Relationships between Salt Marsh Vegetation and Surface Elevation in Coos Bay Estuary, Oregon

Authors: Mary V. Santelmann, Brett A. Boisjolie, Rebecca Flitcroft, and Megan Gomez

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Mary V. Santelmann[1], and **Brett A. Boisjolie**[2], 104 CEOAS Administration Building, College of Earth, Ocean and Atmospheric Sciences, Oregon State University, Corvallis, Oregon 97331

Rebecca Flitcroft, USDA Forest Service Research Laboratory, 3200 Jefferson Way SW, Corvallis, Oregon 97330

and

Megan Gomez, The Evergreen State College, 2700 Evergreen Parkway NW, Olympia, Washington 98505

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Abstract

Salt marsh habitats support a diverse array of estuarine species but are vulnerable to increased inundation resulting from sea-level rise. In order to characterize relationships between vegetation and elevation and inform assessments of risk to salt marsh communities from projected sea-level rise, we collected vegetation and elevation data at 42 salt marsh sites in Coos Bay Estuary, Oregon. For 1-m^2 plots along transects from the bayside edge to the upland, we recorded height and percent cover of all plant species present. We determined plot location and elevation at 1-m intervals with a Trimble Pathfinder Pro XRS differential GPS and TOPCON GTS223 Total Station for comparison with existing LiDAR. Cluster analysis distinguished six vegetation groups. Two low marsh groups (average elevation 1.74 and 1.91 m) were characterized by swampfire (*Sarcocornia perennis*) with an average height of 31 cm, and saltgrass (*Distichlis spicata*) with an average height of 22 cm. Plots in the high marsh groups had average elevations ranging from 2.21 to 2.57 m and were characterized by tufted hairgrass (*Deschampsia cespitosa*) and Oregon gumweed (*Grindelia stricta* var. *stricta*), with an average height of 50 cm and 43 cm, respectively. Mid-marsh groups (average elevations of 2.01 and 1.99 m) were dominated by Lyngbye's sedge (*Carex lyngbyei*) with an average height of 64 cm. The data collected along these transects allowed us to assess LiDAR elevation accuracy, identify sites where LiDAR data require correction, and provide species-specific height data for correction of LiDAR in areas of dense vegetation.

Keywords: salt marshes, coastal wetlands, vegetation patterns, accuracy assessment, Coos Bay

Introduction

Estuarine wetlands are some of the world's most productive habitats (Costanza et al. 1997) and support ecologically and commercially important species (Miller and Sadro 2003, Bottom et al. 2005). Along the west coast of North America, estuarine salt marshes are important as rearing areas for juvenile anadromous salmon (Reimers 1976, Jones et al. 2014, Weybright and Giannico 2017). However, estuarine salt marshes have also been extensively altered by human activities. Development, including the building of transportation infrastructure, has reduced the extent of marsh environments along Oregon's coast by 50–80% relative to historical coverage (Oregon Division of State Lands 1972, Simenstad et al. 1982, Washington Department of Ecology 1993). Remnant tidal marshes and the ecosystems they support are further threatened by sea-level rise (SLR). Current global projections suggest a possible rise of mean sea level between 0.75 and 1.9 m (Vermeer and Rahmstorf 2009), other models suggest that increases of up to 2.7 m are possible (Bamber and Aspinall 2013). Tidal marsh habitat is expected to decline globally, particularly in areas where development or topography limit the ability of marsh vegetation to migrate inland (Craft et al. 2009). Recent analysis of coastal wetland vulnerability in 14 estuaries along the Pacific coast of the US estimate that even under their more conservative SLR scenario, 60% of middle marsh

[1] Author to whom correspondence should be addressed. Email: santelmm@oregonstate.edu
2 Current address: Massachusetts Department of Conservation & Recreation, 485 Ware Road, Belchertown, Massachusetts 01007

habitat and 95% of high marsh habitat will be lost by the end of the century (Thorne et al. 2018). Understanding the relationships between surface elevation and different marsh vegetation types is a key to understanding the relative vulnerability of salt marshes to SLR and to identifying appropriate potential sites for restoration.

Marsh vegetation types have been linked to surface elevation and frequency of tidal inundation (Jefferson 1974, Weilhofer et al. 2013), as well as patterns of groundwater input and evapotranspiration (Moffet et al. 2012). More recently, studies of species-specific zonation patterns in salt marshes of the Pacific coast (Janousek et al. 2018) have investigated the occurrence of individual species and species niche breadth. Janousek et al. (2018) compared species zonation in 12 sites from California to Washington, along gradients of inundation (within and between sites) and latitude (between sites) using a standardized tidal datum. However, their study focused on the occurrence of individual species and niche breadth across latitudinal gradients rather than vegetation assemblages. The study of species assemblages adds additional information that can be particularly useful for comparison of present-day assemblages to those characterized in previous studies of salt marsh vegetation in the region (e.g., Jefferson 1974, Frenkel et al. 1981, Chellew 2017).

Airborne Light Detection and Ranging (LiDAR) technology has emerged as an important source of data on land surface elevation and can be useful for investigating the influence of tidal inundation on vegetation and the effects of sea-level rise on coastal ecosystems (United States Climate Change Science Program 2009). However, LiDAR returns from the top of dense vegetation or the water surface can underestimate surface elevation, obscuring relationships between vegetation and elevation. This bias leads to underestimation of the potential impact of SLR and vulnerability of these key habitats (Liu 2008, National Oceanic and Atmospheric Administration (NOAA) 2010, Parrish 2012). Recognition of these potential sources of error has led to the development of species-specific correction factors in some coastal environments (Sadro et al. 2007, Hladik and Alber 2012, Ewald 2013, Fernandez-Nuñez et al. 2017). However, for tidal marshes on the Oregon Coast, species-specific data on vegetation height have not yet been published in the peer-reviewed literature.

The goals of this study were: 1) to investigate relationships between salt marsh vegetation types and surface elevation in the Coos Bay Estuary, one of the largest estuaries in Oregon; 2) to use field surveys to evaluate and quantify the accuracy of LiDAR data collected in 2008 at the Coos Bay Estuary; and 3) to develop data sets on vegetation height that could be used in efforts to correct historic LiDAR data biased by presence of dense vegetation. While such species-specific height correction data exist for salt marshes of the Atlantic coast (Hladik and Alber 2012) and have been used to correct LiDAR in that region, the data presented here are the first published data on vegetation height for salt marshes of the Oregon coast.

We measured elevation and sampled vegetation along transects from the bayside edge to the upland bank at 42 salt marsh sites in the Coos Bay Estuary (Figure 1). Our specific research questions were:

1. What are the relationships between major vegetation types and physical characteristics of the sampling plot, such as surface elevation, and location along the transect?
2. Where do the transect profiles (transect slope and elevation) of the marsh surface, as estimated by the LiDAR and field survey, differ in ways that indicate error resulting from tidal inundation or dense vegetation?
3. What is the potential magnitude of inaccuracy in existing LiDAR data that may be due to tidally-inundated sites or presence of dense vegetation?

We hypothesized that the LiDAR elevation data would have a higher global accuracy than field survey elevation data except where dense vegetation or high tide had obscured returns from ground surfaces. However, we expected that the field survey elevation would be more accurate than LiDAR at sites where LiDAR data were acquired at high tide or from the top of dense vegetation.

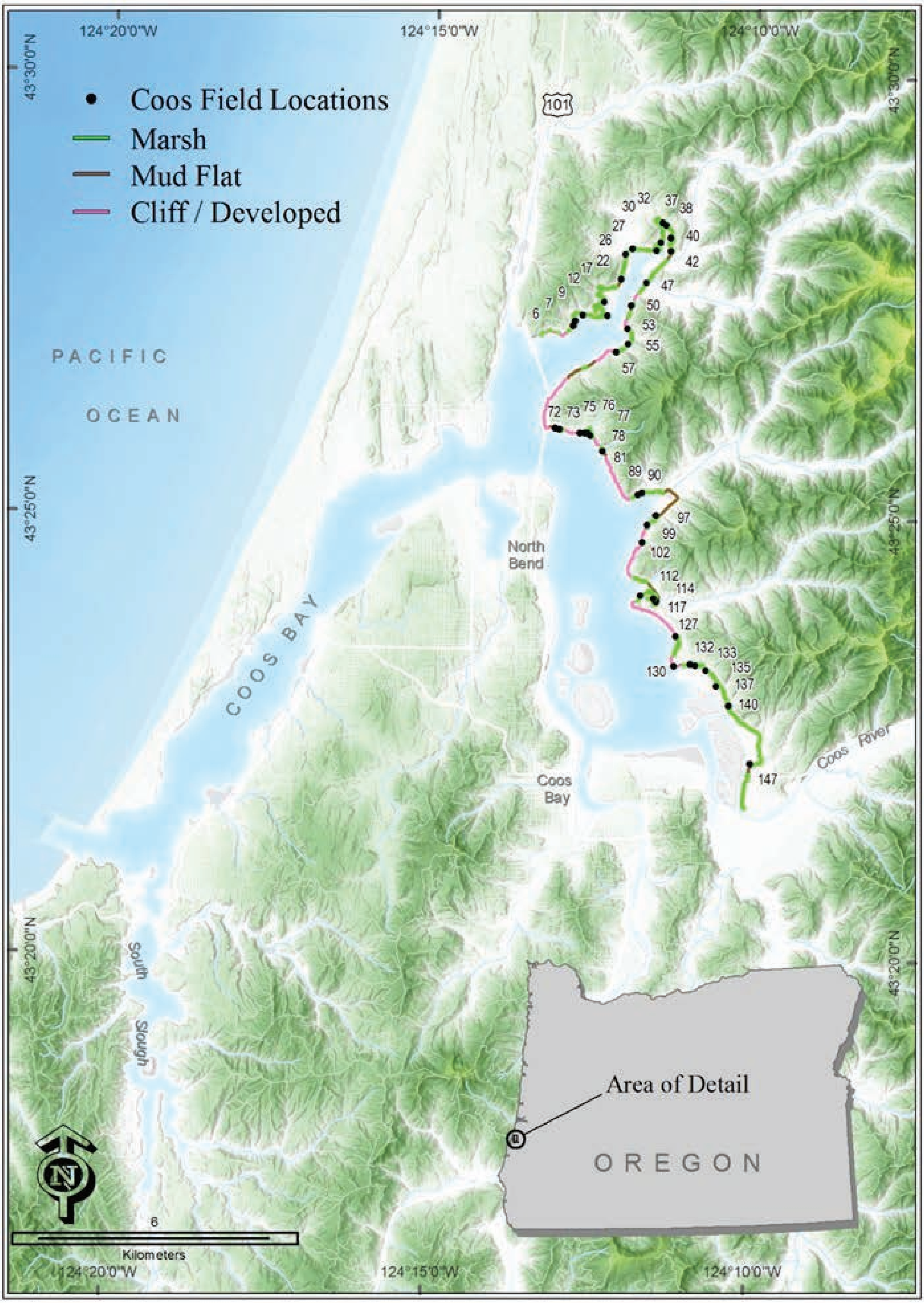

Figure 1. Study area in Coos Bay, Oregon with site locations.

Where the LiDAR data are not biased by deep water or dense vegetation, we expected that the LiDAR and field survey data would have congruent slopes and similar estimates of surface relief due to high within-site relative accuracy (4–5 cm) for both methods (see Methods section). While within-site relative accuracy is comparable for both methods, we hypothesized that field survey data would be better at identifying small channel features often obscured by dense vegetation. Findings from this study will assist in appropriate interpretation of existing LiDAR data, improve the accuracy of coastal modeling efforts, and inform comparisons of data collected in the past with data to be collected in the future.

Methods

Study Area

The Coos Bay Estuary (54 km^2; Figure 1) is a drowned river mouth estuary constrained by surrounding topographic relief created by the foothills of the Oregon Coast Range. The climate of this region is temperate-maritime, with winter rain as the dominant form of precipitation (Franklin and Dyrness 1988). Limited water storage in high-gradient headwater areas results in increased periodic flooding associated with storm events that flush high volumes of sediment into the estuary. These sediments are generally deposited in the upper bay. Winter high flows also result in a freshwater-dominated hydrologic regime through the winter months. In contrast, low freshwater flows in the summer allow seawater inflows to dominate the estuary (Coos Watershed Association 2006). The Millicoma River, South Fork Coos River, and Coos Bay Lowland watersheds are the three fifth-field watersheds (United States Geological Survey 2013) that drain into the Coos Bay Estuary. Along low-gradient tributaries, sloughs are formed in areas of limited freshwater inflow with incomplete tidal flushing, and the bay itself contains broad mud flats. Mudflat edges contain fringing remnant salt marsh areas where finer particles of silt and clay accumulate. Tidal marshes cover about 20% (10.9 km^2) of the bay, and another 5.6 km^2 of the bay consist of eelgrass (*Zostera marina* L.) tideland, an important habitat for many estuarine organisms (Phillips 1984).

The combined cities of Coos Bay/North Bend form the largest coastal community in Oregon (Portland State University 2013). Urban and rural residential use occupy much of the perimeter of the estuary, with additional agricultural use upstream in the river valleys to the east and south, and logging in the surrounding hills. Historical land-use practices and development have significantly altered estuary ecosystems. Within the estuary itself, dredging and diking continue to allow use of the area as a major port. The building of roads, railroads, and other infrastructure has also altered floodplain areas. Tide-gates are common on the lower reaches of streams, allowing these tributaries to drain only at low tide, preventing flooding of pasture and cropland at high tides while limiting the passage of organisms to upstream habitats (Bass 2010).

Restoration efforts have been undertaken to protect the economically, culturally, and ecologically important salmonid species of the bay. These efforts have targeted wetlands for their important function of water quality improvement, groundwater recharge, floodwater attenuation, and ecosystem habitat. The Coos Bay Watershed Association has invested more than $1 million into restoration efforts through partnerships with the Bureau of Land Management, US Fish and Wildlife Service, Oregon Department of Fish and Wildlife, and other partners (Coos Watershed Association 2012).

Field Elevation Survey Techniques

We conducted field surveys of marsh elevation and vegetation characteristics at 42 salt marsh sites along the eastern perimeter of Coos Bay (Figure 1). Site selection used a combined systematic and random sample approach. A systematic sample was created by delineating the bay perimeter into 155 segments 200 m in length using the dynamic segmentation tool in ArcGIS 10.1 (ESRI). Sample sites were placed every 1,000 m around the estuary, resulting in 31 systematically-selected sample locations. In addition, to increase the number of salt marsh sites included in the survey, a random sample of 21 additional sites were selected from the 98 total sites identified as salt marshes from interpretation of digital aerial photography (0.3 m resolution, collected 06 July 6 2010). This gave us 52 total site locations; we obtained permission to survey at 42 of the sites.

We conducted field surveys in July and August 2014, collecting vegetation and elevation data along transects from the bayside edge of the marsh to the upland bank. At each site, we determined horizontal and vertical position of ground reference points and established temporary benchmarks, recorded using a Trimble Pathfinder Pro XRS differential GPS. We applied post-processing differential corrections using Trimble Pathfinder Office software version 5.4 (Trimble 2012), UNAVCO base station coordinate values, and National Geodetic Survey's Online Positioning User Service (OPUS) software solutions (National Geodetic Survey 2014). After differential corrections, the horizontal accuracy of benchmarks was better than 50.7 cm (RMS). The Trimble Pathfinder Pro XRS is not graded for submeter elevation assessments, thus, we could not use the elevation data from the GPS unit to assess the absolute accuracy of the LiDAR elevation data. However, we obtained data that allowed us to compare the relative accuracy of LiDAR data against field survey data at each site using a high-accuracy total station (TOPCON GTS223, Topcon Positioning Systems, Livermore, California) set up on the temporary benchmark location. Total station elevations were assessed to be accurate within 2 cm, with a horizontal accuracy of $\leq$ 2 cm, based on before- and after- field season observations at NGS (National Geodetic Survey) elevation benchmarks and temporary benchmarks at each survey site. The TOPCON GTS-223 has an angular accuracy of 3 seconds (TOPCON 2005), making it an appropriate tool for assessing fine-scale variations in marsh elevations within a site (10-120 m long transects). We used the total station to collect elevation data at 1-m intervals along transects. All elevation measurements are reported in North American Vertical Datum 1988 (NAVD88).

At each site, we surveyed two transects approximately 15 m apart. Transects were laid out perpendicular to the water's edge and encompassed the elevation change from the bayside edge, where salt marsh vegetation replaced mud flat, to the upslope break where marsh vegetation transitioned to the upland. To obtain replicate data for the vegetation analysis, we established a second transect at each site. The second transect was up to 20 m long and approximately parallel to the main transect. Because sites varied in size, shape, and thus total distance from the water's edge to the upland bank, transect length varied across sites.

Vegetation Survey

We conducted vegetation sampling using 1-m x 1-m plots placed at 5-m intervals along each transect for the first 20 m from the bayside edge and transitioned to 10 m intervals at distances from 20 to 50 m. This sampling design reflected the pattern of vegetation change along the distance gradient, since vegetation change was most rapid in the first 20 m from the water's edge. Thus, for a 50-m transect, we placed vegetation plots at distances of 0, 5, 10, 15, 20, 30, 40, and 50 m. We sampled along two transects at each site to replicate vegetation change across the distance and elevation gradient within sites; the second transect was never more than 20 m long.

In every plot, we identified all vascular plant species and visually estimated percent cover of each species. We then measured the heights of dominant species (those with more than 25% cover in each plot) in three locations per plot. Most plots had only one (occasionally two) dominant species. If they occurred in a plot, presence of tidal channels, large logs, or overhanging tree branches was noted. We identified plants in the field and collected specimens to confirm field identification in the lab. Nomenclature and identification to species follows Hitchcock and Cronquist (1973) for most species, updated to 2019 nomenclature using the USDA PLANTS database (USDA NRCS 2019). However, Dennis and Halse (2008) was used for identification of swampfire (*Sarcocornia perennis* (Mill.) A. J. Scott).

LiDAR Data

LiDAR data for the study area were collected in Coos Bay, OR from August through September

2008. The average pulse density (measure of LiDAR returns) was 8.28 points m^{-2} and the average ground density (measure of ground returns) was 0.69 points m^{-2}. Both first and last return data were recorded, as well as return intensity and ground density information. Bare earth and highest hit grids were delivered in ArcInfo Grid format within 3-ft (0.91 m) pixels. The absolute accuracy of these data was determined by the vendor using 20,024 ground-survey points, primarily in upland regions and on road surfaces. The absolute vertical accuracy (2σ) of the LiDAR data was found to be 0.1 ft (4 cm). The relative accuracy was not reported (Watershed Sciences 2009). Shapefiles of LiDAR flight lines were acquired from the Digital Elevation Model (DEM) included with returns (Watershed Science 2009). By cross-checking flight times against historical tidal observations from the National Oceanic and Atmospheric Administration at Charleston, OR (NOAA 2008), we could estimate tidal height at the time of LiDAR data collection. Although Charleston is 13–18 km from the site, and tidal heights vary across the Coos Bay system, this information served as a useful approximation of tidal height at the time of the LiDAR survey.

Comparison of LiDAR and Field Elevation Data

We calculated LiDAR focal elevation (LFE) for each survey point location to characterize the LiDAR elevation for the corresponding field survey plot. LiDAR focal elevation is the average elevation across the nine 1-m^2 pixels within 1 m of each survey point (the point itself and eight neighboring pixels). Use of focal-elevation data minimizes errors due to georeferencing of the field survey plots with corresponding LiDAR data. We calculated field survey elevation (FSE) by averaging elevations measured from the total station, using each 1-m point and the two neighboring points for each meter point along field survey transects. Averaging of both LFE data and FSE data allowed for better comparison between the two methods. We then compared LFE values against FSE values to assess differences and possible sources of error in the LiDAR data.

Although the LiDAR data were collected in 2008, and our surveys were performed in 2014, data from salt marshes along the Coos Bay Estuary show rates of surface elevation change of only –0.7 to 3.1 mm per year (Schon Schooler, South Slough National Estuarine Reserve, personal communication). For Bull Island near Coos Bay, net accretion rates from soil cores were estimated to be approximately 3.3–3.5 mm per year (Thorne et al. 2015). These data indicate that magnitude of error introduced due to changes in marsh surface elevation between 2008 and 2014 would be less than 4 cm, within the elevational accuracy of the instrumentation.

Statistical Analyses

We used single factor ANOVA to test for differences in mean elevation among the vegetation groups. We then tested for significant differences between means using Tukey's Honest Significant Difference (HSD) *a posteriori* test. The ANOVA and tests for significant differences in elevation were calculated separately for sites at which LiDAR data were acquired at low tide and sites at which LiDAR data were acquired at high tide.

Cluster analysis and non-metric multidimensional scaling (NMS) ordination of the vegetation data were conducted in PC-ORD v. 6.0 (McCune and Grace 2002). We performed data summaries and outlier analysis on the vegetation data set and removed plots identified by the program as outlier plots, leaving 368 plots containing a total of 24 species for use in the cluster analysis. Cluster analysis was conducted on a distance matrix using Euclidean distances and Ward's method for clustering. We selected cutoff heights at the points where at least 60% of the information was explained by the clusters. Data used in the cluster analysis did not include explanatory variables or site attributes; the only data used in the cluster analysis were data on the percent cover for the 24 salt marsh species that occurred within the salt marsh plots. However, attributes of the plots (such as measures of surface elevation, distance along transect, and presence of channels within the plots), were used in the NMS ordination. NMS is a non-parametric ordination method based on ranked distances that uses a distance matrix calculated from the main matrix (here a matrix of species percent cover in the plots) and a second matrix of explanatory variables (for those same plots) to rank and place plots and species along k dimensions (axes). This ordination method begins with a random start and then iteratively searches for positions of entities on axes to minimize the stress of the configuration. "Stress" is a measure of the departure from monotonicity in the relationship between the distance in the original p-dimensional space (here, p = number of species) and distance in the reduced k-dimensional ordination space. Stress values between 10 and 20 are common in ecological data (McCune and Grace 2002); values approaching or exceeding 20 are considered cause for concern.

In our NMS ordination, we used one grouping variable (vegetation group from the cluster analysis) and six potential explanatory variables in the second matrix:

1. Distance along transect
2. LiDAR elevational range within transect
3. LiDAR focal elevation
4. Field survey elevation
5. Presence of channels
6. Distance to road

For the NMS ordination, in order to minimize issues with spurious results that can occur with an overabundance of zero values (McCune and Grace 2002), we retained only species that were found in at least 4% of the plots (a total of 14 species, Table 1). Once low frequency species were removed, several plots no longer had species entries, and those plots were then removed from the ordination analysis. The final NMS ordinations reported here were thus performed on data from 346 plots for the 14 most commonly occurring species. We ran NMS ordinations separately on the sites where flight records and our field surveys indicated that the LiDAR data were acquired at low tide (246 plots) and those where the LiDAR data were acquired at tidal heights of over 2 m (100 plots). The NMS analysis used penalties for ties.

Results

Field Surveys and Transect Profiles

Field survey data confirmed that for several salt marsh sites in the Coos Bay Estuary, the 2008 LiDAR data are inaccurate from the bay's edge up to elevations in the salt marsh between 2.0–2.5 m NAVD88 (depending on the site). These inaccuracies appear to have resulted from acquisition of the LiDAR data at high tide at those sites. From our field survey data, we estimate that the difference between actual elevation of salt marsh plots and LiDAR elevation can be greater than 1 m at the water's edge for several sites (Figure 1, sites 72, 73, 75) and ranges from 0.5–1.0 m for other sites (Figure 1, sites 6, 7, and 89–117). The presence and extent of channel networks within these marshes is also poorly reflected in the LiDAR data, owing to inundation of channels at some sites, and the obscuring of channels by dense vegetation at others.

The elevation profiles generated from the LiDAR data deviated in a set of five consistent patterns from the field survey elevation profiles. These patterns allowed us to create a typology of profiles based on potential types of errors (Table 2, Figure 2, and Supplemental Table S1 [available online]). This typology may assist in accuracy assessment of other pre-existing data sets in which coastal LiDAR data were used to generate DEMs in areas of dense marsh vegetation, or with limited controls on tidal height during data collection. Our results suggest the following with respect to the comparison of our field survey and LiDAR data:

- Profile type a: Profile types in which the difference between LiDAR and field survey surface elevations average less than 0.1 m (Figure 2a), we infer that both of these congruent data sets have similar accuracy. It is also possible that both methods are inaccurate and their similarity simply reflects similar magnitude of error, or offsetting errors.
- Profile type b: Profile types in which the difference between LiDAR and field survey surface elevations average less than 0.2 m, but correlation between the two elevation profiles is lowest of all profile types (Table 2). While the overall

TABLE 1. Frequency of occurrence (as a percent of all plots) and mean and range in elevation (m) for species found in at least 4% of the 346 salt marsh plots used in cluster analysis. Plant species codes are from USDA PLANTS Database (2019). Elevations are extracted from LiDAR digital elevation model (DEM), and in this table include only plots corresponding with LiDAR data collected at low tide, and excluding end-of-transect plots outside the salt marsh. Elevations are reported in orthometric height (NAVD88, relative to GEOID03). Elevation values relative to local tidal elevation at mean lower low water (MLLW) can be estimated by subtracting 0.157 m from the values in this table, based on data from the North Bend tidal station (Station ID 9432895) and the average difference of 0.14 m between LiDAR elevations and reported NOAA benchmark elevations from this LiDAR dataset (Flitcroft et al. 2018).

Species	Common Name	Plant Species Code	Frequency (percent of plots)	Mean Elevation (m)	Elevation Range (m) for all plots	Elevation Range (m) for plots in middle quartiles
Carex lyngbyei Hornem.	Lyngbye's sedge	CALY3	57%	1.96	0.81–3.47	1.64–2.26
Sarcocornia perennis (Mill.) A. J. Scott	swampfire	SAPE	48%	1.90	0.81–2.67	1.54–2.23
Triglochin maritima L.	seaside arrowgrass	TRMA20	46%	1.92	0.81–2.67	1.56–2.22
Distichlis spicata (L.) Greene	saltgrass	DISP	36%	2.07	0.81–3.47	1.94–2.29
Deschampsia cespitosa (L.) P. Beauv.	tufted hairgrass	DECE	30%	2.03	0.81–3.15	1.88–2.30
Jaumea carnosa (Less.) A. Gray	marsh jaumea	JACA4	17%	1.99	0.81–2.59	1.64–2.32
Juncus arcticus ssp. *littoralis* (Engelm.) Hultén	mountain rush	JUARA	13%	1.94	1.35–2.85	1.62–2.22
Agrostis stolonifera L.	creeping bentgrass	AGST2	11%	2.14	0.81–2.80	2.11–2.40
Grindelia stricta D. C. var. *stricta*	Oregon gumweed	GRST3	11%	2.46	1.48–3.32	2.39–2.56
Atriplex patula L.	spear saltbush	ATPA4	10%	2.20	1.28–3.15	2.03–2.47
Argentina egedii (Wormsk.) Rydb.	Pacific silverweed	AREG	8%	2.35	1.20–3.15	2.33–2.56
Schoenoplectus americanus (Pers.) Volkart ex Schinz & R. Keller	chairmaker's bulrush	SCAM6	6%	1.81	1.36–2.52	1.49–2.05
Cuscuta salina Engelm.	saltmarsh dodder	CUSA	6%	1.93	0.81–2.41	1.89–2.18
Glaux maritima L.	sea milkwort	GLMA	4%	2.15	1.28–2.52	2.18–2.34

TABLE 2. Attributes of each profile type and potential sources of error for elevation profile discrepancy. Column 2: mean (range in parentheses) of the difference in elevation between LFE (LiDAR focal elevation) and FSE (field survey running average elevation). Column 3: mean (range in parentheses) of correlation coefficients for profiles of each type. Columns 4 and 5 note potential sources of error for elevation profiles.

Profile Type	LFE-FSE (m)	Correlation between LFE and FSE Profiles	LiDAR acquired when Tidal Level > 2 m	Profiles differ at channels, logs, tall vegetation
a	0.05 (−0.03 to 0.12)	0.93 (0.86 to 1.00)	No	No
b	0.16 (0.08 to 0.29)	0.41 (0.04 to 0.82)	No	Yes
c	−0.03 (−1.61 to 1.28)	0.83 (0.24 to 0.99)	No	Occasionally
d	0.97 (−0.31 to 1.57)	0.72 (0.40 to 0.91) *0.91 (0.90 to 0.97)	Yes	No
e	0.50 (0.06 to 1.25)	0.67 (0.35 to 0.93) *0.69 (0.35 to 0.99)	Yes	Yes

*when data are corrected for plots inundated at high tide

slope and elevation of LiDAR and field survey transects for profiles of type b are similar, only field surveys identified the small channels present (Figure 2b), resulting in lower correlation between the two types of surveys. We infer that the field surveys are more accurate with respect to local microtopography. It is also possible that both methods are inaccurate (as described for profile type a above).

- Profile type c: Where the slopes of LFE and FSE profiles are highly correlated but absolute elevations are offset (Figure 2c), we infer that LiDAR data have higher global accuracy, and field survey data differ due to poorer vertical accuracy for the anchor point of the data.
- Profile types d and e: Where LFE and FSE profiles differ in both slope and elevation (Figure 2d and 2e), accuracy of LiDAR may be impaired by tidal inundation and/or dense vegetation or logs (also seen in some profiles of type c).

At these sites in Coos Bay Estuary, field survey data can help identify areas of the marsh in which the LiDAR data appear to be inaccurate and provide estimates of the magnitude of that inaccuracy.

Vegetation Community Analysis and Ordination

Once outlier plots (primarily end-of-transect plots along the edge of the marsh containing upland species such as Sitka spruce (*Picea sitchensis* (Bong.) Carrière) and salal (*Gaultheria shallon* Pursh) were removed from the data set, a total of 47 species remained that were present in salt marsh plots. The complete list of species occurring in the salt marsh plots is included as Supplemental Table S2 (available online).

Cluster analysis identified six vegetation groups whose vegetation attributes are listed in Table 3. Vegetation groups defined by cluster analysis also tended to separate into well-defined groups along the NMS ordination axes in species space, with the exception of the plots in vegetation Group C, which overlapped the other cluster groups. For the three-dimensional NMS solution of all plots where LiDAR were flown at low tide, the final stress = 19.62, instability = 0.00161. The three-dimensional NMS solution of all plots for which LiDAR were flown at high tide was similar to that for the low tide plots, final stress = 17.68, instability = 0.0008. The strongest explanatory variable was LiDAR Focal Elevation in both the high tide and low tide NMS ordinations.

On average, the 1-m x 1-m plots contained about four species (Table 3). The greatest species diversity occurred in plots of Groups E and B, in which an average of 5.9 and 4.9 species were found, respectively. The Shannon-Weiner index of diversity (H) was 1.23 for Group E, and 1.17 for Group B. Average species richness per plot in Groups A, C, and F ranged from 3.1 to 4.3, with H ranging from 0.67 to 0.92 in these groups. Lowest diversity was found in plots of Group D, which tended to be dominated by a single species (e.g., Lyngbye's sedge with an average cover percent of more than 70%). Plots in this group had the

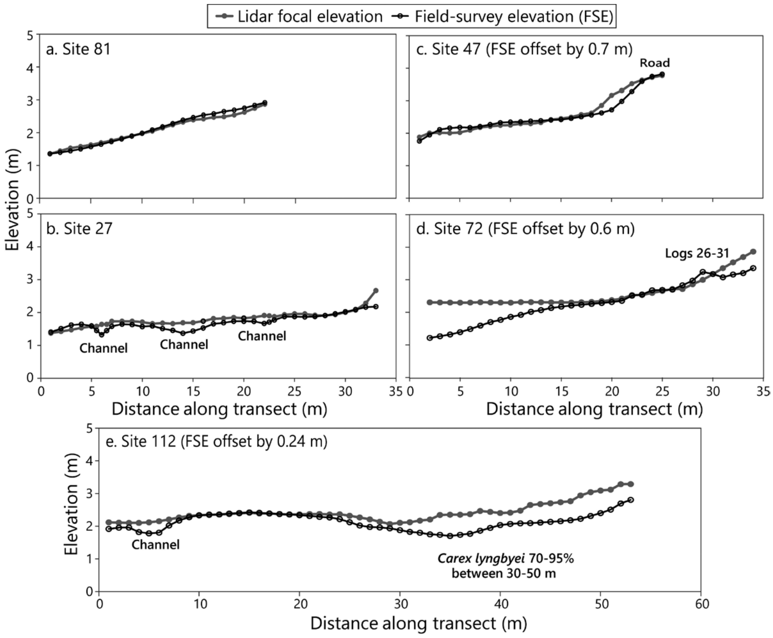

Figure 2. Transect profile comparisons for five sites illustrating the different profile types described in Table 2. Profiles compare LiDAR focal elevation (LFE) with field survey running average elevation (FSE) for transect 1 at each site. Elevations (m) are in NAVD88 datum.

TABLE 3. Attributes of each vegetation group identified by cluster analysis.

	Vegetation Group					
	A	B	C	D	E	F
Total species (S)	21	17	24	16	15	18
Average species per plot	3.9	4.9	3.1	2.8	5.9	4.3
Evenness (E)	0.71	0.76	0.55	0.40	0.70	0.54
Shannon-Weiner index (H)	0.92	1.17	0.67	0.50	1.23	0.78
Number of plots	54	34	149	68	36	27

lowest average number of species per plot (2.8) and the lowest Shannon-Weiner index (H = 0.5).

Table 4 shows the mean and range of elevations (m) for plots in each of the vegetation groups, and Table 5 presents the average percent cover of the most frequently occurring marsh species for each group. Group A was associated with high cover abundance values for low marsh species such as swampfire , interspersed with seaside arrowgrass (*Triglochin maritima* L.) and species such as salt sandspurry (*Spergularia salina* J. Presl & C. Presl) and common brassbuttons (*Cotula coronopifolia* L.). Group B had the highest abundance of saltgrass and marsh jaumea (*Jaumea carnosa* (Less.) A. Gray). Group C was associated with a relatively diverse set of several common marsh species, including Lyngbye's sedge, mountain rush (*Juncus arcticus* ssp. *littoralis* (Engelm.) Hultén) and seaside arrowgrass. In contrast, plots in Group D all had more than 70% cover of Lyngbye's sedge. The plots in Group D were often found in sites that had been intensively disturbed, including visible evidence of hydrologic modifications. For example, site 147 (Figure 1) had clearly been graded at some point, with berms on all sides which shaped the site into a rectangle. Group E was associated with high percent cover of tufted hairgrass. High marsh species such as Oregon gumweed were associated with Group F.

Lyngbye's sedge was the most common species (occurring in 57% of plots), followed by swampfire (48% of plots) and seaside arrowgrass (46% of plots) (Table 1). Plots in Group C tended to have several species with moderate cover abundance, rather than a single dominant species. Species characterizing Group C included Lyngbye's sedge, mountain rush, and seaside arrowgrass, species which also occurred in other vegetation groups. The highest diversity (Shannon-Weiner index > 1) was found in Group B and Group E, whereas the highest species richness occurred in Group A

TABLE 4. Elevation in meters (NAVD88) as calculated from LiDAR Focal Elevation for plots in each vegetation group (and Group C subgroups) identified by cluster analysis (excluding plots with large logs). Mean elevations that are not significantly different at the 5% level are shown with the same lower-case letter. For sites in which LiDAR was flown at low tide, the mean elevations for plots with high marsh vegetation are significantly different from those for low marsh vegetation. For sites flown at high tide, mean elevation of plots in different vegetation groups do not differ, since LiDAR returns are from the water rather than the marsh surface.

		Low Tide Plots			High Tide Plots		
Vegetation Group	Marsh Vegetation Descriptor	Mean Elevation (SD)	Elevation Range	*n*	Mean Elevation (SD)	Elevation Range	*n*
A	low	1.74[a] (0.41)	1.16–2.65	45	2.33 (0.24)	1.80–2.77	9
B	low	1.91[ab] (0.39)	0.97–2.40	20	2.31 (0.14)	1.73–2.62	14
C	mid	2.01[ab] (0.48)	0.81–3.12	91	2.37 (0.28)	1.87–3.08	44
C-1	mid	1.79[a] (0.32)	1.36–2.21	16	2.35 (0.28)	2.16–2.97	7
C-2	mid	1.85[ab] (0.34)	1.35–2.24	10	2.30 (0.13)	2.14–2.63	13
C-3	mid	1.97[ab] (0.45)	0.81–2.60	50	2.27 (0.27)	1.87–2.94	15
C-4	high	2.51[c] (0.49)	1.35–3.12	15	2.67 (0.38)	2.21–2.94	9
D	mid	1.99[ab] (0.40)	1.15–3.47	44	2.24 (0.23)	1.96–3.09	24
E	mid to high	2.21[bc] (0.20)	1.53–2.49	27	2.40 (0.10)	1.86–2.57	9
F	high	2.57[c] (0.27)	2.16–3.15	13	2.59 (0.13)	2.41–2.81	14

TABLE 5. Average percent cover of key species by cluster analysis vegetation group (species codes as in Table 1). Plots in Group C have been sub-divided here into sub-groups C1 to C4 to help illustrate the heterogeneity within the group, and differences in percent cover among sub-groups. Values in shaded cells highlight where average percent cover for a species within that group or sub-group is 9% or more.

GROUP	AGST2	AREG	CALY3	DECE	DISP	GRST3	JACA4	JUARA	SAPE	SCAM6	TRMA20
A	0.7	0.1	5.1	5.3	4.3	0.9	1.0	0.2	34.4	0.1	4.5
B	2.6	0.0	6.4	2.5	32.1	1.0	14.8	4.1	8.6	0.3	4.1
C-1	0.0	0.2	1.5	0.0	0.4	0.0	0.0	0.0	0.0	30.9	0.2
C-2	1.6	0.0	2.7	3.3	3.6	0.0	0.9	38.9	5.8	0.2	2.8
C-3	3.0	0.3	19.8	4.2	2.7	0.3	1.4	0.1	6.8	0.1	11.5
C-4	9.6	7.5	0.1	0.1	0.4	0.0	0.4	0.4	0.0	0.0	0.8
D	0.9	0.0	70.5	2.7	5.4	0.0	0.2	0.8	1.8	0.3	3.3
E	1.2	0.2	8.7	43.8	6.0	2.7	3.4	1.4	5.7	0.0	7.4
F	2.0	1.7	2.1	2.4	1.1	48.9	0.7	0.9	1.0	0.0	0.9

and Group C, with 21 and 24 species, respectively (Table 3). The plots in Group D had the lowest diversity, lowest average number of species per plot, and the lowest evenness score, owing to the exceptionally high cover of just one species, Lyngbye's sedge, in the plots of this vegetation group (Tables 3, 4). The relatively high within-group diversity identified by the NMS led us to subdivide plots in Group C into four sub-groups based on the most abundant species in the plot, information about these sub-groups are included in Tables 4 and 5.

Relationship Between Elevation and Vegetation Type

Mean elevation and range in elevation were calculated based on LiDAR Focal Elevation for plots in each group (Table 4), and illustrate differences in elevation range among several groups. To reduce error introduced by the presence of logs in the plot, plots in which large logs occurred were excluded from the data set for these calculations.

At the sites where LiDAR data were acquired at low tide, the mean elevation for high marsh plots (2.21 m and 2.57 m for Groups E and F, respectively) were significantly higher than for plots with low marsh vegetation (1.74 m and 1.91 m for Groups A and B, respectively) and mid-marsh vegetation (2.01 m and 1.99 m for Groups C and D, respectively). Mean elevations for plots in the sub-groups of vegetation group C (except for subgroup C-4) are similar to those for vegetation groups A, B, C, and D, with mean elevation for subgroups C-1, C-2, and C-3 ranging from 1.79 to 1.97 (Table 4). Plots in subgroup C4, characterized by high percent cover of *Agrostis,* tended to occur at the end of the transects and have a mean elevation that is not significantly different from mid to high marsh Group E and high marsh Group F, which are characterized by high percent cover of tufted hairgrass (DECE) and Oregon gumweed (GRST3), respectively.

Low marsh plots (Groups A and B) are characterized by abundance of swampfire, saltgrass, and marsh jaumea (Table 5) and low elevations (Table 4). These vegetation types tended to occur in plots near the bayside edge of the marsh and along channels, and are thus the plots most frequently inundated by the tide. High marsh plots, characterized by Oregon gumweed (Group F), and creeping bentgrass (*Agrostis stolonifera* L.) (Group C-4) often occurred at the edge of the sites nearest the upland, with mid and mid to high marsh plots (Groups D and E, respectively) in between. Figure 3 shows a plot of percent cover vs. elevation for a low marsh species (swampfire) and high marsh species (Oregon gumweed) in the low tide plots.

Although Lyngbye's sedge was the most abundant species in both Groups C and D, average cover of Lyngbye's sedge in Group C plots was less than 50%, with other species making up significant portions of the remaining cover, whereas in plots of vegetation for Group D, Lyngbye's sedge made up more than 70% of the plot cover, and was often the only species present. Figure 4 illustrates this difference between the vegetation groups, with Group D dominated by Lyngbye's sedge, and Group C a mixture of sedge, mountain rush, and seaside arrowgrass. The difference in the nature of vegetation in Group D, in which Lyngbye's sedge is a dense monoculture, and plots in all other vegetation groups, in which this species is a minor but frequent component of the vegetation, highlight the usefulness of both analyses of individual species ranges and the added information provided by examining species assemblages as well as individual species occurrences.

For sites flown at high tide, results of single factor ANOVA indicated that none of the vegetation groups differed with respect to estimated mean elevation for plots in the group. We interpret this result as indication that for sites flown at high tide, LiDAR returns are from the top of the water rather than the marsh surface. Owing to these inaccuracies, use of LiDAR data from these sites would have made it difficult to identify the significant differences in average plot elevation among vegetation groups (Table 4). These results highlight the importance of using our typology of error to identify sites at which error in the LiDAR data would introduce significant error in the estimation of the mean elevation associated with the different vegetation types.

Vegetation Height

Average heights of dominant species in vegetation plots ranged from 15 cm for marsh jaumea to 64 cm for Lyngbye's sedge (Table 6). Vegetation heights of species associated with low marsh groups were among the lowest measured, including saltgrass with an average height of 22 cm, and swampfire with an average height of 31 cm. Mid-marsh species were dominated by tall stands of Lyngbye's sedge of variable height (average height 64 cm, SD = 21 cm). Oregon gumweed, a high-marsh species, averaged 43 cm in height.

Discussion

Vegetation Communities

Through analysis of vegetation patterns and topography, we found salt marsh communities that varied across elevational gradients. We were able to identify average elevations associated with the different vegetation groups and distinguish low marsh (vegetation groups A and B) from high marsh plots (Group F) in salt marshes of the Coos Bay Estuary (Table 4). Previous studies of salt marsh vegetation in the Oregon coastal region have also investigated the relationships between salt marsh vegetation and environmental conditions. Jefferson (1974) identified six vegetation types based on elevation and substrate (silt or sand) and 29 species assemblages/communities within those types that characterized the Oregon salt marshes she studied. By identifying sources of error in the LiDAR data, we were able to use the more accurate data to distinguish relationships between plot elevation and salt marsh vegetation types (Tables 4, 5) which would have been obscured had we included the sites that were inundated at the time of LiDAR acquisition. Several groups and subgroups identified in our study are equivalent to those identified by Jefferson (1974):

Group A: Low Silt Marsh *Salicornia-Triglochin* and *Salicornia-Cotula*

Group B: Low Sand Marsh, *Jaumea-Salicornia-Distichlis*

Group C-1: Low Sand Marsh, *Scirpus americanus* (now *Schoenoplectus americanus*)

Group C-3: Immature High Marsh, *Carex-Salicornia-Triglochin maritimum*

Group D: Sedge Marsh, *Carex lyngbyei*

Group E: Low Silt Marsh, *Deschampsia-Carex-Triglochin maritimum*

Our Groups C-2 (dominated by mountain rush), C-4 (with high percent cover of creeping bentgrass), and Group F (dominated by Oregon gumweed) do not have an analog among Jefferson's

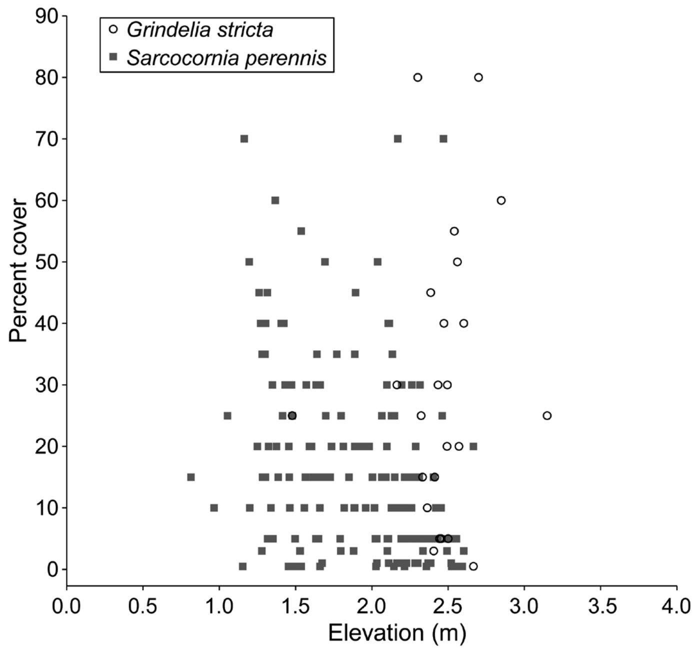

Figure 3. Percent cover and elevation (NAVD88, m) of *Sarcocornia perennis* and *Grindelia stricta* in salt marshes of the Coos Bay Estuary. Data reported here are from sites where LiDAR was flown at low tide.

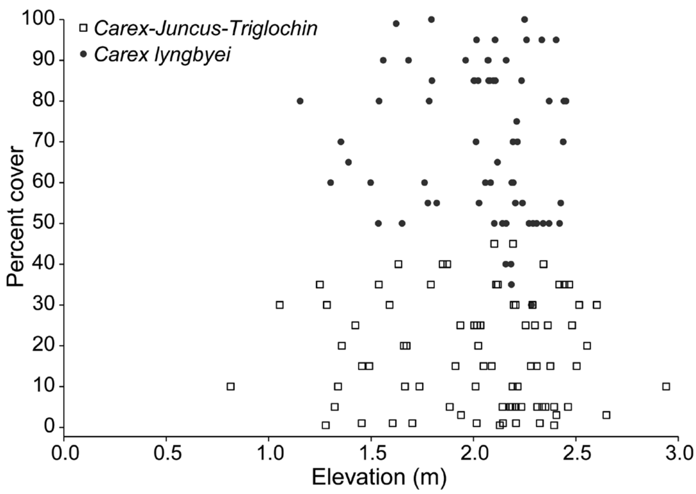

Figure 4. Percent cover and elevation (NAVD88, m) of *Carex lyngbyei* in plots of vegetation group C (open squares), in which several species co-occur with Lyngbye's sedge, and in vegetation group D (filled circles), which are nearly monocultures of the sedge. Data reported here are from sites where LiDAR was flown at low tide.

TABLE 6. Average height (cm) and standard deviation (in parentheses) calculated across all plots for dominant species (those with > 25% cover in the plot) in vegetation plots.

Species Name	Common Name	Height (SD)	*n*
Carex lyngbyei Hornem.	Lyngbye's sedge	64 (21)	124
Deschampsia cespitosa (L.) P. Beauv.	tufted hairgrass	50 (12)	49
Distichlis spicata (L.) Greene	saltgrass	22 (12)	42
Grindelia stricta D.C. var. *stricta*	Oregon gumweed	43 (12)	29
Jaumea carnosa (Less.) A. Gray	marsh jaumea	15 (6)	19
Juncus arcticus ssp. *littoralis* (Engelm.) Hultén	mountain rush	49 (15)	34
Sarcocornia perennis (Mill.) A.J. Scott	swampfire	31 (10)	70
Triglochin maritima L.	seaside arrowgrass	50 (15)	28
Schoenoplectus americanus (Pers.) Volkart ex Schinz & R. Keller	chairmaker's bulrush	49 (8)	11

(1974) communities, however, others have identified vegetation types with high percent cover of Oregon gumweed as characteristic of high marsh (Janousek et al. 2018, Weilhofer et al. 2013).

Weilhofer et al. (2013) used regression tree analysis and NMS to identify two groups of marsh-site types, oceanic and mixed, in their studies of 50 sites along the Oregon coast. They used soil chemistry and salinity rather than surface elevation as key explanatory variables, and found that the plant communities in the sites they studied were most closely correlated with salinity gradients and soil chemistry within the sites, and with vegetation adjacent to the sites, rather than with land cover at the scale of the surrounding watersheds. Frenkel et al. (1981) investigated the tidal datum for the upper limit between salt marsh vegetation and adjacent uplands, but did not distinguish specific elevations for transitions between different plant communities within the marsh.

Janousek et al. (2018) identified the elevation ranges for the fourteen most common species in salt marshes of the Pacific coast, noting that these elevation ranges and even rank order varied across sites for some species. As in our study, they found Oregon gumweed associated with high marsh, and Lyngbye's sedge occupying a broad range of elevations within the sites. In their study, saltgrass was also found over a relatively broad range of elevations and was not consistently associated with the low marsh plots as it was in our study and that of Weilhofer et al. (2013). In our low marsh sites, as with the oceanic sites identified by Weilhofer et al. (2013), vegetation in plots that are more frequently inundated differ from the vegetation in plots that are rarely inundated, and/or those which receive freshwater inputs from the adjacent upland (mixed or high marsh sites).

Vegetation types are also related to vegetation height. The species commonly found in vegetation types that occur close to the water's edge in the sites we studied (saltgrass, swampfire, marsh jaumea, sea milkwort [*Glaux maritima* L.]) tend to be shorter in height (average heights ranging from 15–31 cm) than species occurring in mid-marsh or high marsh (Table 6). Any error introduced as a result of LiDAR returns off the top of low marsh vegetation would thus be on the order of 15–30 cm. Mid-marsh communities, such as Group D, with an average of 71% cover of Lyngbye's sedge and Group E, with an average of 44% cover of tufted hairgrass, and high marsh communities such as Group F, dominated by Oregon gumweed (average cover of 49%) tend to have much denser vegetation (plots ranged from 70–100% vegetation cover). These vegetation types are also dominated by taller species (average height 43–64 cm). Thus, there is greater potential for error in LiDAR elevation data for mid-marsh communities such as Group D, owing to returns off the top of these dense stands of Lyngbye's sedge.

In addition to the influence of elevation and tidal inundation on vegetation also reported by others (Weilhofer et al. 2013, Janousek et al. 2018), we noted an influence of disturbance at many of our sites; sites that had hydrologic alterations or evidence of intense disturbance tended to favor the occurrence of vegetation dominated by high percent cover (> 50%) of Lyngbye's sedge, plots of Group D. This influence of disturbance on salt marsh vegetation was also found for restored salt marshes in the Salmon River Estuary (Chellew 2017), where sites that had been heavily disturbed prior to restoration, (and were the most recently restored), were characterized by dense stands of Lyngbye's sedge ranging from 90–100% cover. Not only elevation and inundation patterns, but also disturbance and time since restoration are key determinants of vegetation at restored salt marsh sites. This is important information for restoration planning. Maintaining sufficient spatial extent of salt marsh sites that include the range of vegetation communities will require anticipatory planning and action, since it may take several decades to establish diverse salt marsh vegetation types in restored sites that will be within the appropriate tidal ranges for supporting diverse salt marsh vegetation communities in the future.

Comparison of LiDAR and Field Survey Elevation Data

The LiDAR data collected in 2008 were obtained by a consortium for the purpose of coastal hazard mapping for road and infrastructure planning. Although highly accurate for their primary purposes, we found problems in LiDAR elevation accuracy within the Coos Bay Estuary that indicate some systematic inaccuracies of the data. These sources of error should be considered in elevation mapping, vegetation and habitat mapping, sea-level rise modeling, restoration planning and other applications. Other investigators have found similar issues with LiDAR accuracy. For example, Chassereau et al. (2011) found LiDAR ineffective at modeling tidal channels (similar to the error characterized by our profile type b). McClure et al. (2015) and Hladik and Alber (2012) studied marshes along the coast of the southeastern US, and found vertical error along transects corresponding with different species, similar to those we identified in our profile type c, and which may reflect the presence of dense vegetation. For example, Ewald (2013) found an average 48.8 cm discrepancies between field elevation and LiDAR in *Carex lyngbyei* patches in Oregon salt marshes. Flitcroft et al. (2013) found varying tidal heights in Oregon LiDAR data, evidence that support our inference that some of the error in LiDAR data from 2008 (e.g., profile type d and e) is the result of LiDAR acquisition at high tide.

Because the LiDAR data for Coos Bay Estuary were collected during the late summer and early autumn, when salt marsh vegetation is both dense and at its tallest, dense vegetation may also have interfered with LiDAR accuracy—artificially increasing the estimated height of the ground surface. Inaccuracies in the LiDAR data owing to the presence of dense vegetation are more difficult to identify and quantify than the presence of high water. However, discrepancies between the LiDAR and field survey data at some sites suggest that in some areas, the LiDAR point returns are coming from the top of dense stands of Lyngbye's sedge (averaging 64 cm tall), which tend to occur in the mid-marsh (Figure 2, panel e). Elevation errors due to vegetation are likely to be lower near the bayside edge of the marsh since shorter species (saltgrass and swampfire) are dominant at low-marsh sites.

The influence of different vegetation communities on LiDAR accuracy has also been described by other researchers. For example, Fernandez-Nuñez et al. (2017) found that community composition directly affected LiDAR accuracy in Spain and offered correction factors based on vegetation types. Hladik and Alber (2012) applied species-specific correction factors to improve the accuracy of LiDAR DEMs in Georgia, USA. Ewald (2013) found elevation bias in LiDAR-derived ground-surface elevations associated with a diversity of vegetation types in Oregon tidal marshes, a finding consistent with our field survey results.

We identified numerous sites where tidal inundation confounded the collection of accurate surface elevation data in low- to mid-marsh environments (Table S1). Owing to the potential for inaccuracies in LiDAR elevation data from both dense vegetation and tidal height, care should be taken when using historical salt marsh surface elevation data developed from LiDAR. At several sites, the 2008 LiDAR data acquired for Coos Bay Estuary identified the marsh surface at about 1 m higher than it actually is for bayside locations, thus underestimating the risk to these salt marshes from sea-level rise. Inaccurate data (as much as 1.2 m for some areas we surveyed) can affect both current modeling efforts and future studies of change over time. Future comparisons of the marsh surface between the LiDAR data acquired in 2008 and more recent or future LiDAR would reflect not only real changes, but also differences due to error in the historical coverage.

Fine-resolution surface elevation information can be particularly informative for marsh systems, where small variations in marsh surface topography can exert considerable influence on numerous biophysical processes including vegetation colonization, fish access, tidal channel development, and vertical accretion (Cornu and Sadro 2002). Additional ground-surface control points implemented at the time of LiDAR data collection would facilitate higher accuracy and stronger predictive ability directly along the coastal margin. Newer methods and instrumentation, and careful timing of LiDAR acquisition at the coastal margin can minimize the sources of error identified in our study. For example, Buffington et al. (2016) use the LEAN-LiDAR Elevation Adjustment method based on remote-sensing of normalized difference vegetation index (NDVI) and vegetation analyses associated with real time kinematic (RTK)-GPS derived field survey points. Other techniques include minimum-bin gridding (Schmid et al. 2011, Ewald 2013) as well as statistically-based corrections (specifically for full waveform LiDAR) (Parrish et al. 2014). However, when it is necessary to use LiDAR data that have been collected in the past under less than ideal conditions, the field survey methods such as those described here can help identify areas of the marsh inundated at the time of data acquisition.

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