal swamp remains (red areas). Most former tidal swamps have been diked. Some former tidal swamps are non-diked but have been converted to other vegetation types (see Appendix 1 maps); of these, many have other alterations such as restrictive culverts, ditching, and grazing.

Mapping artifacts -- narrow fringing wetlands: In these maps, narrow strips of historical tidal swamp are often visible along rivers and bays (blue linear features). If current tidal swamps (red linear features) are lacking in such areas, this may not be due to tidal swamp loss, but rather to artifacts of the analysis, primarily differences in scale between source layers. Areas of tidal wetland loss due to diking are shown in the Appendix 1 maps. For further information on scale discrepancies, see "**Scale issues**" above.

Can tidal swamps be restored in their historical locations? As noted on each map, wetland subsidence and related factors may present challenges to restoration of tidal swamp in some of its historical locations. Selection of appropriate locations for tidal swamp restoration requires careful analysis of the landscape, as well as field investigation of physical conditions at the potential restoration site compared to least-disturbed tidal swamp reference sites. See Appendix 11 for further discussion of these issues and approaches to tidal swamp restoration.

Coos Bay estuary, north half: Historical vs. current tidal swamp (forested and scrub-shrub tidal wetlands)
Most of the historical tidal swamp (blue) is now diked; only the red/orange areas remain.



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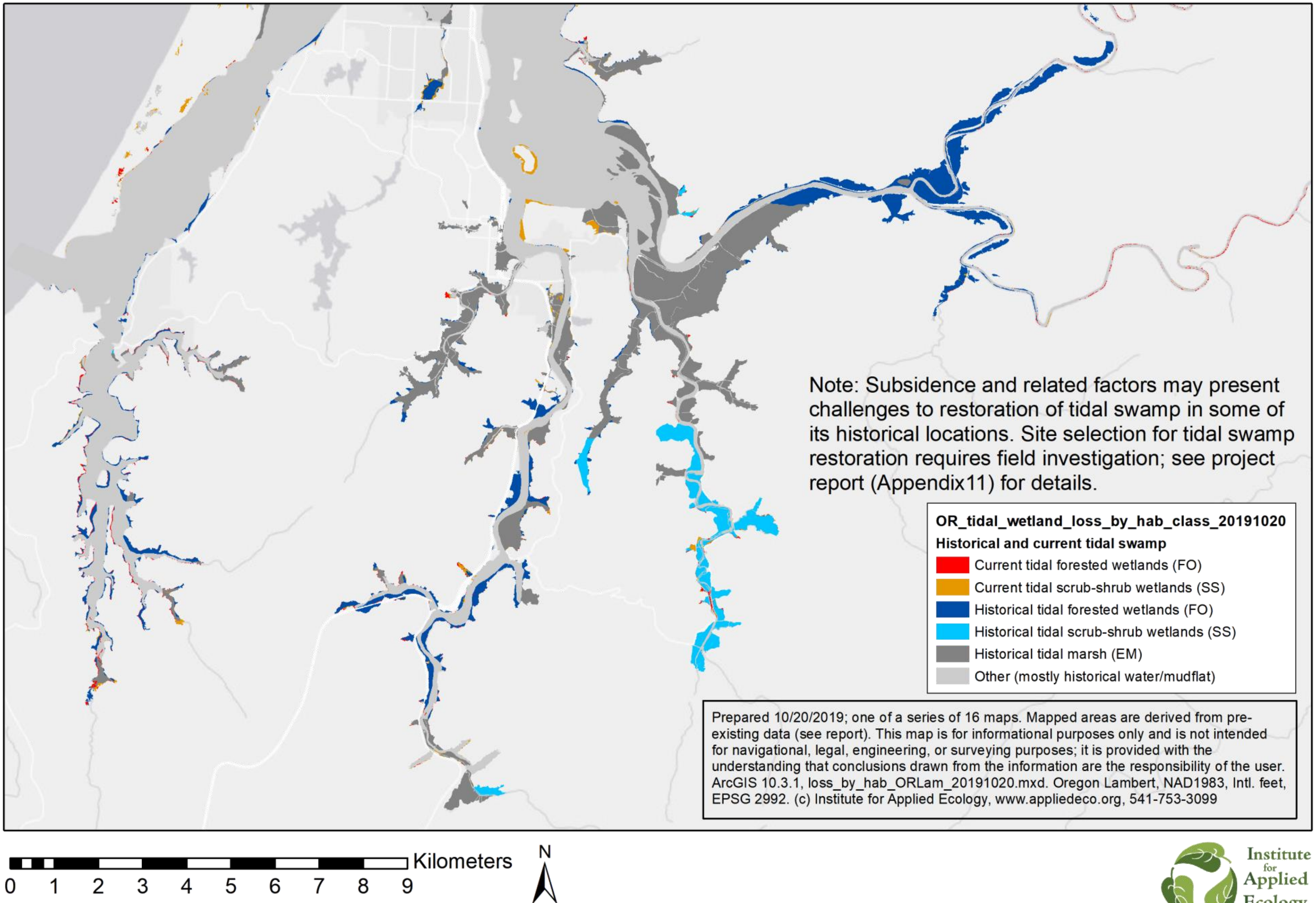
Coos Bay estuary, south half: Historical vs. current tidal swamp (forested and scrub-shrub tidal wetlands) Most of the historical tidal swamp (blue) is now diked; only the red/orange areas remain.



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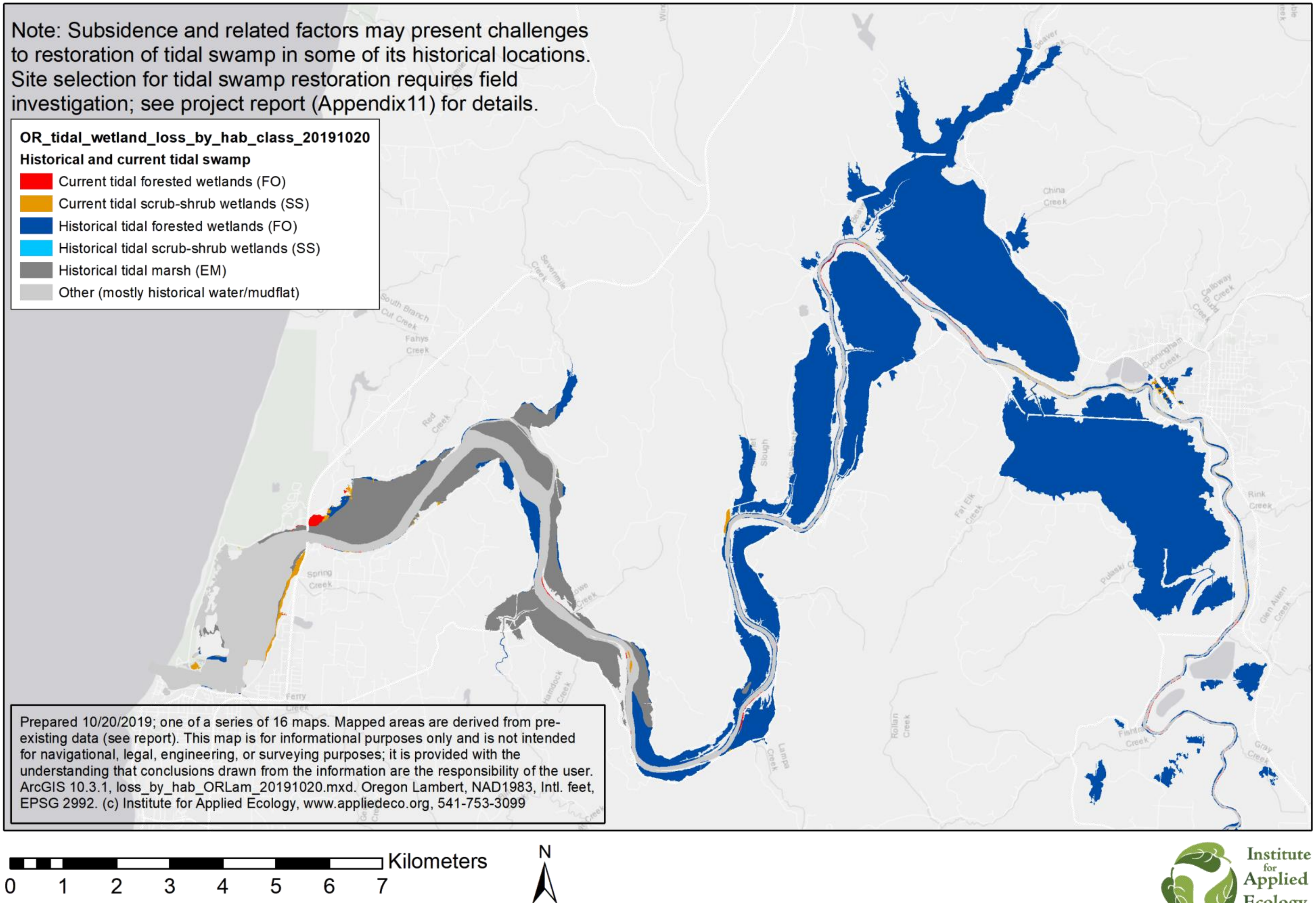
Coquille River estuary: Historical vs. current tidal swamp (forested and scrub-shrub tidal wetlands)
Most of the historical tidal swamp (blue) is now diked; only the red/orange areas remain.



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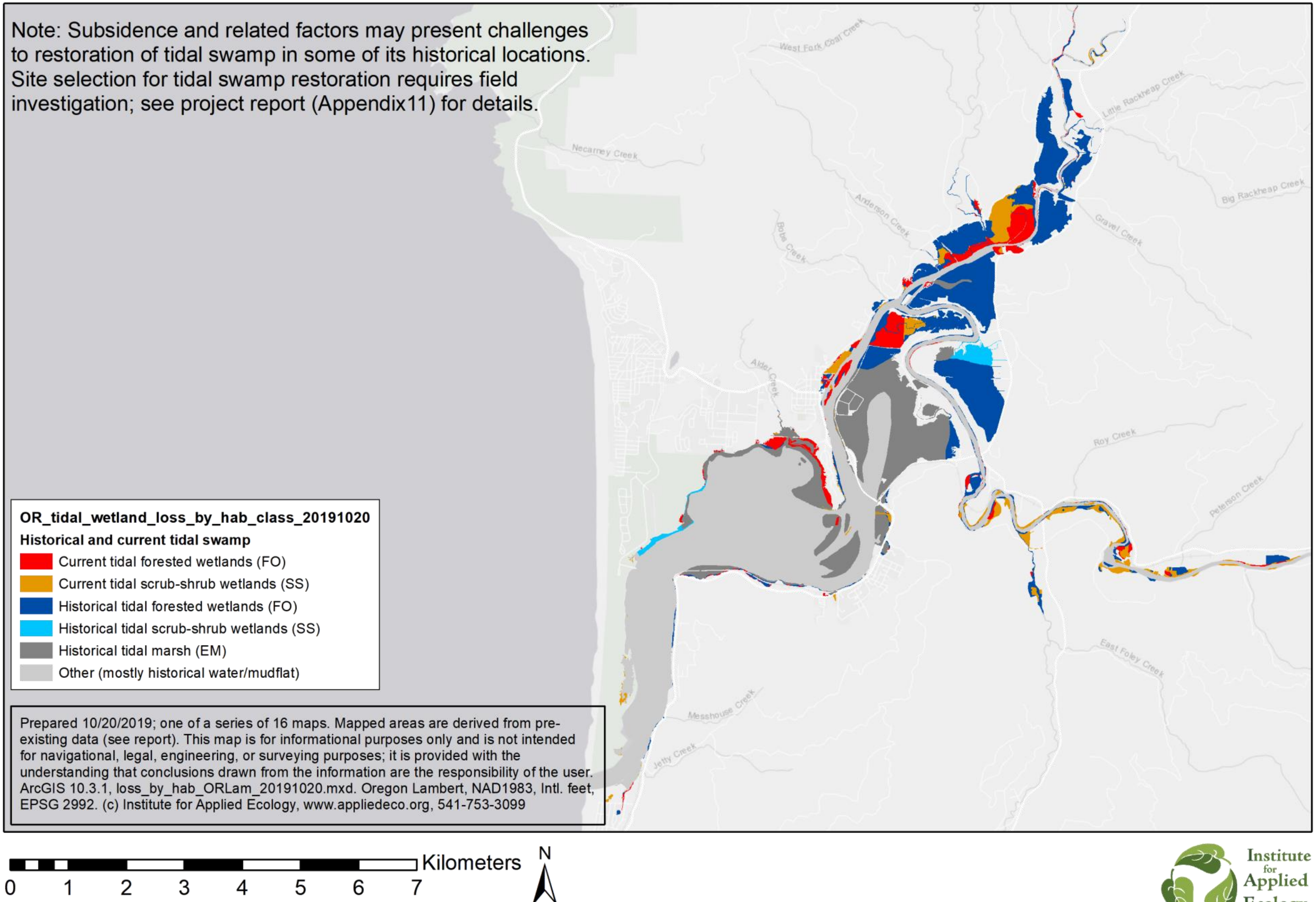
Nehalem Bay estuary: Historical vs. current tidal swamp (forested and scrub-shrub tidal wetlands)
Most of the historical tidal swamp (blue) is now diked; only the red/orange areas remain.



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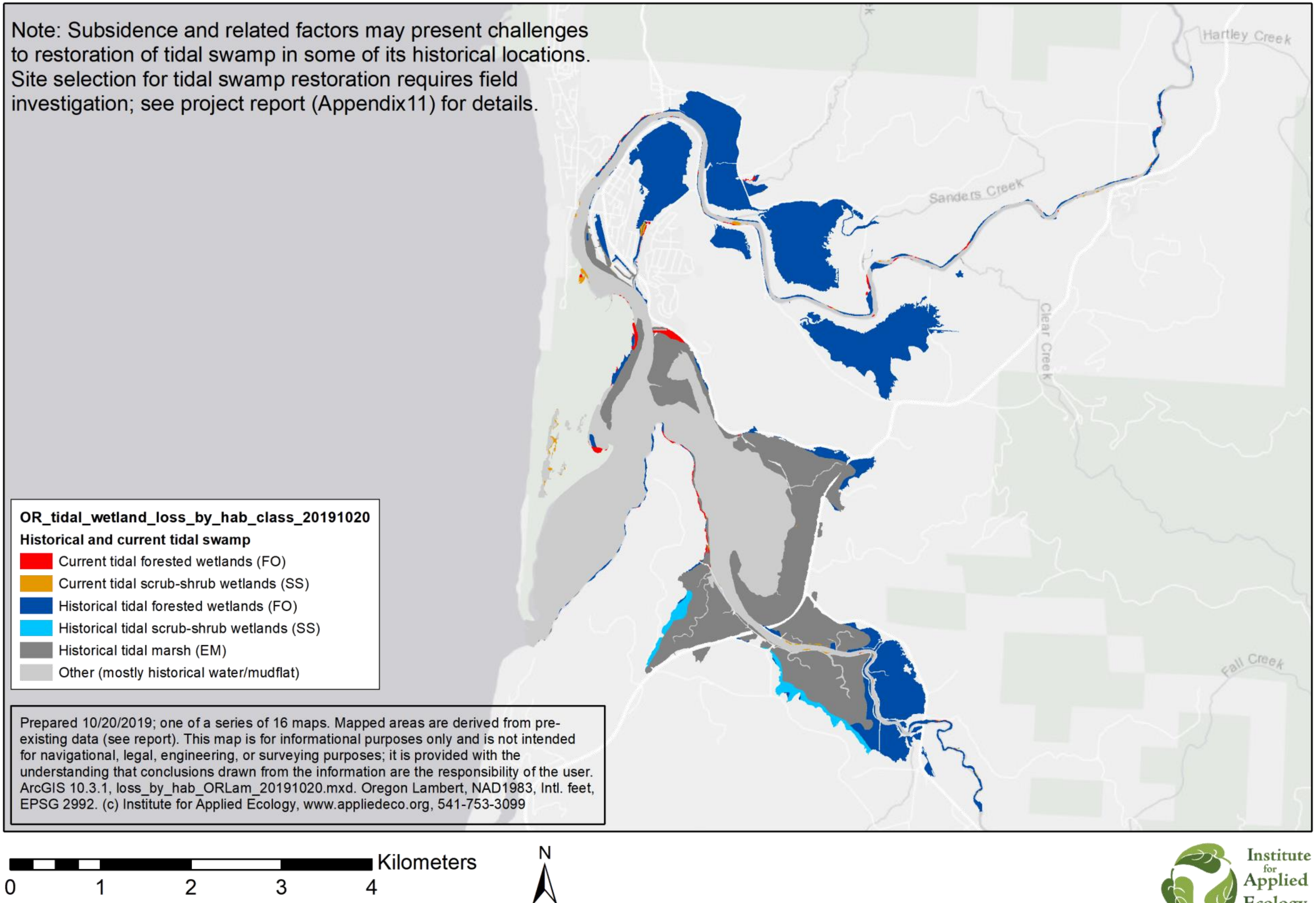
Nestucca Bay estuary: Historical vs. current tidal swamp (forested and scrub-shrub tidal wetlands)
Most of the historical tidal swamp (blue) is now diked; only the red/orange areas remain.



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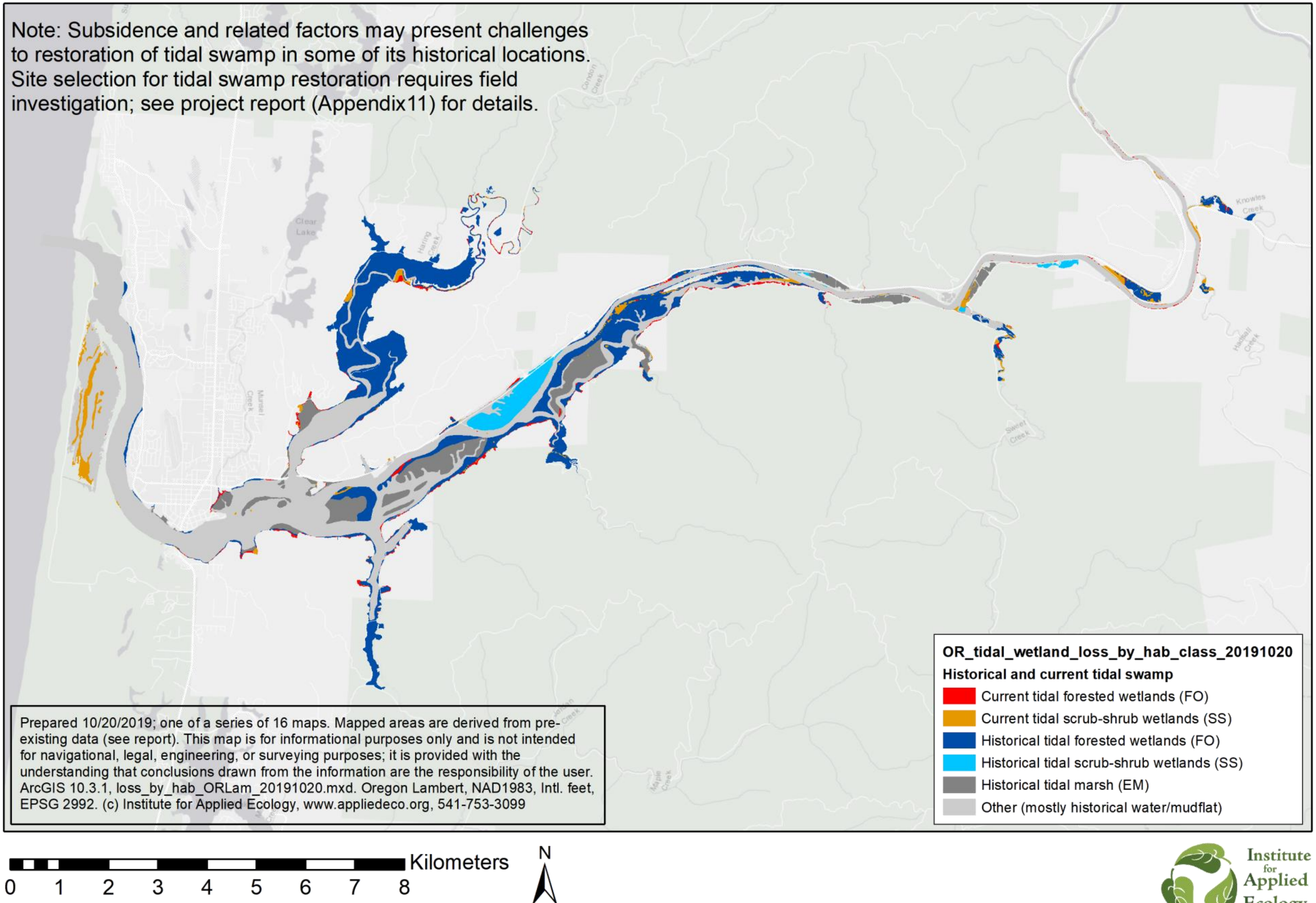
Siuslaw River estuary: Historical vs. current tidal swamp (forested and scrub-shrub tidal wetlands)
Most of the historical tidal swamp (blue) is now diked; only the red/orange areas remain.



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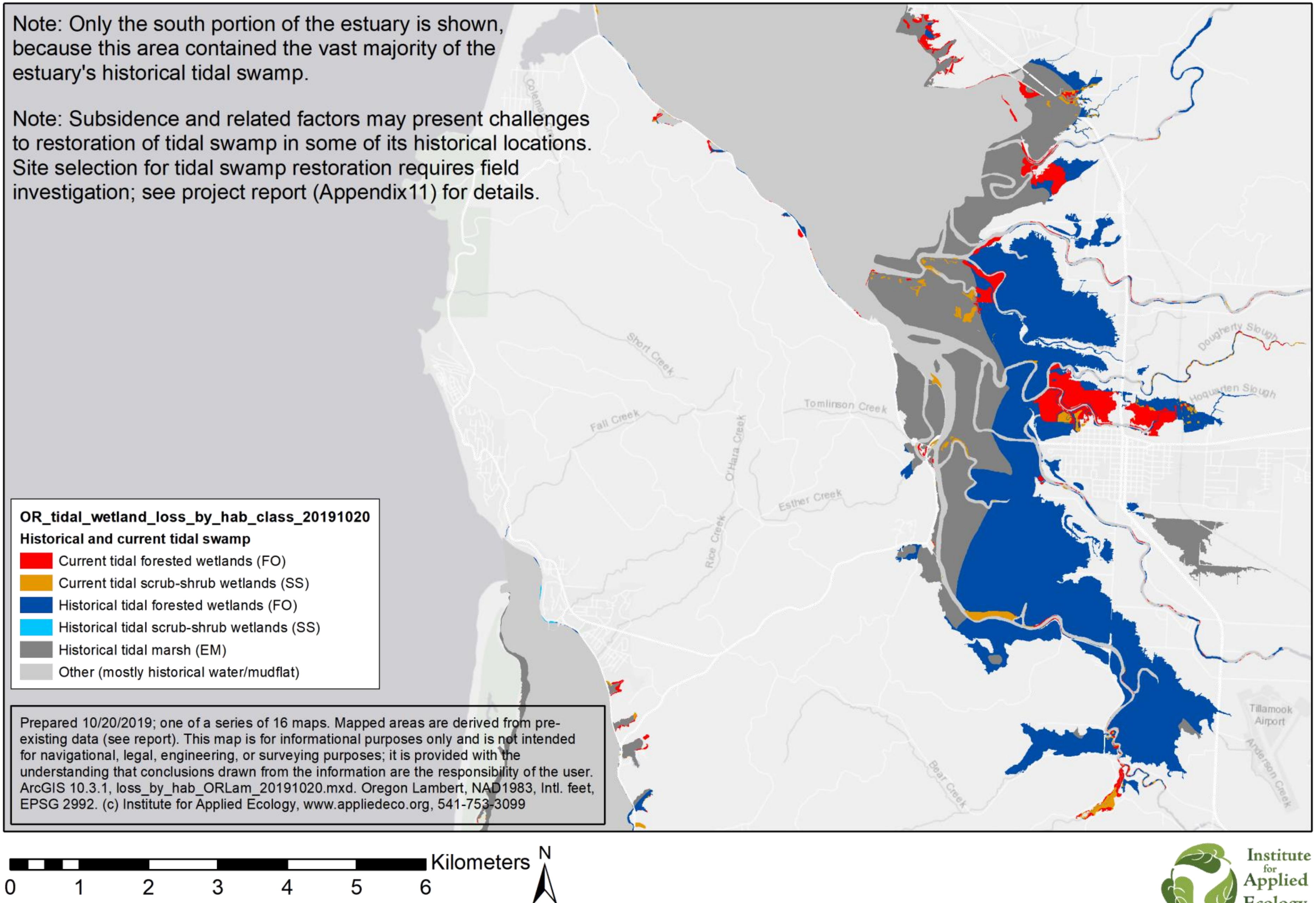
Tillamook Bay estuary: Historical vs. current tidal swamp (forested and scrub-shrub tidal wetlands)
Most of the historical tidal swamp (blue) is now diked; only the red/orange areas remain.



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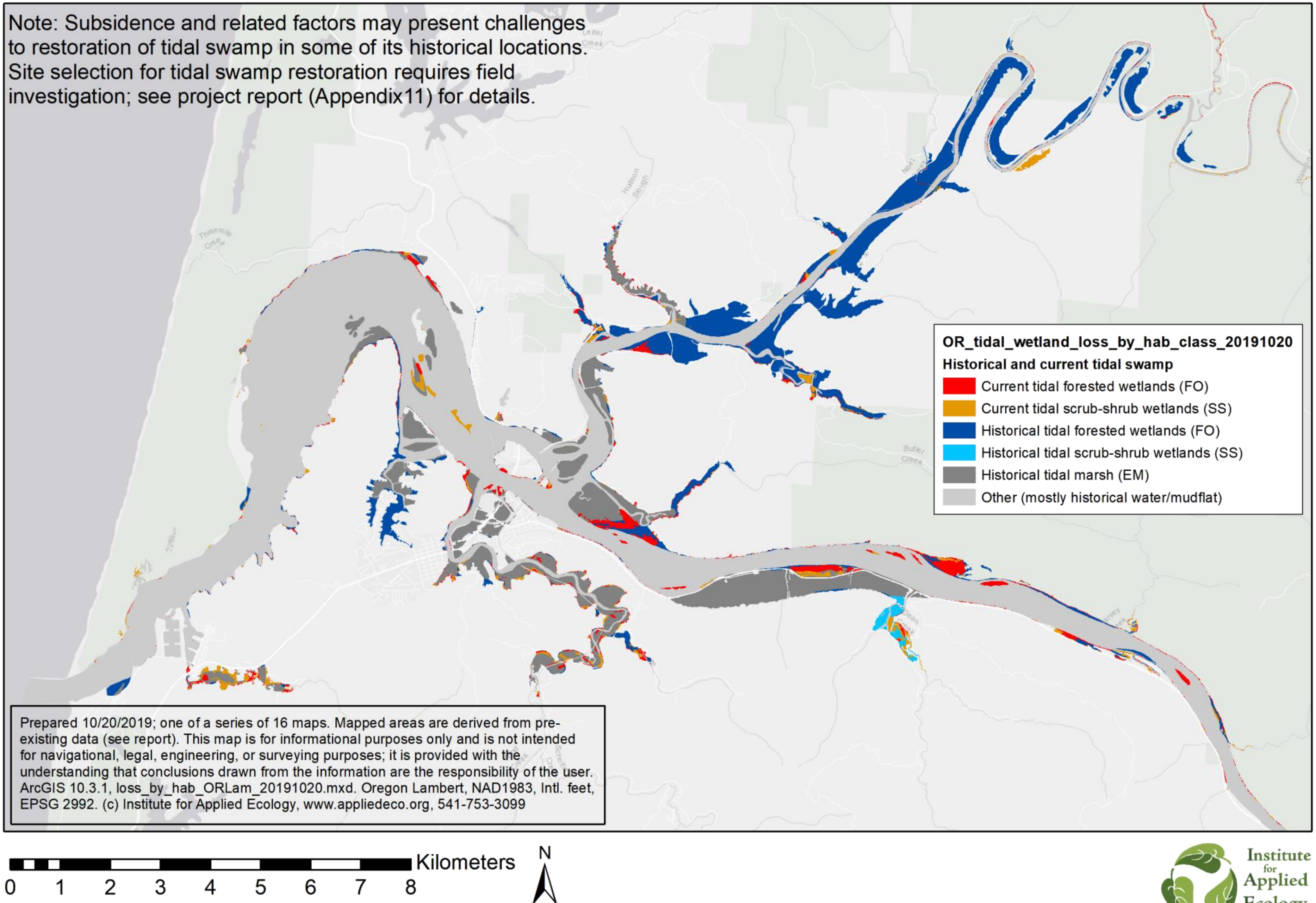
Umpqua River estuary: Historical vs. current tidal swamp (forested and scrub-shrub tidal wetlands)
Most of the historical tidal swamp (blue) is now diked; only the red/orange areas remain.



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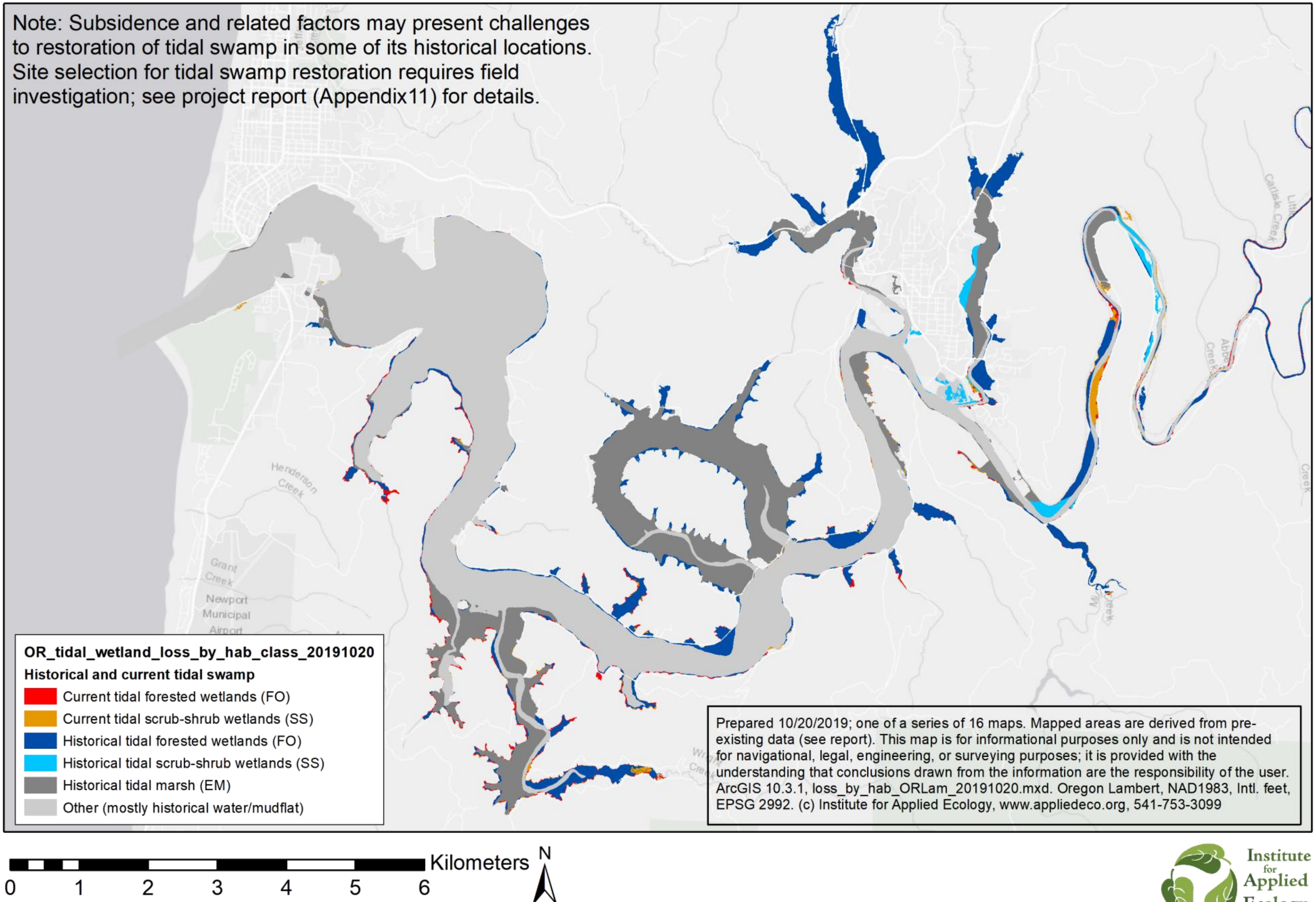
Yaquina Bay estuary: Historical vs. current tidal swamp (forested and scrub-shrub tidal wetlands) Most of the historical tidal swamp (blue) is now diked; only the red/orange areas remain.



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Appendix 3. Spatial reference system

Map products for this study use the spatial reference system described below.

NAD_1983_Oregon_Statewide_Lambert_Feet_Intl
WKID: 2992 Authority: EPSG

Projection: Lambert_Conformal_Conic
False_Easting: 1312335.958005249
False_Northing: 0.0
Central_Meridian: -120.5
Standard_Parallel_1: 43.0
Standard_Parallel_2: 45.5
Latitude_Of_Origin: 41.75
Linear Unit: Foot (0.3048)

Geographic Coordinate System: GCS_North_American_1983
Angular Unit: Degree (0.0174532925199433)
Prime Meridian: Greenwich (0.0)
Datum: D_North_American_1983
Spheroid: GRS_1980
Semimajor Axis: 6378137.0
Semiminor Axis: 6356752.314140356
Inverse Flattening: 298.257222101

Appendix 4. Area of diked former tidal wetlands ("Diked area") and current tidal wetlands ("Non-diked area") for each estuary, broken down by historical and current vegetation class

These tables are equivalent to Table 4 of the main report, but broken down by estuary. Blank cells indicate zero values. Where a historical vegetation class is missing for an estuary, that class was not mapped for that estuary in the historical vegetation data.

The example table below describes components of the table and shows the input data for the sums shown (circles).

Text in the column below shows the historical vegetation class ↓

The 6 columns below show the area of former (historical) tidal wetlands that are now ***diked***, broken down by current vegetation class (columns) and historical vegetation class (rows)

This column sums ***diked*** wetlands across all current vegetation classes, broken down by historical veg class

The 6 columns below show the area of current tidal wetlands (***non-diked***), broken down by current vegetation class (columns) and historical vegetation class (rows)

This column sums current, ***non-diked*** wetlands across all current vegetation classes, broken down by historical veg class

This column shows total area for each ***historical vegetation class*** (summed across all diking and current vegetation classes)

This row sums across historical veg classes →

These two rows sum across historical and current veg classes →

Estuary	Historical vegetation class ↓	Diked area (ha), by current vegetation class: Emer-gent (EM)	Scrub-shrub (SS)	Forest-ed (FO)	Aquatic bed (AB)	Un-classified (NA)	Not mapped (UNK)	Diked total	Non-diked area (ha), by current vegetation class: Emer-gent (EM)	Scrub-shrub (SS)	Forest-ed (FO)	Aquatic bed (AB)	Un-classified (NA)	Not mapped (UNK)	Non-diked total	Grand total area (ha)
Alsea Bay																
	Emergent (EM)	50	3	4		5	3	66	160	2	1		29	1	193	259
	Scrub-shrub (SS)	8	6	9		1		24	5	1	1				7	31
	Forested (FO)	7		1		3		12	65	7	14		55	1	143	156
	Non-vegetated (NONVEG)	3			2	16	1	21	48	2	2	125	694	3	874	895
	Not mapped (UNK)						1	1	5	2	4		84	4	98	99
		68	10	13	2	26	5	124	283	15	22	125	862	9	1316	1440
		Sum of historical EM, SS and FO that is now diked →						102	Sum of historical EM, SS and FO (diked & non-diked) →							445
									Sum of current EM, SS and FO →						320	

		Diked area (ha), by current vegetation class							Non-diked area (ha), by current vegetation class							
Estuary	Historical vegetation class ↓	Emer-gent (EM)	Scrub-shrub (SS)	Forest-ed (FO)	Aquatic bed (AB)	Un-classified (NA)	Not mapped (UNK)	Diked total	Emer-gent (EM)	Scrub-shrub (SS)	Forest-ed (FO)	Aquatic bed (AB)	Un-classified (NA)	Not mapped (UNK)	Non-diked total	Grand total area (ha)
Alsea Bay																
	Emergent (EM)	50	3	4		5	3	66	160	2	1		29	1	193	259
	Scrub-shrub (SS)	8	6	9		1		24	5	1	1				7	31
	Forested (FO)	7		1		3		12	65	7	14		55	1	143	156
	Non-vegetated (NONVEG)	3			2	16	1	21	48	2	2	125	694	3	874	895
	Not mapped (UNK)						1	1	5	2	4		84	4	98	99
	Total	68	10	13	2	26	5	124	283	15	22	125	862	9	1316	1440
		Sum of historical EM, SS and FO that is now diked →						102	Sum of historical EM, SS and FO (diked & non-diked) →							445
									Sum of current EM, SS and FO →						320	
Beaver Creek																
	Emergent (EM)								21				4		26	26
	Forested (FO)								54	3		1	6		64	64
	Non-vegetated (NONVEG)								4				3		8	8
	Total								79	3		1	14		97	97
		Sum of historical EM, SS and FO that is now diked →						0	Sum of historical EM, SS and FO (diked & non-diked) →							90
									Sum of current EM, SS and FO →						82	

Estuary	Historical vegetation class ↓	Diked area (ha), by current vegetation class: Emergent (EM)	Scrub-shrub (SS)	Forested (FO)	Aquatic bed (AB)	Un-classified (NA)	Not mapped (UNK)	Diked total	Non-diked area (ha), by current vegetation class: Emergent (EM)	Scrub-shrub (SS)	Forested (FO)	Aquatic bed (AB)	Un-classified (NA)	Not mapped (UNK)	Non-diked total	Grand total area (ha)
Coos Bay																
	Emergent (EM)	743	26	9		29	84	891	606	56	19	1	164	52	899	1790
	Scrub-shrub (SS)	121	3	3		2	1	129	103	4	4		4	1	116	245
	Forested (FO)	366	9	9		7	16	406	183	19	29	4	123	15	373	779
	Non-vegetated (NONVEG)	89	1	1		9	12	112	375	33	8	420	4286	61	5184	5296
	Not mapped (UNK)	8	5	1			19	33	23	3	10		111	20	168	201
	Total	1328	44	21		47	132	1572	1289	116	70	426	4688	149	6740	8312
		Sum of historical EM, SS and FO that is now diked →						1426	Sum of historical EM, SS and FO (diked & non-diked) →							2815
									Sum of current EM, SS and FO →						1475	
Coquille River																
	Emergent (EM)	240	2			6	5	254	253	9	4		40	6	311	565
	Forested (FO)	2581	82	10	1	71	57	2802	44	11	5	2	114	11	187	2989
	Non-vegetated (NONVEG)	22				1	3	26	120	6	3	13	629	14	784	810
	Not mapped (UNK)												9		9	9
	Total	2843	84	11	1	78	65	3082	417	25	12	16	791	30	1291	4373
		Sum of historical EM, SS and FO that is now diked →						3056	Sum of historical EM, SS and FO (diked & non-diked) →							3554
									Sum of current EM, SS and FO →						454	
Necanicum River																
	Emergent (EM)								3	1	1	4	10		19	20
	Forested (FO)							1	45	12	17	4	28	1	107	108
	Non-vegetated (NONVEG)								21	5	2		111	6	146	146
	Total					1		1	69	19	20	8	149	7	272	273
		Sum of historical EM, SS and FO that is now diked →						1	Sum of historical EM, SS and FO (diked & non-diked) →							127
									Sum of current EM, SS and FO →						108	

Estuary	Historical vegetation class ↓	Diked area (ha), by current vegetation class: Emergent (EM)	Scrub-shrub (SS)	Forested (FO)	Aquatic bed (AB)	Unclassified (NA)	Not mapped (UNK)	Diked total	Non-diked area (ha), by current vegetation class: Emergent (EM)	Scrub-shrub (SS)	Forested (FO)	Aquatic bed (AB)	Unclassified (NA)	Not mapped (UNK)	Non-diked total	Grand total area (ha)
Nehalem River																
	Emergent (EM)	190	2	3		5	19	218	112	1	12		21	3	149	367
	Scrub-shrub (SS)	16				1		17	2		1		8		10	28
	Forested (FO)	214	43	43		9	6	316	103	76	79		31	4	293	609
	Non-vegetated (NONVEG)	61	3	1		1	2	68	156	10	11	14	826	5	1022	1090
	Not mapped (UNK)									3	1		27		31	31
	Total	481	48	47		16	27	619	373	90	104	14	913	11	1506	2125
		Sum of historical EM, SS and FO that is now diked →						551	Sum of historical EM, SS and FO (diked & non-diked) →							1004
									Sum of current EM, SS and FO →						568	
Nestucca Bay																
	Emergent (EM)	183	1	1		3	6	194	78		3	2	13	4	100	293
	Scrub-shrub (SS)	15	1					16								16
	Forested (FO)	278	1	14		2	9	305	17	1	3		19	3	43	347
	Non-vegetated (NONVEG)	9				1	1	11	46	3	1	31	369	1	451	462
	Total	485	3	16		6	15	525	141	4	7	32	400	8	593	1118
		Sum of historical EM, SS and FO that is now diked →						514	Sum of historical EM, SS and FO (diked & non-diked) →							656
									Sum of current EM, SS and FO →						152	
Netarts Bay																
	Emergent (EM)								52	1	3	2	10		68	68
	Forested (FO)								38	1	6		8		54	54
	Non-vegetated (NONVEG)								11			277	654	1	943	943
	Total								101	2	9	279	673	1	1065	1065
		Sum of historical EM, SS and FO that is now diked →						0	Sum of historical EM, SS and FO (diked & non-diked) →							122
									Sum of current EM, SS and FO →						111	

Estuary	Historical vegetation class ↓	Diked area (ha), by current vegetation class: Emergent (EM)	Scrub-shrub (SS)	Forested (FO)	Aquatic bed (AB)	Unclassified (NA)	Not mapped (UNK)	Diked total	Non-diked area (ha), by current vegetation class: Emergent (EM)	Scrub-shrub (SS)	Forested (FO)	Aquatic bed (AB)	Unclassified (NA)	Not mapped (UNK)	Non-diked total	Grand total area (ha)
Salmon River																
	Emergent (EM)	3						3	202	1	3		16	2	225	228
	Scrub-shrub (SS)								1				1		3	3
	Forested (FO)								24		7		4		36	36
	Non-vegetated (NONVEG)								10			4	76		90	90
	Total	3						3	238	2	11	4	97	2	353	356
		Sum of historical EM, SS and FO that is now diked →						3	Sum of historical EM, SS and FO (diked & non-diked) →							266
									Sum of current EM, SS and FO →						250	
Sand Lake																
	Emergent (EM)	21		1				22	166	6	6	1	11	1	190	212
	Forested (FO)	4		1		1		5	5	6	2				13	18
	Non-vegetated (NONVEG)	6		1				7	58		1	6	174		239	246
	Total	30		3		1		34	229	13	8	7	185	1	442	476
		Sum of historical EM, SS and FO that is now diked →						27	Sum of historical EM, SS and FO (diked & non-diked) →							230
									Sum of current EM, SS and FO →						249	
Siletz Bay																
	Emergent (EM)	32	4	1		1	2	40	170	8	16	1	47	19	260	300
	Scrub-shrub (SS)	22		5		1		29	3		1				4	33
	Forested (FO)	15	1	1		2	2	21	28	4	22		24	2	80	101
	Non-vegetated (NONVEG)								50	4	4	41	437	4	539	539
	Not mapped (UNK)		1	1				3	12	8	6		91	3	120	123
	Total	69	6	9		5	4	94	262	24	49	42	599	27	1002	1096
		Sum of historical EM, SS and FO that is now diked →						90	Sum of historical EM, SS and FO (diked & non-diked) →							434
									Sum of current EM, SS and FO →						334	

Estuary	Historical vegetation class ↓	Diked area (ha), by current vegetation class: Emergent (EM)	Scrub-shrub (SS)	Forested (FO)	Aquatic bed (AB)	Un-classified (NA)	Not mapped (UNK)	Diked total	Non-diked area (ha), by current vegetation class: Emergent (EM)	Scrub-shrub (SS)	Forested (FO)	Aquatic bed (AB)	Un-classified (NA)	Not mapped (UNK)	Non-diked total	Grand total area (ha)
Siuslaw River																
	Emergent (EM)	25	5	1		1		32	187	4	3		30	6	230	262
	Scrub-shrub (SS)	72	3			1	2	79	5	3	1		1	1	10	89
	Forested (FO)	244	22	14	2	5	8	295	238	37	30	2	120	19	445	740
	Non-vegetated (NONVEG)	24	1	1	2	4	6	37	227	43	5	15	958	16	1263	1300
	Not mapped (UNK)						1	1	7	4	3		136	11	163	164
	Total	365	31	15	4	12	17	444	663	90	42	17	1245	53	2110	2554
		Sum of historical EM, SS and FO that is now diked →						406	Sum of historical EM, SS and FO (diked & non-diked) →							1090
									Sum of current EM, SS and FO →						796	
Tillamook Bay																
	Emergent (EM)	369	3	4		6	23	404	209	16	20	1	22	23	290	694
	Scrub-shrub (SS)									2			1		4	4
	Forested (FO)	819	25	46		9	39	938	77	18	90		37	17	240	1178
	Non-vegetated (NONVEG)	28	1	2	3	5	6	45	380	10	23	35	3280	22	3751	3796
	Total	1216	29	51	4	20	68	1388	666	46	134	36	3340	63	4285	5673
		Sum of historical EM, SS and FO that is now diked →						1343	Sum of historical EM, SS and FO (diked & non-diked) →							1876
									Sum of current EM, SS and FO →						846	
Umpqua River																
	Emergent (EM)	236	11	19	5	12	47	331	317	37	39	4	40	19	456	787
	Scrub-shrub (SS)	9						11	11	8	2		1		22	32
	Forested (FO)	371	41	35	6	11	24	488	146	36	82	4	55	17	340	828
	Non-vegetated (NONVEG)	19	2	1	8	7	8	45	216	18	25	99	2538	29	2925	2969
	Not mapped (UNK)						2	2	16	8	16	2	352	6	400	402
	Total	636	54	56	19	31	81	876	706	107	164	108	2985	72	4143	5019
		Sum of historical EM, SS and FO that is now diked →						829	Sum of historical EM, SS and FO (diked & non-diked) →							1647
									Sum of current EM, SS and FO →						977	

Estuary	Historical vegetation class ↓	Diked area (ha), by current vegetation class: Emergent (EM)	Scrub-shrub (SS)	Forested (FO)	Aquatic bed (AB)	Unclassified (NA)	Not mapped (UNK)	Diked total	Non-diked area (ha), by current vegetation class: Emergent (EM)	Scrub-shrub (SS)	Forested (FO)	Aquatic bed (AB)	Unclassified (NA)	Not mapped (UNK)	Non-diked total	Grand total area (ha)
Yaquina Bay																
	Emergent (EM)	344	25	22		22	11	425	139	7	5		47	8	206	631
	Scrub-shrub (SS)	9	1			2		13	9	2	1		7	6	24	37
	Forested (FO)	82	15	22		8	4	130	108	12	29	3	87	6	244	374
	Non-vegetated (NONVEG)	9	1			18	1	29	48	5	3	65	1477	18	1616	1645
	Total	444	42	44		51	16	597	304	27	37	67	1617	38	2090	2687
		Sum of historical EM, SS and FO that is now diked →						568	Sum of historical EM, SS and FO (diked & non-diked) →							1042
									Sum of current EM, SS and FO →						368	

Appendix 5. Tables of historical vs. current tidal wetland area and wetland loss, by vegetation class, for each estuary

Tables are equivalent to Tables 2 and 3 of the main report, but broken out by estuary.

Alsea Bay

Vegetation class	% of tidal wetland area (historical)	% of tidal wetland area (current)
Emergent ("tidal marsh", EM)	58.1%	88.5%
Scrub-shrub (SS)	7.0%	4.5%
Forested (FO)	35.0%	6.9%
All three classes (EM, SS, FO)	100.0%	100.0%

Historical vegetation class	% loss from diking	% loss from conversion to another vegetation class	Total % loss
Emergent ("tidal marsh", EM)	25.3%	12.8%	38.1%
Scrub-shrub (SS)	77.5%	18.8%	96.3%
Forested (FO)	8.0%	82.8%	90.8%
All three classes (EM, SS, FO)	22.9%		

Beaver Creek

Vegetation class	% of tidal wetland area (historical)	% of tidal wetland area (current)
Emergent ("tidal marsh", EM)	28.9%	95.8%
Scrub-shrub (SS)	0.0%	3.7%
Forested (FO)	71.1%	0.6%
All three classes (EM, SS, FO)	100.0%	100.0%

Historical vegetation class	% loss from diking	% loss from conversion to another vegetation class	Total % loss
Emergent ("tidal marsh", EM)	0.0%	17.4%	17.4%
Scrub-shrub (SS)			
Forested (FO)	0.0%	99.6%	99.6%
All three classes (EM, SS, FO)	0.0%		

Coos Bay

Vegetation class	% of tidal wetland area (historical)	% of tidal wetland area (current)
Emergent ("tidal marsh", EM)	63.6%	87.4%
Scrub-shrub (SS)	8.7%	7.9%
Forested (FO)	27.7%	4.8%
All three classes (EM, SS, FO)	100.0%	100.0%

Historical vegetation class	% loss from diking	% loss from conversion to another vegetation class	Total % loss
Emergent ("tidal marsh", EM)	49.8%	16.4%	66.1%
Scrub-shrub (SS)	52.6%	45.6%	98.2%
Forested (FO)	52.2%	44.2%	96.3%
All three classes (EM, SS, FO)	50.7%		

Coquille River

Vegetation class	% of tidal wetland area (historical)	% of tidal wetland area (current)
Emergent ("tidal marsh", EM)	15.9%	91.8%
Scrub-shrub (SS)	0.0%	5.6%
Forested (FO)	84.1%	2.6%
All three classes (EM, SS, FO)	100.0%	100.0%

Historical vegetation class	% loss from diking	% loss from conversion to another vegetation class	Total % loss
Emergent ("tidal marsh", EM)	44.9%	10.3%	55.3%
Scrub-shrub (SS)			
Forested (FO)	93.7%	6.1%	99.8%
All three classes (EM, SS, FO)	86.0%		

Necanicum River

Vegetation class	% of tidal wetland area (historical)	% of tidal wetland area (current)
Emergent ("tidal marsh", EM)	15.4%	64.1%
Scrub-shrub (SS)	0.0%	17.1%
Forested (FO)	84.6%	18.8%
All three classes (EM, SS, FO)	100.0%	100.0%

Historical vegetation class	% loss from diking	% loss from conversion to another vegetation class	Total % loss
Emergent ("tidal marsh", EM)	1.6%	83.6%	85.1%
Scrub-shrub (SS)			
Forested (FO)	0.9%	83.2%	84.1%
All three classes (EM, SS, FO)	1.0%		

Nehalem River

Vegetation class	% of tidal wetland area (historical)	% of tidal wetland area (current)
Emergent ("tidal marsh", EM)	36.6%	65.7%
Scrub-shrub (SS)	2.8%	15.9%
Forested (FO)	60.6%	18.4%
All three classes (EM, SS, FO)	100.0%	100.0%

Historical vegetation class	% loss from diking	% loss from conversion to another vegetation class	Total % loss
Emergent ("tidal marsh", EM)	59.3%	10.3%	69.6%
Scrub-shrub (SS)	62.6%	37.3%	99.9%
Forested (FO)	51.8%	35.2%	87.1%
All three classes (EM, SS, FO)	54.9%		

Nestucca Bay

Vegetation class	% of tidal wetland area (historical)	% of tidal wetland area (current)
Emergent ("tidal marsh", EM)	44.7%	92.8%
Scrub-shrub (SS)	2.4%	2.6%
Forested (FO)	52.9%	4.6%
All three classes (EM, SS, FO)	100.0%	100.0%

Historical vegetation class	% loss from diking	% loss from conversion to another vegetation class	Total % loss
Emergent ("tidal marsh", EM)	66.0%	7.3%	73.3%
Scrub-shrub (SS)	100.0%	0.0%	100.0%
Forested (FO)	87.7%	11.6%	99.3%
All three classes (EM, SS, FO)	78.3%		

Netarts Bay

Vegetation class	% of tidal wetland area (historical)	% of tidal wetland area (current)
Emergent ("tidal marsh", EM)	55.7%	90.3%
Scrub-shrub (SS)	0.4%	1.5%
Forested (FO)	43.9%	8.2%
All three classes (EM, SS, FO)	100.0%	100.0%

Historical vegetation class	% loss from diking	% loss from conversion to another vegetation class	Total % loss
Emergent ("tidal marsh", EM)	0.0%	24.2%	24.2%
Scrub-shrub (SS)			
Forested (FO)	0.0%	88.0%	88.0%
All three classes (EM, SS, FO)	0.0%		

Salmon River

Vegetation class	% of tidal wetland area (historical)	% of tidal wetland area (current)
Emergent ("tidal marsh", EM)	85.5%	95.1%
Scrub-shrub (SS)	1.0%	0.6%
Forested (FO)	13.5%	4.3%
All three classes (EM, SS, FO)	100.0%	100.0%

Historical vegetation class	% loss from diking	% loss from conversion to another vegetation class	Total % loss
Emergent ("tidal marsh", EM)	1.4%	9.7%	11.1%
Scrub-shrub (SS)			
Forested (FO)	0.0%	80.4%	80.4%
All three classes (EM, SS, FO)	1.2%		

Sand Lake

Vegetation class	% of tidal wetland area (historical)	% of tidal wetland area (current)
Emergent ("tidal marsh", EM)	92.3%	91.7%
Scrub-shrub (SS)	0.0%	5.1%
Forested (FO)	7.7%	3.2%
All three classes (EM, SS, FO)	100.0%	100.0%

Historical vegetation class	% loss from diking	% loss from conversion to another vegetation class	Total % loss
Emergent ("tidal marsh", EM)	10.4%	11.5%	21.9%
Scrub-shrub (SS)			
Forested (FO)	27.2%	63.4%	90.5%
All three classes (EM, SS, FO)	11.7%		

Siletz Bay

Vegetation class	% of tidal wetland area (historical)	% of tidal wetland area (current)
Emergent ("tidal marsh", EM)	69.2%	78.3%
Scrub-shrub (SS)	7.5%	7.1%
Forested (FO)	23.3%	14.6%
All three classes (EM, SS, FO)	100.0%	100.0%

Historical vegetation class	% loss from diking	% loss from conversion to another vegetation class	Total % loss
Emergent ("tidal marsh", EM)	13.5%	30.1%	43.5%
Scrub-shrub (SS)	89.0%	10.2%	99.2%
Forested (FO)	20.9%	57.2%	78.1%
All three classes (EM, SS, FO)	20.9%		

Siuslaw River

Vegetation class	% of tidal wetland area (historical)	% of tidal wetland area (current)
Emergent ("tidal marsh", EM)	24.0%	83.4%
Scrub-shrub (SS)	8.1%	11.4%
Forested (FO)	67.9%	5.3%
All three classes (EM, SS, FO)	100.0%	100.0%

Historical vegetation class	% loss from diking	% loss from conversion to another vegetation class	Total % loss
Emergent ("tidal marsh", EM)	12.3%	16.3%	28.5%
Scrub-shrub (SS)	88.9%	8.2%	97.1%
Forested (FO)	39.9%	56.1%	96.0%
All three classes (EM, SS, FO)	37.2%		

Tillamook Bay

Vegetation class	% of tidal wetland area (historical)	% of tidal wetland area (current)
Emergent ("tidal marsh", EM)	37.0%	78.7%
Scrub-shrub (SS)	0.2%	5.5%
Forested (FO)	62.8%	15.8%
All three classes (EM, SS, FO)	100.0%	100.0%

Historical vegetation class	% loss from diking	% loss from conversion to another vegetation class	Total % loss
Emergent ("tidal marsh", EM)	58.3%	11.6%	69.9%
Scrub-shrub (SS)			
Forested (FO)	79.7%	12.7%	92.3%
All three classes (EM, SS, FO)	71.6%		

Umpqua River

Vegetation class	% of tidal wetland area (historical)	% of tidal wetland area (current)
Emergent ("tidal marsh", EM)	47.8%	72.2%
Scrub-shrub (SS)	2.0%	11.0%
Forested (FO)	50.3%	16.8%
All three classes (EM, SS, FO)	100.0%	100.0%

Historical vegetation class	% loss from diking	% loss from conversion to another vegetation class	Total % loss
Emergent ("tidal marsh", EM)	42.0%	17.6%	59.7%
Scrub-shrub (SS)	32.5%	41.8%	74.3%
Forested (FO)	58.9%	31.1%	90.0%
All three classes (EM, SS, FO)	50.3%		

Yaquina Bay

Vegetation class	% of tidal wetland area (historical)	% of tidal wetland area (current)
Emergent ("tidal marsh", EM)	60.5%	82.7%
Scrub-shrub (SS)	3.5%	7.3%
Forested (FO)	35.9%	10.0%
All three classes (EM, SS, FO)	100.0%	100.0%

Historical vegetation class	% loss from diking	% loss from conversion to another vegetation class	Total % loss
Emergent ("tidal marsh", EM)	67.4%	10.6%	78.0%
Scrub-shrub (SS)	34.4%	60.9%	95.3%
Forested (FO)	34.8%	57.5%	92.3%
All three classes (EM, SS, FO)	54.5%		

Appendix 6. Detailed geoprocessing methods

Geoprocessing steps:

1. Assembled input data and projected to Oregon Lambert (WKID2992):
   - PMEP CMECS Biotic Component V1.1 (PMEP "CMECS Biotic")
   - PMEP Historical and Current Estuary Extent V1.0 (PMEP "Estuary Extent")
   - OCMP CMECS Biotic Component V0.4.1 (OCMP "CMECS Biotic")
   - OCMP CMECS Aquatic Setting V0.4.1 (OCMP "Aquatic")
   - 1:24k historical vegetation for the Oregon Coast (Hawes et al. 2008, filename coast_glo_2008_03.shp)
2. Assembled additional interpretation layers:
   - Aerial photos (current ESRI imagery; NAIP imagery from recent years)
   - LIDAR-based digital elevation models (DEMs) from 2009 Oregon coastwide LIDAR
   - In-house data from monitoring and estuary assessment projects
   - National Wetland Inventory
3. Deleted small estuaries from PMEP's datasets that are not in OCMP's. These are all unsuitable for the analysis method, since they have no diked areas and scale issues overwhelm any meaningful change in vegetation mapping boundaries. Deleted: Clatsop Spit, Daley Lake, Sunset Bay, Port Orford Head, Brush Creek, Myers Creek, Thomas Creek, and Whaleshead Creek.
4. Reduced the PMEP data (both CMECS Biotic and Estuary Extent) to Oregon only, by selecting all polygons with Data_source = OCMP.
5. Updated the Oregon coast historical vegetation data (Hawes et al. 2008) to incorporate data from Coast Survey charts (T sheets), improving accuracy near the mouths of several estuaries. This work was conducted by John Christy; results were published in Hawes et al. (2018) and methods are described in Christy (2018).
6. In collaboration with John Christy, completed the historical vegetation layer for the outer coast estuaries by adding areas beyond the geographic extent of Hawes et al. (2018). The features were generated from PMEP's CMECS Biotic layer and were attributed by Christy as emergent = EM, scrub-shrub = SS or forested = FO. The attribution used the same historical data sources as Hawes et al. (2018); results are published only within this study's products.
7. Established the study area boundary (PMEP Estuary Extent) and clipped the historical vegetation data (Hawes et al. 2018) to this extent. Merged (geoprocessing tool: union) this clipped historical vegetation dataset with Christy's newly attributed areas to create a unified historical vegetation layer. Retained the detailed vegetation description from Hawes et al. 2018 (final shapefile attribute: HISTVEGABB).
8. Developed a correspondence table relating historical vegetation classification to the three major vegetation classes for this analysis (emergent = EM, scrub-shrub = SS, and forested = FO) (Appendix 9).
9. Attributed all features in the unified historical vegetation layer according to the correspondence table above. This attribute was passed through the remainder of the steps to the final shapefile (attribute: HISTVEG_CL).
10. At each step below, recalculated geometry (area) and compared to the previous steps to ensure there were no inadvertent changes to the analysis area.
11. Created a unified layer containing data on diking and current vegetation by merging (geoprocessing tool: union) PMEP's CMECS Biotic and OCMP's CMECS Aquatic.
12. Merged (geoprocessing tool: union) the above unified diking/current veg layer with the unified historical vegetation layer to create the final analysis layer.

13. Within the final analysis layer, deleted polygons that had no estuary name or estuary link: China Creek, Crooked Creek, Johnson Creek, Twomile Creek (between Coquille and Coos), Spencer Creek, and a few tiny sliver polygons.
14. Developed a correspondence table relating current vegetation classification (in CMECS Biotic) to the three major vegetation classes for this analysis (emergent = EM, scrub-shrub = SS, and forested = FO) (Appendix 8).
15. Attributed all features in the final analysis layer with current vegetation class, using the correspondence table above. Final shapefile attribute: CUR_VEG_CL.
16. Within the final analysis layer, attributed all areas with the AI07 modifier in either CMECS Biotic (attribute: CM_BC_MOD) or CMECS Aquatic (attribute: CM_AQ_CODE) as diked, and all areas lacking the AI07 modifier as non-diked. All areas within the full PMEP estuary extent are now attributed as either diked or non-diked. Final shapefile attribute: DIKED_YN (Y = diked, N = non-diked).
17. Reviewed results for each estuary and determined which estuaries can be included in the final products, and which should be omitted due to lack of diked areas and/or scale issues. The 15 estuaries included in final results are: Alsea Bay, Beaver Creek, Coos Bay, Coquille River, Necanicum River, Nehalem River, Nestucca Bay, Netarts Bay, Salmon River, Sand Lake, Siletz Bay, Siuslaw River, Tillamook Bay, Umpqua River, and Yaquina Bay.
18. Reviewed PMEP's restored areas data (Sherman et al. 2019); for any restored areas that were previously attributed as diked (i.e. DIKED_YN = Y), changed DIKED_YN to "N" and described the reason for the correction in the shapefile attribute "CORRECTION." Most of these were already attributed as non-diked in the OCMP source data, so only a few corrections were made.
19. Made needed additional corrections to diking status within the final analysis layer using aerial photo and LIDAR interpretation; described the corrections in the shapefile attribute "CORRECTION."
20. Ensured final analysis layer's boundaries matched PMEP's Estuary Extent.
21. Developed a feature symbolization to represent major categories of diking status and vegetation change, and incorporated the symbolization into the attribute table (attribute: MAP_SYMB). Queries for the symbolization are provided in Appendix 10 of this report.
22. Saved the final product to shapefile "OR_tidal_wetland_loss_by_hab_class_20191020.shp" and accompanying shapefile components.
23. Prepared maps of diking and vegetation conversion for each study estuary, using the above feature symbolization (this report, Appendix 1).
24. Prepared additional maps to show historical prevalence and losses of tidal swamp (this report, Appendix 2).
25. Exported layer files for the Appendix 1 and Appendix 2 maps to allow users to apply or adjust the symbolizations used in products.
26. Exported attribute table from final shapefile and prepared tabular summaries of results within and across estuaries, using pivot tables in Microsoft Excel (Version 1911).

Appendix 7. Shapefile attributes

Shapefile name: OR_tidal_wetland_loss_by_hab_class_20191020.shp

Field name	Description
FID	Internal feature number (generated by ArcGIS)
Shape	Feature geometry (generated by ArcGIS)
Estuary_Na	Estuary name, from PMEP CMECS Biotic Component data
Link	Estuary link (from PMEP data)
HECTARES	Area in hectares (calculated using "Calculate geometry" in ArcGIS)
CM_BC_CODE	CMECS Biotic Component classification code, from PMEP CMECS Biotic data V1.1 (PMEP 2018c); inherited directly from Oregon CMECS data (OCMP 2014b)
CM_BC_MOD	CMECS Biotic Component modifier, if any, from PMEP CMECS Biotic data V1.1 (PMEP 2018c); inherited directly from OCMP CMECS Biotic data (OCMP 2014b)
CM_AQ_CODE	CMECS Aquatic Setting classification, including modifiers if any, from OCMP CMECS Aquatic data (OCMP 2014a)
DIKED_YN	Diking status, from CM_BC_MOD and CM_AQ_CODE plus corrections listed in CORRECTIONS field. If AI07 modifier is present in either CM_BC_MOD or CM_AQ_CODE, or if the CORRECTION field indicates the area is diked, DIKED_YN = Y. If AI07 modifier is absent from CM_BC_MOD and CM_AQ_CODE, or if CORRECTION field indicates the area is not diked, DIKED_YN = N.
HISTVEGABB	Abbreviation for historical vegetation type (from Hawes et al. 2018)
HISTVEG_CL	Historical vegetation class, based on historical vegetation data from Hawes et al. 2018 and additional unpublished digital maps produced by John Christy for this study. Classes: EM = emergent, SS = scrub-shrub, FO = forested, NONVEG = non-vegetated, and UNK = not mapped (unknown).
CUR_VEG_CL	Current vegetation class, from PMEP CMECS Biotic data (field: CM_BC_CODE), with a small number of corrections based on aerial photo interpretation (listed in CORRECTIONS). Classes: EM = emergent, SS = scrub-shrub, FO = forested, AB = aquatic bed, NA = unclassified (CM_BC_CODE = 9.9.9.9), UNK = not mapped (unknown).
CORRECTION	Description of any corrections made to the diking status or vegetation class due to errors or gaps in source data
MAP_SYMB	Map symbol for visualizing major categories of diking and vegetation conversion.
Shape_Leng	Shape length (generated by ArcGIS)
Shape_Area	Shape area (generated by ArcGIS)

Appendix 8. Correspondence table for current vegetation classification

Data source for current vegetation type: PMEP's digital maps of the CMECS Biotic Component (PMEP 2018c), attribute "CMECS_BC_Code."

CMECS_BC_Code	Current vegetation class (CUR_VEG_CL)	Description
2.5	AB	Aquatic Vegetation Bed
2.5.1	AB	Benthic Macroalgae
2.5.2	AB	Aquatic Vascular Vegetation
2.6	EM	Emergent Wetland
2.6.1	EM	Emergent Tidal Marsh
2.6.1.1	EM	Brackish Emergent Tidal Marsh
2.7	SS	Scrub-Shrub Wetland
2.7.1	SS	Tidal Scrub-Shrub Wetland
2.7.1.1	SS	Brackish Tidal Scrub-Shrub Wetland
2.8	FO	Forested Wetland
2.8.1	FO	Tidal Forest/Woodland
2.8.1.1	FO	Brackish Tidal Forest/Woodland
9.9.9.9.9	NA	Unclassified (not available): these are generally non-vegetated areas such as open water and mudflats
Blank	UNK	Not mapped (unknown): these are generally manmade features (e.g. roads, dikes) which were clipped out of the Oregon CMECS Biotic Component, but are included in the overall estuary mapping (CMECS Aquatic Setting)

Appendix 9. Correspondence table for historical vegetation classification

Data sources for historical vegetation type: Hawes et al. (2018), https://drive.google.com/file/d/1KnHm47Bk4WbfqkQ9v7gPqlfEKLCa29SM/view?usp=sharing (attributes "VEGABB" and "VEGTEXT"), plus additional geospatial data developed for this study by John Christy.

Historical vegetation type (VEGABB)	Historical vegetation class (HISTVEG_CL)	Historical vegetation description, from Christy et al. 2008 (may be truncated; for full descriptions and further information, see the source publication)
FALW	FO	Ash-alder-willow swamp, sometimes with bigleaf maple. May include vine maple, ninebark, hardhack, cattail, "coarse grass", and briars. Ground "very soft," "miry," or "muddy," usually with extensive beaver dams.
FE	FO	Alder "groves" and "flats" if no mention of water or "swamp." Usually on mountain slopes, benches, and flats. May contain cherry. No conifers.
FF	FO	Douglas fir forest, often with bigleaf maple, dogwood, red alder, ash, and grand fir. Brushy understory may include vine maple, hazel, salal, willow, briars, fern, viburnum, Oregon grape, rhododendron, yew, fern, cherry, salmonberry, cascara.
FFBu	FO	Burned Douglas fir forest, often with scattered trees surviving fire. May include alder or willow.
FFCL	FO	Red alder-mixed conifer riparian forest, with various combinations of red cedar, grand fir, Douglas fir, western hemlock, bigleaf maple, and sometimes ash. Understory may include yew, dogwood, vine maple, elder, hazel, willow, salmonberry.
FFHC	FO	Northern mesic mixed conifer (or "fir, etc.") forest with mostly deciduous understory. May include various combinations of Douglas fir, western hemlock, red cedar, grand fir, with lesser amounts of bigleaf maple, dogwood, white oak, red alder, madrone…
FFHCBu	FO	Burned northern mesic mixed conifer (or "fir, etc.") forest with mostly deciduous understory. May include various combinations of Douglas fir, western hemlock, red cedar, grand fir. Often with scattered trees surviving fire.
FFHV	FO	Unmappable mixture of mostly northern mesic mixed conifer forest on north slopes, with elements of southern xeric conifer forest on S to W slopes and ridgetops. Includes various combinations of Douglas fir, western hemlock, red cedar, Port Orford cedar…
FFHVBu	FO	Burned mix of mostly northern mesic mixed conifer forest on north slopes, with elements of southern xeric conifer forest on S to W slopes and ridgetops. Includes various combinations of Douglas fir, western hemlock, red cedar, Port Orford cedar…
FFY	FO	Young Douglas fir forest, burned within last 20 years. Diameters < 12-14 inches. May include cedar, hemlock, alder, maple, rhododendron, salal, ceanothus, hazel.
FL	FO	Red alder swamp, usually with salmonberry, sometimes willow and bigleaf maple.

Historical vegetation type (VEGABB)	Historical vegetation class (HISTVEG_CL)	Historical vegetation description, from Christy et al. 2008 (may be truncated; for full descriptions and further information, see the source publication)
FOAM	FO	Southern mixed riparian forest with various combinations of oak, ash, bigleaf maple, myrtle, willow, alder, Douglas fir, grand fir ("yellow fir"), and white fir. "Dense" or "brushy" understory may include hazel, fern, ninebark, wild grape, and briars.
FSH	FO	Sitka spruce forest with various combinations of Douglas fir, grand fir, western hemlock, red cedar, red alder, bigleaf maple. "Dense" understory of vine maple, salmonberry, thimbleberry, huckleberry, salal, devils club, gooseberry, cascara, elderberry…
FSHBu	FO	Burned Sitka spruce forest with various combinations of Douglas fir, grand fir, western hemlock, red cedar, red alder, bigleaf maple. "Dense" understory of vine maple, salmonberry, thimbleberry, huckleberry, salal, devils club, gooseberry, cascara.
FSHL	FO	Riparian Sitka spruce forest with various combinations of Douglas fir, grand fir, western hemlock, red cedar, red alder, cottonwood, bigleaf maple, ash. Myrtle present farther south. "Dense" understory of salmonberry, salal, vine maple, willow, thimbleberry…
FSL	FO	Sitka spruce swamp, with various combinations of willow, red alder, red cedar, hemlock. Rarely with ash or bigleaf maple. Dense understory may include salmonberry, crabapple, elderberry, gooseberry, briars, ferns, skunk cabbage, vine maple.
FSP	FO	Shore pine forest on sandy soils. May include Douglas fir, Sitka spruce, western hemlock, and madrone, with Port Orford cedar ("white cedar") and chinquapin present in Coos and Curry counties. Understory may include manzanita, salal, evergreen huckleberry…
HB	SS	Brush fields or thickets on slopes and ridges, with few or no witness trees. May include vine maple, red alder, salmonberry, thimbleberry, rhododendron, hazel, cherry, fern, and salal. Ceanothus ("greasewood," "buckbrush"), chinquapin, garrya ("tassel")…
HC	SS	Crabapple swamp, often with willow, alder, salmonberry, huckleberry, briars.
HD	SS	Brush fields or thickets on bottoms or wet terraces, with few or no trees. May include willow, vine maple, elderberry, red alder, cherry, crabapple, salmonberry, thimbleberry, dogwood, salal, sedge.
HG	SS	Brush fields on dry coastal bluffs. Dense stands with combinations of salal, huckleberry, thimbleberry, garrya ("tassel"), twinberry, hazel, "lilac," crowberry, coyote bush. May contain scattered and scrubby shore pine, Sitka spruce, red alder.
HSP	SS	"Dense" or "scrubby" shore pine. May include Sitka spruce, Douglas fir, red alder, salmonberry.
HSS	SS	Shrub swamp ("brushy swamp," "marshy thicket," "swampy thicket"), composition unknown.
HU	SS	Brush, composition unknown. Includes "thickets" if no species or other descriptors are given.

Historical vegetation type (VEGABB)	Historical vegetation class (HISTVEG_CL)	Historical vegetation description, from Christy et al. 2008 (may be truncated; for full descriptions and further information, see the source publication)
HW	SS	Willow swamp or "willow swale", sometimes "scattering." May include alder, cascara, ninebark, hardhack, briars, salmonberry, gooseberry, "swamp grass." Includes riparian stands on gravel or sand bars, with young cottonwood or driftwood.
OFHC	FO	Mesic mixed-conifer woodland, with various combinations of Douglas fir, red cedar, and western hemlock, with lesser amounts of bigleaf maple, white oak, ash, madrone, and red alder. Understory may include vine maple, dogwood, hazel, viburnum, fern.
OFSL	FO	Sitka spruce swamp with widely scattered trees and dense shrub understory. May include various combinations of willow, red alder, red cedar, hemlock. Rarely with ash or bigleaf maple. Dense understory may include salmonberry, crabapple, elderberry.
OFZ	FO	Douglas fir woodland, often with bigleaf maple, alder or dogwood. Brushy understory may include hazel, vine maple, young Douglas fir, bracken or "ferns." May include "small openings," "part openings," or "some open."
OSH	FO	Sitka spruce woodland with various combinations of Douglas fir, western hemlock, red cedar, grand fir, red alder, bigleaf maple. "Dense" understory may contain vine maple, salmonberry, thimbleberry, huckleberry, salal, garrya ("tassel"), twinberry, hazel…
OSP	FO	Shore pine woodland on sandy soils or rocky headlands. May include scattering Douglas fir, Sitka spruce, western hemlock, or madrone, with Port Orford cedar ("white cedar") along south coast. Understory may include salal, manzanita, hazel, "lilac."
P	EM	Prairie, wet and dry undifferentiated. Includes "swale" and "glade" if adjacent line segments are prairie. May contain "thickets" or "scattering" trees if most distances > 100 links.
PB	EM	"Brushy prairie," "brush and fern prairie," "fern prairie," containing mostly fern and salal. In southern Coast Range, may contain hazel, chinquapin, whortleberry, thimbleberry, bunchgrass.
PD	EM	Sand dune prairie or grassland, "sandy prairie," "sandy plains," "sand hills covered with grass," "sand glades."
PW	EM	Seasonally wet prairie, "prairie marsh," "swamp prairie." May have scattering ash trees or willow "patches" or "strips," most with distances from corners > 100 links.
SSH	EM	"Lightly timbered" Sitka spruce savanna with "no undergrowth." May contain various combinations of Douglas fir, western hemlock, red cedar, grand fir, red alder, bigleaf maple.
SSP	EM	Shore pine savanna on sandy soils or rocky headlands. May include Douglas fir, Sitka spruce, western hemlock, madrone, with Port Orford cedar ("white cedar") and chinquapin present in Coos and Curry counties. Understory may include salal, evergreen huckleberry…

Historical vegetation type (VEGABB)	Historical vegetation class (HISTVEG_CL)	Historical vegetation description, from Christy et al. 2008 (may be truncated; for full descriptions and further information, see the source publication)
US	NONVEG	Sand bar, "sandy barrens," sand dunes (witness trees > 400 links distant), tidal mudflats (estuarine or riverine), "quicksand." May have scattered vegetation in unmappable patches.
W	NONVEG	Water bodies >1 chain across. Includes ocean, rivers, sloughs, ponds, beaver ponds, lakes, "marshy lakes" and "bayous."
WG	EM	"Grass marsh."
WMU	EM	Marsh or "wet meadow," composition unknown.
WPC	EM	Coastal sphagnum bog with cranberry, shore pine, red alder, bracken fern. May include unmappable mix of crabapple swamp, salal thickets, shore pine thickets.
WSM	EM	Tidal marsh, salinity undifferentiated. Includes "tide lands," "tidal prairie," "grass tide marsh," "subject to overflow at high tide," and "freshet" if along coast. Few or no trees. Sitka spruce or crabapple may be included on elevations.
WSP	EM	Unmappable mixture of shore pine swamp and undifferentiated "marsh." May contain dwarf shore pine, Sitka spruce, crabapple, salal. Ground "mucky," some flooded.
WSU	FO	"Swamp," composition unknown.
WU	EM	Wetland, composition unknown. Includes "swale" in forest or shrubland.
blank	UNK	Not mapped

Appendix 10. Symbolization for Appendix 1 maps of diking and vegetation conversion

This table shows the major categories of tidal wetland change identified in this project, along with the GIS queries used to define and map them. These categories make up the map symbolization used in Appendix 1. Narrative descriptions of the categories are provided in the report (see "**Major categories of tidal wetland change**").

Type of change	Query
1. Diked	DIKED_YN = 'Y'
2. Non-diked, remained emergent	DIKED_YN = 'N' AND "HISTVEG_CL" = 'EM' AND "CUR_VEG_CL" = 'EM'
3. Non-diked, forested or shrub changed to emergent	DIKED_YN = 'N' AND "CUR_VEG_CL" = 'EM' AND ("HISTVEG_CL" = 'FO' OR "HISTVEG_CL" = 'SS')
4. Non-diked, marsh advance	DIKED_YN = 'N' AND "HISTVEG_CL" = 'NONVEG' AND "CUR_VEG_CL" = 'EM'
5. Non-diked, remained forested	DIKED_YN = 'N' AND "HISTVEG_CL" = 'FO' AND "CUR_VEG_CL" = 'FO'
6. Non-diked, remained shrub	DIKED_YN = 'N' AND "HISTVEG_CL" = 'SS' AND "CUR_VEG_CL" = 'SS'
7. Non-diked, other vegetated (mostly currently forested/ shrub)	("DIKED_YN" = 'N' AND "HISTVEG_CL" = 'EM' AND "CUR_VEG_CL" = 'SS') OR ("DIKED_YN" = 'N' AND "HISTVEG_CL" = 'UNK' AND "CUR_VEG_CL" = 'SS') OR ("DIKED_YN" = 'N' AND "HISTVEG_CL" = 'NONVEG' AND "CUR_VEG_CL" = 'SS') OR ("DIKED_YN" = 'N' AND "HISTVEG_CL" = 'EM' AND "CUR_VEG_CL" = 'FO') OR ("DIKED_YN" = 'N' AND "HISTVEG_CL" = 'UNK' AND "CUR_VEG_CL" = 'FO') OR ("DIKED_YN" = 'N' AND "HISTVEG_CL" = 'NONVEG' AND "CUR_VEG_CL" = 'FO') OR ("DIKED_YN" = 'N' AND "HISTVEG_CL" = 'FO' AND "CUR_VEG_CL" = 'SS') OR ("DIKED_YN" = 'N' AND "HISTVEG_CL" = 'SS' AND "CUR_VEG_CL" = 'FO') OR ("DIKED_YN" = 'N' AND "HISTVEG_CL" = 'UNK' AND "CUR_VEG_CL" = 'EM')
8. Non-diked, non-vegetated or unclassified (mostly water, mudflat, etc.)	("DIKED_YN" = 'N' AND "HISTVEG_CL" = 'NONVEG' AND "CUR_VEG_CL" = 'AB') OR ("DIKED_YN" = 'N' AND "HISTVEG_CL" = 'UNK' AND "CUR_VEG_CL" = 'UNK') OR ("DIKED_YN" = 'N' AND "HISTVEG_CL" = 'SS' AND "CUR_VEG_CL" = 'NA') OR ("DIKED_YN" = 'N' AND "HISTVEG_CL" = 'SS' AND "CUR_VEG_CL" = 'UNK') OR ("DIKED_YN" = 'N' AND "HISTVEG_CL" = 'FO' AND "CUR_VEG_CL" = 'NA') OR ("DIKED_YN" = 'N' AND "HISTVEG_CL" = 'NONVEG' AND "CUR_VEG_CL" = 'UNK') OR ("DIKED_YN" = 'N' AND "HISTVEG_CL" = 'EM' AND "CUR_VEG_CL" = 'NA') OR ("DIKED_YN" = 'N' AND "HISTVEG_CL" = 'EM' AND "CUR_VEG_CL" = 'UNK') OR ("DIKED_YN" = 'N' AND "HISTVEG_CL" = 'UNK' AND "CUR_VEG_CL" = 'NA') OR ("DIKED_YN" = 'N' AND "HISTVEG_CL" = 'FO' AND "CUR_VEG_CL" = 'UNK') OR ("DIKED_YN" = 'N' AND "HISTVEG_CL" = 'FO' AND "CUR_VEG_CL" = 'AB') OR ("DIKED_YN" = 'N' AND "HISTVEG_CL" = 'NONVEG' AND "CUR_VEG_CL" = 'NA') OR ("DIKED_YN" = 'N' AND "HISTVEG_CL" = 'UNK' AND "CUR_VEG_CL" = 'AB') OR ("DIKED_YN" = 'N' AND "HISTVEG_CL" = 'EM' AND "CUR_VEG_CL" = 'AB')

Appendix 11. Restoring tidal swamps: a priority for research and practice

Given the very high losses of tidal swamps (particularly tidal forested wetlands), as stated above, protection and restoration of tidal swamps should be considered a top priority for the Oregon coast (and likely for other areas in the Pacific Northwest). Of course, conservation and restoration of tidal marsh is also a very high priority; however, this appendix focuses on tidal swamp conservation and restoration to help fill an urgent need for this information.

Conservation of the few remaining tidal swamps is urgent and can proceed immediately; potential mechanisms include land conservation agreements with willing landowners (e.g. conservation easements) and purchase from willing landowners by land trusts. Restoration of tidal swamps is also urgently needed but can present several challenges, as described below.

Restoration challenges related to physical conditions at restoration sites

Soils of tidal swamps on Oregon's outer coast tend to have high organic matter content (Brophy 2005b, 2009; Brophy et al. 2011, 2014, 2018; Kauffman et al. in preparation). This high organic content makes these wetlands vulnerable to subsidence (sinking or settling of the soil surface) when diked and drained (Turner 2004). Subsidence occurs due to a combination of oxidation of organic matter due to drainage, compaction by machinery and livestock, and loss of regular sediment inputs (Frenkel and Morlan 1991, Turner 2004). Subsidence of 30 cm to 2 m has been described for diked sites on the Oregon coast that were historically tidal forested and tidal scrub-shrub wetlands (Brophy 2004, 2009; Brophy et al. 2015).

If the subsided elevation at a diked restoration site is much lower than nearby tidal swamp reference sites, it may not be possible to restore tidal swamp at that site, even if the site was historically a tidal swamp. Instead, the restored site may be too wet for woody species to survive and may restore to tidal marsh (Diefenderfer et al. 2008, Brophy 2009, Borde et al. 2012); or may support different woody species than were present historically (e.g. willows instead of Sitka spruce). However, the historical vegetation type could eventually be re-established, depending on the rate of sediment and organic matter accumulation as well as future changes such as sea level rise (Diefenderfer et al. 2008, Brophy et al. 2018).

Besides subsidence, diked and drained former tidal swamps are often affected by other soil changes such as compaction (increased bulk density), and by channel network changes such as ditching and the resulting reduction in channel density (Brophy 2004, 2009; Diefenderfer et al. 2008; Coleman et al. 2015; Brophy et al. 2015a, b). These changes strongly affect rooting conditions and may also present challenges to re-establishing tidal swamp in its historical locations, particularly when combined with subsidence. For example, soil compaction at a subsided site, combined with a sparse tidal channel network, may lead to surface ponding, reduced soil oxygenation, and evaporative concentration of salts leading to salinities well above expected (Zedler et al. 2003), all of which can prevent establishment of woody vegetation or alter the species composition in comparison to historical conditions (Brophy and Janousek 2013, Brophy et al. 2014).

Due to the factors above, selection of appropriate sites for tidal swamp restoration requires careful analysis of the landscape, as well as monitoring of physical conditions at least-disturbed tidal swamp reference sites and potential restoration sites, as described below.

Restoration site selection: the role of research and monitoring

The state of the knowledge

If we had ample data on the optimal salinity regimes, tidal inundation regimes, groundwater fluctuation, soil conditions, and other factors for survival and growth of tidal swamp plant communities, it would be relatively easy to choose appropriate locations for tidal swamp restoration. However, those data are very sparse; to date, only a handful of Oregon's remnant tidal swamps have been monitored. Results from the few existing studies (Brophy 2005b; Brophy 2009; Borde et al. 2011; Brophy et al. 2011, 2015a, 2015b) reveal a broad range of physical and biotic characteristics, despite the small number of available sites—likely reflecting the broad diversity of tidal swamps historically.

Ideally, restoration sites should be selected using knowledge of thresholds—what are the environmental thresholds (boundaries) within which the target ecosystem can be established and thrive? However, due to the early state of knowledge, there is little information on such thresholds. For example, we have data on inundation regimes at individual tidal swamp sites (e.g. Brophy 2009, Borde et al. 2011, Brophy et al. 2011), but what are the maximum winter inundation depths and durations that Sitka spruce can survive? What about Hooker willow? What is the maximum dry season soil salinity that these species can survive? Do these thresholds differ for saplings versus mature shrubs/trees? These questions cannot yet be answered, so focused research is needed on these and similar topics. The results will help practitioners choose appropriate sites for restoration, and will also help us understand the functions and climate change resilience of tidal swamps.

Choosing a restoration site: reference sites, existing data and monitoring

Currently, given the sparse data about physical conditions of tidal swamps, the best way practitioners can choose sites for tidal swamp restoration is to measure conditions at tidal swamp reference sites – preferably nearby – and select restoration sites with similar conditions. However, given the near-eradication of tidal swamps from the Oregon coast, it can be hard for practitioners to locate suitable reference sites. Therefore, reference conditions databases for tidal swamps are needed (e.g. Brophy et al. 2011). Such databases describe physical and biological conditions at multiple tidal swamps, allowing practitioners to understand the range of conditions that could support tidal swamp development. As described above, scientists have only begun to measure these conditions during the past decade, and more data are urgently needed. However, practitioners can use the data from the studies listed above (Brophy 2005b; Brophy 2009; Borde et al. 2011; Brophy et al. 2011, 2015a, 2015b) to gain some understanding of tidal swamp characteristics and to help choose appropriate restoration sites.

Although reference conditions databases are useful, it's still best to locate and monitor a suitable tidal swamp reference site or sites, and use that data to choose the restoration site and design the restoration. In this case, it is important to develop an appropriate and cost-effective monitoring program that measures the same characteristics at both the reference site and the potential restoration site(s) (Brophy 2007, Roegner et al. 2009). Restoration success will depend greatly on the basic ecosystem drivers of tidal inundation and salinity, so basic monitoring should include at least those two drivers (as well as key outcomes such as vegetation and fish use). To predict post-restoration tidal inundation, tidal water levels from a tide gauge near the site can be compared to the topography of the reference and restoration sites. LIDAR digital elevation models can provide useful elevation estimates during preliminary site selection, but final site selection and restoration planning must include onsite elevation measurements (e.g. leveling or RTK-GPS) for accuracy.

Monitoring salinity in the water body adjacent to the restoration site is vital for restoration planning, but post-restoration salinity regimes inside a restoration site can be hard to predict. Salinity regimes are complex in least-disturbed tidal wetlands, and even more so in restoration sites. For example, soil salinity is likely to drive tidal swamp plant community development, yet soil salinity has seldom been monitored in Pacific Northwest tidal wetlands. The few studies of soil salinity in Oregon tidal wetlands show that it differs markedly from surface water salinity, even within least-disturbed reference sites (Brophy et al. 2015b; Janousek et al. in preparation). Salinity patterns can vary greatly from season to season, across tide cycles, and in different locations within a single site (e.g. hillslope base vs. riverbank) (Brophy et al. 2014). Disturbance-related factors like soil compaction, channel system density, and graded microtopography are likely to have strong effects on soil and channel salinity patterns (Brophy et al. 2014). The resulting complexity makes post-restoration salinity difficult to predict. Therefore, in polyhaline to oligohaline estuary zones, it may be best to delay woody plantings until post-restoration salinities at the restoration site have been measured, or to plant species tolerant of a wide range of salinities.

Beyond tidal hydrology and salinity, other monitoring parameters should be strategically chosen for monitoring at tidal swamp restoration and reference sites. Their selection should be based on project goals, data needed to evaluate restoration effectiveness, and site characteristics. Many of the monitoring parameters will be the same as those monitored at tidal marsh sites (e.g. Rice et al. 2005, Brophy 2007, Roegner et al. 2009), but understanding tidal swamp functions and resilience will also require monitoring of several parameters not commonly measured in tidal marsh, such as shallow groundwater levels and fluctuation, groundwater salinity, soil bulk density, and soil texture (Brophy 2009; Brophy et al. 2011, 2015b; Janousek et al. 2018). Of course, monitoring of biological characteristics (e.g. vegetation, birds, fish, and fish prey) is also vital, to build our understanding of the relationships between physical conditions and biotic responses, and for immediate applications such as planning woody plantings at restoration sites.

Wetland monitoring data are used for many purposes, such as selection of restoration sites, restoration design guidance, evaluation of post-restoration results, and guidance for future projects. For example, pre-restoration (baseline) monitoring results can help the design team choose the best locations for woody plantings, evaluate the risk from invasive species, and determine the potential for use of innovative restoration methods such as nurse logs and topographic mounds (Diefenderfer, Sinks et al. 2018) (see "**System engineers, invasive species, and innovative restoration methods**" below). Our experience monitoring tidal swamp restoration sites has shown that during early years, the habitat type monitored may be predominantly marsh, but the monitoring program must include adaptive plans for measuring woody cover and survival of woody plantings as they become established.

System engineers, invasive species, and innovative restoration methods

Beyond the ecosystem drivers mentioned above, previous studies have shown that tidal swamps can be strongly affected by system engineers such as beaver (Diefenderfer and Montgomery 2008). Even Sitka spruce can be considered a "system engineer" due to its elevated root platforms, which support a more aerobic environment above the saturated soils below (Brophy 2009). These factors should be considered when planning restoration as well as conservation of tidal swamp; for example, beaver re-introductions may help emulate historical conditions and may also contribute to the climate change resilience of wetlands (Dittbrenner et al. 2018). Innovative tidal swamp restoration methods such as nurse logs and topographic mounds may enhance the potential for restoring tidal swamp even at subsided sites or those with invasive species (Diefenderfer, Sinks et al. 2018).

One invasive species, reed canarygrass, currently poses a challenge to tidal swamp restoration in many locations on the Oregon coast (Tanner et al. 2002; Diefenderfer, Borde et al. 2016). This species competes strongly with young trees and shrubs, especially in low salinity areas. At brackish restoration sites, measurements of soil groundwater and salinity dynamics are needed where reed canarygrass persists or establishes and where it dies back, to evaluate the risk posed by this species and develop appropriate control methods. Where conditions are suitable for reed canarygrass, woody plantings must generally be maintained until they can overtop the reed canarygrass. Innovative restoration techniques such as nurse logs and topographic mounds (Diefenderfer, Sinks et al. 2018) may help woody plantings reach this overtopping stage earlier, improving the chance of restoration success.

Climate change

Climate change poses a challenge for our remaining tidal swamps, as well as restoration of tidal swamp. The role of tidal swamps in mitigating climate change, and the potential for tidal swamps to persist under future climate change conditions, is not yet understood. As described above, tidal swamps generally have high soil carbon content. Soil carbon storage can offset greenhouse gas emissions, helping to mitigate climate change; but methane emissions in relatively fresh tidal wetlands may offset carbon storage (Poffenbarger et al. 2011).

The potential for tidal swamps to persist in the face of sea level rise (SLR) has not yet been evaluated; as for other tidal wetlands, it will probably depend on the rates of organic matter accumulation and mineral sediment accretion (Cahoon et al. 2006). Sitka spruce and several other woody species commonly dominant in Pacific Northwest tidal swamps (such as Hooker's willow, Pacific crabapple, and black twinberry) are tolerant of brackish salinities (Christy and Brophy 2007), improving the chances for these tidal swamp types to persist despite SLR – and reducing the likelihood of methane emission. However, rapid SLR could prevent development of the complex channel networks and large woody debris accumulations typical of least-disturbed tidal swamps, thus strongly affecting tidal swamp functions. Major earthquakes and associated land surface subsidence could greatly amplify the effects of SLR. Research is urgently needed to address these unknowns.

Summary

In summary, conservation and restoration of tidal swamps are urgent priorities for the Oregon coast, and restoration of tidal swamps requires careful planning. The first step in planning tidal swamp restoration is selection of an appropriate site, which requires landscape analysis and understanding of historical and current site conditions. Monitoring of physical and biological characteristics of at tidal swamp reference and restoration sites provides necessary data to guide restoration. Innovative restoration techniques such as nurse logs and topographic mounds may help overcome challenges due to invasive species. Monitoring results and "lessons learned" should be shared with other restoration practitioners, thus contributing to the regional advancement of restoration science and practice. Finally, in addition to guiding restoration, monitoring and research at tidal swamps are urgently needed to understand the structure, functions, services, and future resilience of these once-prevalent, now-rare ecosystems.

References

References for this appendix are included in the "**References**" section in the main body of the report.