PORTfolio

PORTfolio Carbon Sequestration Assessment

Prepared on behalf of:

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Executive Summary

This report evaluates the potential for the Port of Seattle PORTfolio Restoration Plan projects in the Lower Duwamish River (LDR) and Elliott Bay to contribute to the Port's strategic goal of becoming carbon neutral by the year 2050. The PORTfolio Restoration Plan includes 19 potential fish and wildlife habitat restoration sites in the LDR and Elliott Bay, combining for a total of over 90 acres of habitat restoration. This report identifies potential carbon sequestration benefits resulting from riparian and aquatic habitat restoration.

This report evaluates peer-reviewed environmental studies and technical information relating to carbon sequestration rates in habitat types important to potential PORTfolio projects, including:

- Riparian vegetation;
- Intertidal marsh vegetation;
- Un-vegetated intertidal substrate, including shellfish beds;
- Shallow subtidal aquatic area, including un-vegetated substrate and eelgrass beds; and
- Deep subtidal habitat, including un-vegetated substrate and kelp beds.

Using regionally relevant information, the report derives estimated rates of carbon sequestration for each habitat type. In general, carbon sequestration in aquatic and riparian habitats occurs when carbon in above- and below-ground biomass is either retained in the organism itself, in the soils and sediments on-site, or exported and sequestered off-site; or alternatively, when carbon from off-site sources accumulates and is buried in aquatic area sediments or upland soils.

Available literature and technical data indicate that vegetated intertidal habitats have substantial carbon sequestration capacity, with rates similar to the well documented and recognized benefits of upland riparian forest habitats (0.98 tC/ac/yr for intertidal marsh and 1.08 tC/ac/yr for riparian forest). Other estuarine habitats are also documented as contributing to carbon sequestration, but at lower rates ranging from 0.18 tC/ac/yr for un-vegetated subtidal habitats to 0.36 tC/ac/yr for subtidal kelp habitats.

Based on estimated sequestration rates for each habitat type in the LDR and Elliott Bay and proposed restoration areas in the PORTfolio Restoration Plan, the combined habitat projects included in the PORTfolio are expected to sequester 33.74 tC/yr. This carbon sequestration benefit would offset approximately 124 tCO_2 emitted per year, or the equivalent of roughly 13,953 gallons of gasoline consumed per year. This finding demonstrates that PORTfolio restoration projects will have a positive sequestration benefit and contribute to the Century Agenda carbon-neutral goal.

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Acronyms and Abbreviations

ac	Acre
C	Carbon
cfs	Cubic feet per second
CH_4	Methane
cm	centimeter
CO_2	Carbon dioxide
ft	foot
ha	Hectare
HEA	Habitat equivalency analysis
lb	Pound
LDR	Lower Duwamish Waterway
LWD	Large woody debris
MLLW	Mean lower low water
N_2O	Nitrous oxide
NPP	Net primary production
ppt	Parts per thousand
t	Metric tons
yr	year

1 Introduction

The Port of Seattle's (Port) Century Agenda establishes strategic objectives, including reduction of direct greenhouse gas emissions from Port-owned and controlled sources, with the goal of becoming carbon neutral by the year 2050. The Century Agenda also proposes to restore, create, and enhance 40 acres of habitat in the Green-Duwamish watershed and Elliott Bay. The Port is developing a PORTfolio Restoration Plan to restore estuarine natural resource values important to migratory and resident fish and wildlife at Port-owned or controlled properties in the Lower Duwamish River (LDR) and Elliott Bay, as well as at sites acquired by the Port or managed in coordination with other property owners in the mid-reaches of the Green-Duwamish watershed.

Recent environmental evaluations and emerging technical understanding of carbon cycling in riparian, wetland, and aquatic area habitats indicate that restoration of estuarine and marine natural resource functions may provide important coincident carbon sequestration benefits. The purpose of this report is to interpret recent scientific literature and apply carbon sequestration data to estimate potential carbon sequestration benefits associated with PORTfolio restoration projects.

1.1 Overview of PORTfolio Restoration Plan

This PORTfolio Restoration Plan details over 90 acres of potential habitat restoration on 19 sites throughout the LDR, including the East and West Waterways, and Elliott Bay.

The 19 PORTfolio projects are located on Figure 1 and listed below with their corresponding acreages:

- Terminal 117 (14.06 acres)
- Terminal 25 South (8.99 acres)
- South Park (2.47 acres)
- Turning Basin 3 (3.46 acres)
- Terminal 5 North (3.93 acres)
- Terminal 18 (2.47 acres)
- Terminal 5 Southeast (1.58 acres)
- Terminal 104 (0.30 acres)
- Terminal 105 (7.61 acres)
- Terminal 108 (3.90 acres)
- Terminal 107 (9.12 acres)
- Terminal 115 (2.64 acres)
- Terminal 10 (2.03 acres)
- Slip 27 (0.35 acres)
- Terminal 102 (1.78 acres)
- Terminal 106 (0.40 acres)

- Pier 34 (0.55 acres)
- Rhone-Poulenc (0.01 acres)
- Terminal 91 (24.98 acres)

These projects involve a range of past and future restoration actions, including the removal of overwater structures to daylight shaded aquatic and intertidal habitat; cleanup of historical industrial debris and removal of fill material; restoration of intertidal marsh, mudflat, shellfish beds, subtidal eelgrass, and kelp habitats; and riparian plantings. Together the PORTfolio projects will exceed the Port's Century Agenda goal for habitat restoration; this report describes how these projects will contribute to the Port's carbon neutral goal.

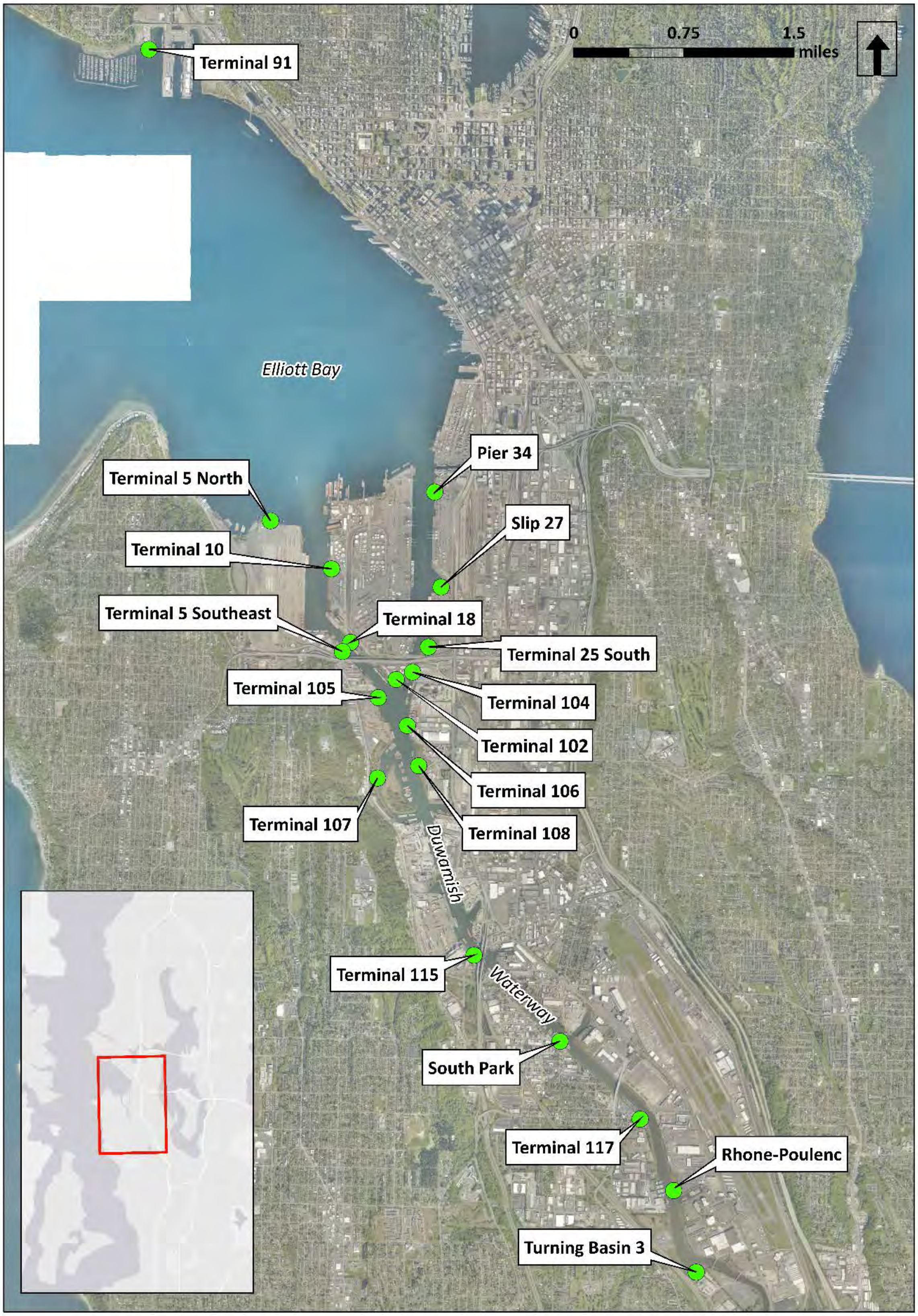

Figure 1. Map of PORTfolio projects.

2 Methods

2.1 Literature review and selection

The PORTfolio Restoration Plan includes 19 potential fish and wildlife habitat restoration sites in the LDR and Elliott Bay, combining for a total of over 90 acres of habitat restoration. PORTfolio habitat sites make use of restoration techniques successfully applied in previous fish and wildlife habitat projects, including removal of structures and debris, removal of fill material, installation of native intertidal marsh and riparian vegetation, and improvement of subtidal algal and plant habitat areas. The review focused on technical information analyzing and evaluating carbon sequestration by habitat types important to potential PORTfolio projects, including:

- Riparian vegetation;
- Intertidal marsh vegetation;
- Un-vegetated intertidal substrate, including shellfish growth;
- Shallow subtidal aquatic area, including plant and algal growth and un-vegetated substrate; and
- Deep subtidal habitat, including algal growth and un-vegetated substrate.

Specifically, the review focused on deriving estimates for annual, per-unit-area rates of carbon sequestration for each of these habitat types. This review did not attempt to quantify the "life cycle" emissions of each habitat or PORTfolio project, accounting for example for indirect emissions associated with construction materials and activity, foregone Port industrial activity, or maintenance over the life of the project. Instead, the review approach aligns with the habitat valuation method used for PORTfolio projects, which focuses on post-construction acreages of restored habitat.

The investigation included review of peer-reviewed primary literature sources, interviews with sequestration experts, and a comparative assessment of existing conditions in the LDR and Elliott Bay. All sources of information were evaluated for relevance, currency, and reliability.

Carbon cycling and carbon sequestration in marine and estuarine systems has received increased attention and technical investigation in recent years. Scientific understanding of the importance of carbon captured and stored in marine, nearshore, and coastal systems – often referred to as "blue carbon" – has progressed significantly over the past 20 years. This review relies on the most current, applicable studies, presenting more precise data and findings with fewer broad assumptions.

Carbon sequestration data for natural or restored habitats may vary widely across regions, species, and even within sites. Where available, regionally derived data were used to represent environmental conditions and species assemblages most similar to those likely to occur at Port restoration sites. Where regionally relevant findings were available but not yet peer-reviewed, those findings are presented with reference to the range of peer-reviewed findings available from other sources. Additionally, limited field assessments in the LDR were conducted to confirm comparisons of the LDR to other regional findings (see discussion of tidal marsh habitats in Section 3.3).

Regardless of the source, this review explicitly considers the relevance and applicability of key data to the Port's planned restoration activities and to the LDR and Elliott Bay. Where literature sources were not available to address certain considerations, those issues are identified as data gaps.

2.2 Application to the PORTfolio

Each PORTfolio project is designed to restore, enhance, ore create maximum possible natural resource values and functions, within the hydrodynamic and physical context of each site. Natural resource values and functions are measured using the Habitat Equivalency Analysis (HEA) model, an analytical tool designed to estimate the value of a restoration project in terms of its ecological services. HEA methods use five habitat types or zones based on elevation, substrate, and cover, described below:

- **Riparian** habitat occurs at an elevation of +12 feet mean lower low water (MLLW) or higher and contains a mixture of native deciduous and conifer trees and understory vegetation. Restoration of riparian habitat may include elimination of invasive species, removal of existing top-of-bank armoring, rubble fill, and impervious surfaces, re-grading, installation of drainage improvements, placement of beneficial soils/mulch, and planting native vegetation (Figure 2). Riparian slopes in PORTfolio projects are typically stabilized with a continuous top-of-bank band of anchored large woody debris (LWD), often embedded in a concealed subgrade rock bolster.
- **Intertidal marsh** includes both low estuarine marsh that occurs between +8 and +10 feet MLLW in the LDR and high estuarine marsh that occurs between +10 and +12 feet MLLW. Both low and high marsh habitats experience regular tidal inundation and are vegetated with native vascular plants (Figure 2). Marsh creation at PORTfolio sites includes placement of embedded LWD to increase habitat complexity and help stabilize the planting substrate.
- **Intertidal mudflat** occurs within the tidal range of -4 and +12 feet MLLW. This habitat type is characterized by relatively shallow grades and un-vegetated silt/clay to fine sand substrate (Figure 3). In PORTfolio projects, this habitat type may be bordered by intertidal marsh or adjacent to riparian habitat. Intertidal mudflat habitat at PORTfolio projects located in more marine environments, such as Terminal 91, may also be enhanced with native shellfish, including oysters, clams, and mussels.
- **Shallow subtidal** habitat occurs within the elevation range of -4 to -14 feet MLLW, with slopes ranging from 3:1 to 20:1. Un-vegetated shallow subtidal habitat in PORTfolio projects is not directly modified, but benefits from restoration actions on adjacent,

upslope habitats, including intertidal mudflat, intertidal marsh, and riparian habitat. PORTfolio projects located in more marine environments, including Terminal 91 and Terminal 25 South, may include shallow subtidal areas enhanced with imported fine sediment substrate and planted with native eelgrass.

- **Deep subtidal** habitat occurs below the elevation of -14 feet MLLW and may extend waterward to the river thalweg or to the center of the federal navigation channel. Like shallow subtidal habitat, un-vegetated deep subtidal habitat is not directly modified, but benefits from restoration actions on upslope habitats. PORTfolio projects located in more marine environments, namely Terminal 91 and Terminal 25 South, include deep subtidal areas enhanced with appropriate holdfast substrate and "planted" with bull kelp.

Figure 2. Restoration at Terminal 107, northwest perspective, illustrating restored conditions with established intertidal marsh and riparian vegetation in formerly un-vegetated and invasive plant area.

Figure 3. Intertidal mudflat, southwest perspective, between Terminal 107 and Kellogg Island, illustrating restored riparian vegetation at right, but without intertidal marsh vegetation.

PORTfolio projects include designated areas featuring one or more HEA habitat type. To estimate annual carbon sequestration rates for each PORTfolio project, the per-unit-area numbers derived from the literature review were applied to the area of each habitat type in the project.

3 Carbon Sequestration in Lower Duwamish River and Elliott Bay Habitats

Table 1 summarizes the literature-derived carbon sequestration rate estimates for habitat types in the LDR and Elliott Bay. The following sections describe the scientific rationale used to arrive at these values.

Table 1. Summary of carbon sequestration rates for habitats in the LDR and Elliott Bay.

Habitat Type	Carbon Sequestration Rate	
	tC/ha/yr	tC/ac/yr
Riparian	2.68	1.08
Intertidal marsh	2.42	0.98
Intertidal mudflat, including shellfish beds	0.46	0.19
Shallow subtidal - eelgrass	0.69	0.28

Habitat Type	Carbon Sequestration Rate	
Deep subtidal - kelp	0.88	0.36
Un-vegetated subtidal (shallow and deep)	0.45	0.18

3.1 Sequestration Processes

Net carbon sequestration can generally be quantified by the sum of the following:

- Carbon in above- and below-ground biomass that is either retained in the organism itself (i.e., long-lived trees), in the soils and sediments on-site, or exported and sequestered off-site (e.g., deep stratified waters of Puget Sound or Pacific Ocean or coastal sediments);
- Carbon from off-site sources that accumulates and is buried in aquatic area sediments and upland soils; and
- Radiative forcing from methane (CH_4) and nitrous oxide (N_2O) emissions (these measures count against sequestration values).

The following sections describe on-site carbon production through above- and below-ground biomass, on-site (autochthonous) retention of carbon through burial or incorporation into on-site soils and aquatic area sediments, and carbon exported and sequestered off-site. Carbon that is not retained on-site may be consumed by herbivores, or plant material may be fragmented or decomposed and exported to adjacent waters. A portion of exported biomass in the form of dissolved and particulate carbon is remineralized in stratified or mixed surface waters and shoreline sediments, while another portion is sequestered either via burial in Puget Sound or coastal sediments or retention below the mixed layer in the deep stratified waters of Puget Sound or the Pacific Ocean (Krause-Jensen and Duarte 2016).

Carbon sequestration refers to the long-term storage of carbon in plants, soils, geologic formations, and the ocean.
Carbon may be sequestered in long-lived biomass, buried in soils or sediments, or stored in deep anoxic waters, which prolongs the decomposition and demineralization process.
Organic biomass that decomposes into smaller biomass, and is eventually remineralized into basal inorganic components, such as carbon dioxide, is not considered sequestered.

Additionally, in estuarine and marine habitats, a significant component of carbon sequestered on-site originates off-site (allochthonous material) and is transported to the subject habitat via fluvial or tidal currents. Shallow, vegetated habitats accumulate this dissolved and particulate carbon when currents slow and suspended material drops out of the water column to become incorporated into area sediments. In the absence of restored habitat conditions, the suspended material would continue to be carried past the site, without potential for on-site sequestration. Because aquatic habitat sediments assimilate carbon from both autochthonous and allochthonous sources through a variety of physical and biological processes, direct measures of carbon accumulation (via carbon density of sediment combined with the accretion rate of aquatic sediments) are useful metrics to account for all potential sources of carbon sequestration in aquatic sediments.

> **Autochthonous** material originates in the same location as its present position.
>
> **Allochthonous** material originates in a place remote from its present position.

Radiative forcing from methane emissions are not considered in this review, as methane emissions are negligible in marine and estuarine environments where sediment pore water salinities are greater than 18 ppt (Bartlett et al. 1987, Poffenbarger et al. 2011, Hiraishi et al. 2013). Pore water salinities were not available for the LDR; however, based on recent hydrologic documentation of the Lower Duwamish Waterway, at mean annual flows (1,650 cfs), the salinity at approximately six feet above mean lower low water (MLLW) (the approximate low intertidal extent of marsh presence) is roughly 18 ppt or greater from the mouth upstream to Turning Basin 3 (Haytor et al. 2016). As all PORTfolio projects are located at or downstream of Turning Basin 3, these projects are consistent with the salinity threshold, such that methane emissions are expected to be negligible. The LDR is characterized as a salt wedge estuary, with dense, higher salinity marine water penetrating the waterway beneath the surface freshwater layer in estuarine transition zones. Vertical water column mixing is limited to entrainment at the lower edge of the fresh water layer in the narrow, protected dimensions of the LDR. Precise sediment salinity measurements are beyond the resolution of this summary; however, future pore water salinity sampling could be used to confirm sediment salinities in locations and elevations relevant to PORTfolio sites.

> **Radiative forcing** refers to the capacity of a gas to affect the balance of incoming and outgoing energy in the Earth-atmosphere system, thereby contributing to climate change.

Nitrous oxide (N_2O) is another potential source of emissions; however, N_2O emissions are primarily only a concern for fish farming aquacultural practices in coastal systems or if there is a significant input of organic or inorganic nitrogen from runoff (Hiraishi et al. 2013). No aquacultural activities occur in the LDR or Elliott Bay, and a relatively small portion of the Green-Duwamish watershed is intensively managed for agricultural production. The Green-Duwamish Basin was previously impaired by high levels of ammonia nitrogen resulting from a Metro-Renton wastewater plant that discharged to the Lower Green River. However, since the primary wastewater treatment discharge location was moved from the Green River to deeper waters below the mixed layer in Puget Sound at Alki Point in 1987, ammonia nitrogen in the LDR decreased, and it now typically meets water quality standards. Today, wastewater discharges are limited to emergency overflows at nine combined sewer overflow outfalls along the LDR. An additional 199 storm drainage outfalls contribute stormwater drainage to the LDR. These conditions suggest that total nitrogen may be elevated during high flows in the LDR as a result of surrounding urban drainage. However, studies on the influence of punctuated events of elevated nitrogen on nitrous oxide emissions from marshes were not found; therefore N_2O emissions are assumed negligible.

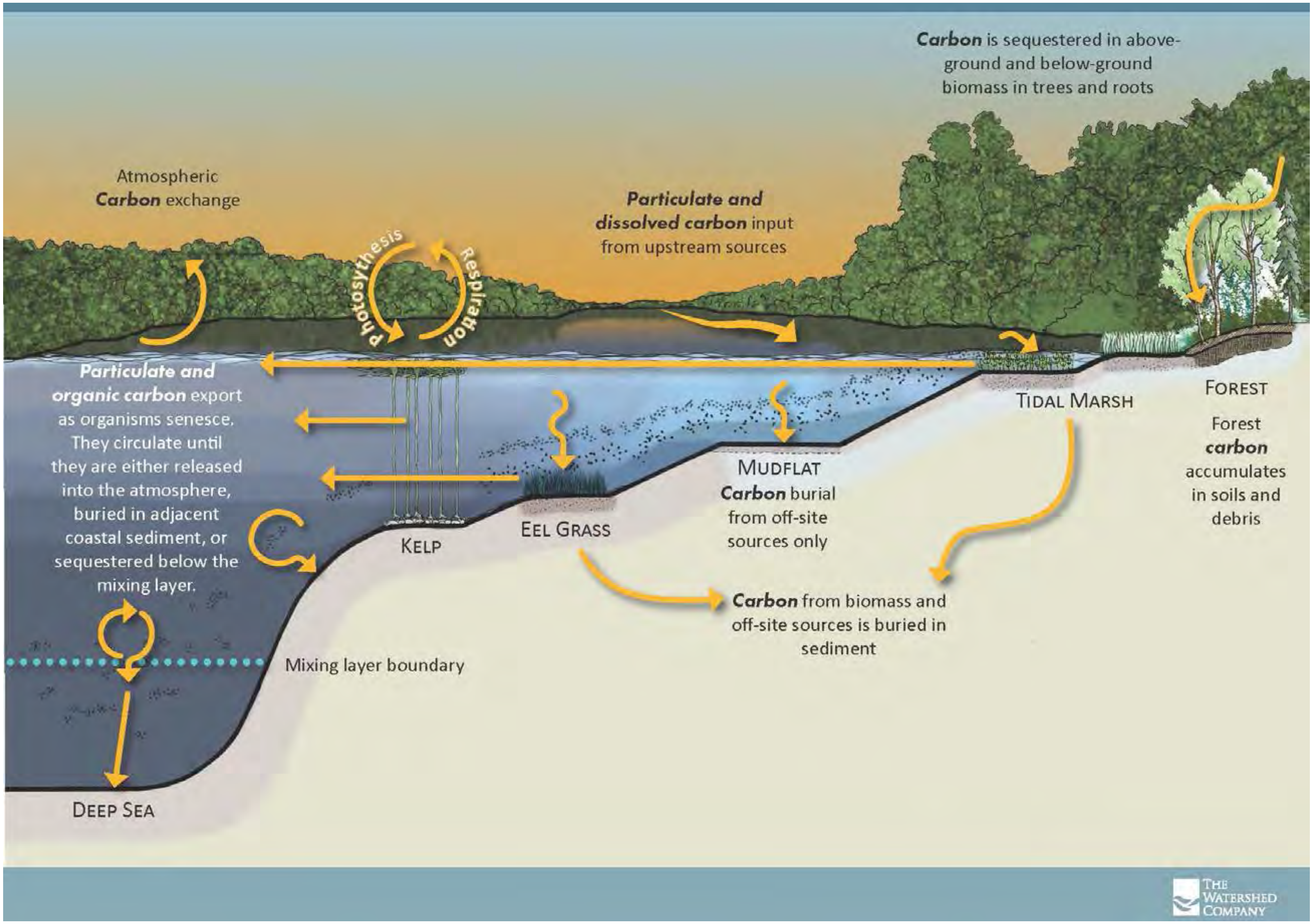

Figure 4. Diagram of carbon exchange and sequestration in aquatic and riparian habitats.

3.2 Sequestration in Riparian Habitats

Forests store carbon in tree biomass, including above- and below-ground biomass, as well as in understory and groundcover vegetation, woody debris (litter) on the forest floor, and soil (Binkley et al. 1997, Aalde et al. 2006, Smithwick et al. 2008). Methodology for calculating carbon stocks and carbon sequestration rates for forest habitats rely on species-specific equations that convert observed tree dimensions (e.g. trunk diameter) to biomass. Biomass is then converted to carbon using a species-specific ratio. Carbon storage in dead organic matter and soil may be estimated from direct measurements or using region-specific estimates (Aalde et al. 2006).

Smithwick et al. (2008) used this approach to calculate the potential upper bounds of carbon stores in Pacific Northwest old growth forests, which experience higher carbon densities than anywhere else in the world. Dushku et al. (2007) converted these results to estimates of annual carbon sequestration for different forest types of various ages found in Washington. Mixed mesic forests, including mixed riparian and coniferous riparian, at 40 years of age are the most relevant for application to PORTfolio riparian habitat areas, and are estimated to sequester carbon at a rate of 4.03 tC/ha/yr (Dushku et al. 2007).

Allometry, also called biological scaling, is the relationship of an organism's size and rate of growth to its shape, anatomy, and physiology. Allometries relating the dimensions of a trunk of a species of tree to the total biomass of the tree are used to estimate total carbon storage of different types of forest. These measures require some adjustment to reflect urban forest environments.

This estimate accounts for gross carbon storage, and does not account for annual biomass loss and decomposition. While the Intergovernmental Panel on Climate Change (IPCC) estimates this loss at approximately five percent of annual biomass accretion, Nowak et al. (2013) found that the net sequestration rate averages 74 percent of the gross sequestration rate in urban areas (a 26 percent average biomass loss).

In addition, McHale et al. (2009) suggests that the application of forest-derived allometries to urban forests is also problematic (Hutyra et al. 2011). Open-grown, maintained trees tend to have less above-ground biomass than predicted by forest-derived biomass equations for trees of the same diameter at breast height. Nowak et al. (2013) suggests a multiplier of 0.8 "to correct for urban allometric overestimation." While restored riparian habitat areas on PORTfolio sites are not open-grown, edge effects resulting from the limited width of such areas and adjacency to industrial properties would be expected to have a similar effect in limiting tree biomass. On the other hand, an abundance of buried and anchored woody debris incorporated into the designs of PORTfolio restoration projects would result in higher biomass than expected in urban forests, and would more closely approximate natural forest biomass conditions. Therefore, a multiplier of 0.9 would account for both the edge effect of smaller areas, but also the higher composition of woody debris at the Port sites.

Applying both of these factors – 0.74 to account for net sequestration and 0.9 to account for urban edge effects – to the regionally appropriate gross sequestration value of 4.03 tC/ha/yr from Dushku et al. (2007) and Smithwick et al. (2008) yields a net sequestration rate of 2.68 tC/ha/yr applicable to riparian habitats in the LDR and Elliott Bay.

3.3 Sequestration in Tidal Marsh Habitats

Tidal marshes are widely recognized as a net carbon sink (Chmura et al. 2003, Hussein et al. 2004, Crooks et al. 2010, 2014, McLeod et al. 2011, Callaway et al. 2012). Tidal marsh vegetation directly sequesters carbon dioxide (CO_2) through photosynthesis and accumulates carbon within above- and below-ground biomass. When marsh vegetation senesces, a portion of the vegetation is incorporated into the soil carbon store, a portion decomposes, and a portion is sequestered in off-site nearshore and coastal sediments or deep stratified waters of Puget Sound or the Pacific Ocean. Tidal wetlands build organic sediments through the incorporation of autochthonous marsh biomass and allochthonous sediment accretion, which incorporates particulate and dissolved organic matter. The result is long-term carbon storage in accumulating anoxic marsh sediments. Although marsh vegetation produces significant above- and below-ground biomass, a study in an established marsh in Port Susan, Washington found that total carbon stored in the top 30 cm of sediment dwarfs the carbon stock in above- and below-ground biomass (Poppe, K. Unpublished data).

> **Anoxic** sediments are depleted in oxygen. Microorganisms responsible for decomposition require oxygen for respiration. Under anoxic conditions, microbial activity will be reduced and associated decomposition will be slowed, resulting in carbon storage.

Few studies have evaluated tidal marsh carbon sequestration rates in the Pacific Northwest. Crooks et al. (2014) conducted the most regionally relevant investigation of carbon sequestration rates in established and restored tidal marshes in the Snohomish River Basin. Using carbon density values determined for the top 30 cm of sediment and sediment accretion rates, they found rates of carbon accumulation ranging from 0.58 to 3.52 tC/ha/yr. These rates of carbon accumulation generally fall within the range of observations from other tidal marshes [0.48-1.88 tC/ha/yr in San Francisco Bay (Callaway et al. 2012); 2.5-5.7 tC/ha/yr in Chesapeake Bay (Hussein et al. 2004); and 0.20-6.54 tC/ha/yr based on global review (Chmura et al. 2003)]. Typical methane emissions of 1.8 tC/ha/yr (Hiraishi et al. 2013) roughly offset the measured carbon accumulation rates at those marshes with sediment pore salinities below 18 ppt.

The variability in sediment accumulation rates along the marsh surface was the primary driver behind variability in the rate of carbon sequestration observed (Crooks et al. 2014). Marshes at lower elevations closer to the river channel tended to have higher accumulation rates. Sediment accretion rates in the Snohomish River marshes ranged from 0.18 cm/yr to 1.61 cm/yr (Crooks et al. 2014). These rates are lower than measured for other regional examples of restored tidal marshes in the Pacific Northwest, such as the Salmon River Estuary, Oregon (mean rate of 3.6 cm/yr) (Frenkel and Morlan 1990) and the Puyallup River Estuary (mean rate of 4.8 cm/yr)

(Simenstad and Thom 1996). The highest carbon accumulation rate in the Snohomish River study occurred at a recently restored site; however, carbon accumulation and sediment accretion at another restored site was lower than at two natural marsh sites (Crooks et al. 2014). Based on these findings, post-restoration maturity of the marsh does not seem to be a primary driver for the rate of carbon accumulation. Natural marshes continue to accrete sediment over time. Through the combination of accretion and soil compaction, the elevation of tidal marshes may gradually increase over time. In some locations, the rate of marsh accretion has been estimated to be similar with recent rates of sea-level rise (Callaway et al. 2012). Due to the combined effects of compaction and sea-level rise, continuing accretion was judged to be sustainable for the timescale of this study.

The rates of sediment accretion at three tidal marsh sites in the LDR restored in the past decade were used to best approximate the rate of carbon accumulation expected at restored tidal marshes in the LDR. Soil conditions were examined in the field to identify the depth of sediment representing post-restoration sediment accretion. This sediment accretion layer was identified based on a comparison of the composition of sediment at adjacent, unrestored locations. Sediment that accreted subsequent to marsh restoration was differentiated from the underlying sediment. In some areas, the underlying sediment consisted of mineral soils, which was easily differentiated from the high organic density characteristics of the restored upper marsh sediment layer. In other areas, underlying soils consisted of rich organic content; however, even in these areas, the underlying soil layer was distinct from the marsh sediment in planted marsh areas. In some cases, the accreted sediment could also be measured where the edge of the vegetated marsh meets the adjacent un-vegetated sediment. Estimated rates of sediment accretion in restored marshes in the LDR are shown in Table 2.

Table 2. Estimated rates of sediment accretion in restored marshes in the LDR.

Site	Depth to underlying soil horizon (cm)	Years since restoration action	Estimated Accretion rate (cm/year)
Terminal 105	6.5	18	0.36
Terminal 107	7.62- 9.5	7-9	1.08
Turning Basin 3	16	19	0.84
Average			**0.76**

Based on this measure, carbon accumulation in the LDR falls in the middle range of values observed in the Snohomish Estuary study. Using an average soil carbon density of 0.26 g/cm^3 for restored and natural marsh sites in the Snohomish Estuary, average soil carbon accumulation rates are approximately 1.97 tC/ha/yr in the LDR.

The IPCC methodology for calculating carbon sequestration in coastal wetlands assumes that increase in biomass stocks in a single year is equal to biomass losses from mortality in that same year leading to no net change (Hiraishi et al. 2013). However, based on recent estimates of sequestered carbon from eelgrass and kelp exports (Krause-Jensen and Duarte 2016, Duarte and Krause-Jensen 2017), a portion of exported tidal marsh biomass is likely sequestered in coastal sediments or in deep waters below the mixing zone. Although no estimates were available to assess the proportion of net primary productivity of coastal marshes sequestered off-site, based on average estimates from Krause-Jensen and Duarte (2016), and Duarte and Krause-Jensen (2017) for eelgrass and kelp, roughly eight percent of net primary productivity may be expected to be exported and sequestered off-site. One study of tidal sedge marshes in Nanaimo, British Columbia estimated net primary production at 5.64 tC/ha/yr (Naiman and Sibert 1979). If eight percent of that primary production is exported and sequestered offsite, that amounts to an additional 0.45 tC/ha/yr sequestered.

Based on estimated soil carbon accumulation and estimated sequestration of exported material, tidal marshes are expected to sequester 2.42 tC/ha/yr, applicable to tidal marsh habitats in the LDR and Elliott Bay.

3.4 Sequestration in Un-vegetated Intertidal Mudflat Habitats

Crooks et al. (2014) included one mudflat site in their analysis of carbon sequestration in the Snohomish River Estuary. This site, Union Slough, is characterized by extensive un-vegetated mudflats with a perimeter of Carex marsh vegetation. The total carbon density of sediment at Union Slough (0.018 gC/cm^3) was lower than any of the eight marsh sites sampled (mean of 0.38 gC/m^3) (Crooks et al. 2014). Representative sediments in the LDR are also estimated to have a total carbon density of 0.018 gC/cm^3. The LDR carbon density estimate is based on a mean percent total organic carbon of 1.9 percent (dry weight) in LDR sediments, and a mean dry bulk density of 60 lb/ft^3 (0.96 kg/cm^3) (AECOM 2012). It seems likely that mudflats adjacent to sources of particulate organic carbon, such as marshes, may have higher carbon densities, but existing sediment data for the LDR, collected during numerous system-wide sediment evaluations, indicate variability in carbon densities within similar mudflat areas, and do not point to an obvious spatial correlation in carbon density trends.

Crooks et al. did not evaluate sediment accretion rates at Union Slough. Mudflat accretion rates measured elsewhere range from net negative (erosional) on a sand flat in Port Susan, Washington (-0.32 cm/yr) (Poppe, K. Unpublished data) to 2.0 cm/yr on a tide flat in the Netherlands (Widdows et al. 2004). Based on limited sampling at two restored mudflat habitats in the LDR, the average accretion rate could be expected to be approximately 0.26 cm/yr. At this rate, if carbon density of the sediment is 0.018 gC/cm^3, the average carbon sequestration rate per year would be 0.46 tC/ha/yr. This value is very close to the general sequestration rate for un-vegetated estuarine habitat estimated by Duarte et al. (2005) of 0.45 tC/ha/yr.

Because there is no above-ground biomass, off-site carbon export is assumed negligible for mudflat habitats. Therefore, the net carbon sequestration rate for mudflats is equivalent to the estimated sediment accumulation value of 0.46 tC/ha/yr, applicable to un-vegetated intertidal mudflat habitats in the LDR and Elliott Bay.

The role of bivalve shellfish (e.g., clams, mussels, and oysters) on the net carbon sequestration balance was also investigated. Based on available studies of clams and mussels, bivalves release more carbon through respiration and the process of calcification than they sequester in their shells (Mistri and Munari 2012, Munari et al. 2013). However, Filgueira et al. (2015) noted that bivalve filter feeders have a larger ecosystem role in carbon sequestration through the effects of biofiltration that occurs through filter feeding processes. As bivalves filter plankton from the water column, they excrete digested and undigested material (feces and pseudofeces, respectively) to the epibenthos, where it may be sequestered in the adjacent sediment. The net effect of bivalves on carbon sequestration, with consideration of these ecosystem processes, is highly dependent on seasonality and local characteristics such as bivalve density, temperature, phytoplankton populations, nutrients, and potential ecological feedback mechanisms. One such potential ecological feedback mechanism would be increased eelgrass productivity either resulting from increased water clarity due to biofiltration (Filgueira et al. 2015) or through a reduction in phytotoxic sulfide levels in sediment as a result of grazing by infaunal bivalves (VanDerHeide et al. 2012). These indirect ecosystem-scale processes from clams have not been quantified, and due to the potential variability in ecosystem-scale effects, this report does not attempt to quantify the carbon sequestration effects of shellfish beds. Therefore, for the purpose of estimating carbon sequestration benefits of PORTfolio habitat types, shellfish beds are assumed to have a sequestration rate equal to that of un-vegetated mudflat.

Ocean acidification is the reduction of the pH of seawater resulting from absorption of atmospheric CO_2. The acidic water reduces the availability of carbonate ions that marine plankton and shellfish use for shell formation. Bivalve shells may buffer the effects of ocean acidification at a local scale.

Bivalve shell aggregations may also have secondary benefits related to local buffering of water conditions to counteract the effects of ocean acidification. Calcium carbonate in bivalve shells creates more alkaline conditions that have been found to support larval settlement under otherwise acidic conditions (Waldbusser et al. 2013).

3.5 Sequestration in Shallow Subtidal Habitats

Vegetated shallow subtidal habitats in the East and West Waterways and Elliott Bay include meadows of the native eelgrass *Zostera marina.* Eelgrass meadows have been identified as significant carbon sinks in the available scientific literature (Duarte et al. 2005, 2013; Howard et al. 2017; Kennedy et al. 2010; McLeod et al. 2011). Data on carbon sequestration rates of *Z. marina* beds in the Pacific Northwest represent a significant data gap. However, a summary of previous studies of eelgrass standing stock in Washington and Oregon by Thom et al. (2001) confirms that eelgrass habitats can contain considerable carbon in sediment, and that restoration of these systems can lead to rapid carbon accumulation. These studies also indicate that Pacific Northwest eelgrass systems export large quantities of carbon, which is either remineralized in stratified or mixed surface waters and beaches, buried in Puget Sound or coastal sediments, or sequestered below the mixing layer in the deep stratified waters of Puget Sound or the Pacific Ocean (Krause-Jensen and Duarte 2016).

> Carbon sequestration in Puget Sound may occur when organic material is transported below the **mixed layer**, or the upper layer where winds and currents mix the freshwater outflow from the region's many rivers with saltwater inflow from the Strait of Juan de Fuca. Recirculation of estuarine waters, caused by shallow sills at the north end (Admiralty Inlet) and at the Tacoma Narrows, limits rapid transport of suspended materials to the Pacific Ocean.

As with tidal marshes, eelgrass beds accumulate carbon in the form of above- and below-ground biomass, including leaves, rhizomes, roots, and an autotrophic epiphyte community (Duarte et al. 2013). A study of eelgrass stocks in Padilla Bay, Washington, including *Z. marina* and *Z. japonica* and seagrass epiphytes observed an annual net primary production (NPP) for the community of 3.51 tC/ha/yr (Thom 1990). Of total NPP, the majority is rereleased to the atmosphere through decomposition and remineralization within the mixed layer. The remainder may accumulate in the sediment or be exported from the meadow.

> **Autotrophic epiphytes** include algae growing on the surface of eelgrass. These autotrophic epiphytes account for 20 to 60 percent of the total NPP of seagrass communities (Duarte et al. 2013).

Eelgrass beds can be efficient at capturing and removing suspended materials from the water column, facilitating sedimentation, and preventing resuspension, particularly when canopy height is more than 10 percent of the water column (Duarte et al. 2013 and Kennedy et al. 2010). Kennedy et al. (2010) indicates that up to 50 percent of carbon found in seagrass sediments is trapped from off-site sources. Large continuous eelgrass meadows accumulate more organic carbon in sediments per unit area compared to patchy meadows, and continuous meadows derive a greater proportion of that organic carbon from autochthonous (on-site), rather than allochthonous (off-site) sources (Ricart et al. 2017). However, the capacity of eelgrass to facilitate on-site sedimentation varies significantly with species and local environmental conditions. Studies of carbon accumulation rates in sediment specific to *Z. marina* are limited, but those available show total on-site carbon burial rates from 0.05 to 0.50 tC/ha/yr in the Pacific Northwest (Poppe, K. Unpublished data;

Hodgson et al. 2016; Prentice, C. Unpublished data). These empirical observations of carbon accumulation in on-site sediments account for both autochthonous and allochthonous inputs. Low accumulation rates in Padilla Bay may be reflective of the lack of nearby fluvial sediment sources. Eelgrass beds in the East and West Waterways and Elliott Bay, by contrast, would be fed by relatively sediment-rich flow from the Green-Duwamish River. While this fluvial source of suspended sediment brings significant potential for allochthonous carbon storage, it may also present a risk to eelgrass growth and survival due to potential light limitations from turbidity (Moore et al. 1996, Thom et al. 2008).

Duarte and Krause-Jensen (2017) reviewed available studies and data relating to the fate of NPP in eelgrass meadows globally. Their synthesis found that approximately 16 percent of eelgrass community NPP is buried in meadow sediments (as autochthonous inputs). Applying estimates of on-site carbon sequestration from Duarte and Krause-Jensen (2017) to regional NPP estimates (Thom 1990), approximately 0.56 tC/ha/yr would be buried in on-site sediments. This value is similar to the results of another study in the Mediterranean, which used a carbon budget to estimate that 0.52 tC/ha/yr of *Z. marina* biomass was available to be buried or exported (Cebrián et al. 1997). These estimates only represent autochthonous inputs and support application of the higher burial rate than documented in the empirical data examples.

NPP exported from the meadow may be sequestered as dissolved organic carbon exported below the mixed layer, or as particulate organic carbon buried in Puget Sound or nearshore sediments. Duarte and Krause-Jensen (2017) estimate that a total of five percent of eelgrass NPP is sequestered through one of these processes. Applying Thom's estimate of regional eelgrass NPP, approximately 0.17 tC/ha/yr of exported NPP is sequestered long-term. The remainder of NPP is remineralized or grazed, or exported without being sequestered, eventually releasing carbon back to the atmosphere. Adding this to carbon buried in on-site sediments gives a total sequestration rate of 0.69 tC/ha/yr, applicable to vegetated shallow subtidal habitats in the East and West Waterways and Elliott Bay.

While this report focuses on the benefits of PORTfolio habitat restoration on carbon sequestration, seagrass beds may also play an important role related to local moderation of the effects of ocean acidification, which stems from increasing atmospheric carbon. Since the industrial revolution, the pH of seawater has decreased by approximately 0.1 units, and reductions of up to 0.4 units are predicted by the end of the century from future increases in atmospheric CO_2 (Feely et al. 2008, Gruber et al. 2012, Hauri et al. 2013). Since pH is measured on a logarithmic scale, this represents a significant increase in acidity. Seagrass beds can alter the pH within the canopy and surrounding vicinity by up to 0.24 units, offering potential local refugia from the effects of ocean acidification (Hendriks et al. 2014). Further research is necessary to understand how these estuarine habitats alter carbonate chemistry at the habitat or landscape scale.

The focus of the literature review was on those habitats that may be improved through PORTfolio restoration actions, and as such emphasizes vegetated shallow subtidal habitats. However, Duarte et al. (2005) reviewed a compilation of published reports to estimate organic carbon burial rates for un-vegetated estuarine habitat. In the absence of local depositional data, their estimated rate of 0.45 tC/ha/yr is a conservative estimate for un-vegetated shallow subtidal habitats in the LDR and Elliott Bay.

3.6 Sequestration in Deep Subtidal Habitats

Vegetated deep subtidal habitats in the East/West Waterways and Elliott Bay include growth of seasonal bull kelp (*Nereocystis luetkeana)*. Bull kelp requires appropriate stable substrate for attachment of basal holdfasts, including naturally occurring rocky surfaces or introduced rock substrate or other in-water structural surfaces. Unlike vascular eelgrass and emergent vegetation, kelp growth does not include extensive rooting systems with the capacity for trapping detritus and sediment and sequestering carbon. As a result, accumulation of biomass in kelp bed sediments is likely negligible (Howard et al. 2017). However, a synthesis of available data on macroalgal carbon by Krause-Jensen and Duarte (2016) indicates that an estimated 0.4 percent of NPP is buried on-site for macroalgae that grow on soft sediments. This estimate could be applied to kelp forests in the East/West Waterways and Elliott Bay: although bull kelp holdfasts adhere to rocks, kelp in these areas tends to grow near sand and silty sediments.

Most of the free-floating, detached, or dead kelp is quickly consumed by marine fauna or decomposes on beaches, and the fraction of kelp-based carbon that is ultimately sequestered through export and burial in ocean sediments is poorly understood (Smale et al. 2013). As with eelgrass, NPP exported from kelp growth may be sequestered as dissolved organic carbon exported below the mixed layer, or as particulate organic carbon buried in off-site sediments or exported to deep marine areas. In their 2016 synthesis, Krause-Jensen and Duarte estimate that a total of 11 percent of kelp NPP is sequestered through one of these processes.

Estimates of kelp NPP in the Pacific Northwest range from 3.13 to 19.00 tC/ha/yr (Wilmers et al. 2012, Thom et al. 2001). For the purposes of kelp restoration in the LDR and Elliott Bay, an average estimate for bull kelp (8.00 tC/ha/yr) was used. Applying export sequestration rates from Krause-Jensen and Duarte (2016), bull kelp beds are estimated to account for a carbon sequestration rate of approximately 0.88 tC/ha/yr, applicable to deep subtidal habitats in the East and West Waterways and Elliott Bay.

> An approach to maximizing sequestration of carbon kelp beds could include **harvest** of live kelp biomass and **physical burial** as mulch and topsoil amendments. This approach would not only provide exact values for carbon sequestration benefits, but would also allow for capture of 100 percent of NPP.

Due to the scarcity of regionally specific studies of kelp carbon sequestration, this estimate includes significant uncertainty. Connectivity to deeper waters of Puget Sound and to off-shore marine areas, and resulting burial rates of exported carbon, are likely highly variable based on local oceanographic conditions. Krause-Jensen and Duarte (2016) confirm that such conditions are the primary driver of variability. In open coastal areas, mixing and stratification of surface and deep waters in open coastal environments are affected by seasonal upwelling and downwelling processes affected by predominant winds and currents. In

Puget Sound, winds and currents play a role in mixing and stratification, but saltwater inflow from the Strait of Juan de Fuca and freshwater runoff from the region's rivers play an equally important role in mixing and stratification processes. Shallow sills at Admiralty Inlet and the Tacoma Narrows also contribute to recirculation of estuarine waters. Based on these characteristics, some portion of exported carbon is transported fairly rapidly through the Strait of Juan de Fuca to the Pacific Ocean with the surface freshwater outflow, while another portion is recycled within the mixing zone of Puget Sound over time before eventually being remineralized within the mixing zone, and another portion eventually reaches deeper waters of Puget Sound below the mixing zone or the open ocean. There is not currently sufficient information to estimate how the proportional sequestration of exported material may differ between most coastal environments and the Puget Sound estuarine setting.

The focus of the literature review was on those habitats that may be improved through PORTfolio restoration actions, and as such emphasizes vegetated deep subtidal habitats. However, as mentioned above, Duarte et al. (2005) reviewed a compilation of published reports to estimate organic carbon burial rates for un-vegetated estuarine habitat. In the absence of local depositional data, their estimated rate of 0.45 tC/ha/yr is a conservative estimate for un-vegetated deep subtidal habitats in the LDR and Elliott Bay.

4 Application of Carbon Sequestration Rates to PORTfolio Projects

4.1 Assumptions

The annual rate of carbon sequestration for each PORTfolio project was calculated based on the carbon sequestration rates derived from the literature review (Table 1) and the estimated areas of each habitat type. Conceptual designs developed for the HEA analysis were used to determine acreage values for each restored habitat type, as defined in the HEA model (see Section 2.2).

The results represent an estimate of the annual carbon sequestration rate for each restoration project in a mature, established condition. The carbon sequestration estimates in Section 4.2 assume a linear rate of carbon sequestration over time, but each project may take several years to fully establish and sequester carbon at this rate. Over time, the rate may vary due to environmental conditions, including climate change.

The approach of this assessment assumes that the carbon sequestration rate of each project in its pre-project, or baseline, condition is zero. In many cases, the baseline condition of the project includes paved, un-vegetated uplands and a riprap bankline that offer no potential for on-site carbon sequestration or export. In some cases, however, existing invasive vegetation or urban landscape conditions, including turf and managed vegetation, may provide some minimal level of carbon sequestration under baseline conditions. A comprehensive assessment of baseline carbon sequestration rates of PORTfolio sites is outside the scope of this assessment.

In most cases, PORTfolio projects focus on riparian, intertidal, and vegetated subtidal habitats. Some projects include recontouring of un-vegetated subtidal areas, but the primary restoration action relates to other adjacent habitats. The net effect of carbon sequestration in these subtidal areas adjacent to restored habitat is not presently understood. For this reason, this analysis does not attribute increased carbon sequestration value for un-vegetated subtidal habitats. This approach differs from HEA calculations, which attribute enhanced functional habitat value to un-vegetated shallow and deep subtidal habitats adjacent to successfully restored intertidal or riparian areas.

Finally, those projects consisting only of overwater cover removal are not expected to result in a significant change in per-acre carbon sequestration rates relative to baseline conditions. These projects, including Pier 34 and Rhone-Poulenc, are therefore excluded from the assessment of carbon sequestration rates.

4.2 Results

The estimated annual carbon sequestration rate for each PORTfolio project is summarized in Table 3. Together, PORTfolio projects are estimated to sequester approximately 34 metric tons of carbon per year.

Table 3. Carbon sequestration of PORTfolio projects (tC/yr).

Site	Habitat Type					Total by Site (tC/yr)
	Riparian	Tidal Marsh	Intertidal Mudflat	Shallow Subtidal - Eelgrass	Deep Subtidal - Kelp	
Turning Basin 3	0.67	0.36	0.35	--	--	**1.38**
Slip 27	0.38	--	--	--	--	**0.38**
South Park	0.29	0.02	0.13	--	--	**0.44**
Terminal 10	0.16	0.10	0.06	--	--	**0.32**
Terminal 102	0.86	0.31	0.12	--	--	**1.29**
Terminal 104	0.19	--	--	--	--	**0.21**
Terminal 105	1.47	0.82	0.30	--	--	**2.59**
Terminal 106	0.43	--	--	--	--	**0.43**
Terminal 107	2.63	0.97	0.84	--	--	**4.44**
Terminal 108	0.78	--	0.29	--	--	**1.07**

Site	Habitat Type					Total by Site (tC/yr)
	Riparian	Tidal Marsh	Intertidal Mudflat	Shallow Subtidal - Eelgrass	Deep Subtidal - Kelp	
Terminal 115	0.29	0.51	0.08	--	--	**0.88**
Terminal 117	1.74	2.98	0.69	--	--	**5.41**
Terminal 18	0.16	0.29	0.06	--	--	**0.51**
Terminal 25 S	0.46	3.88	0.22	0.10	0.12	**4.78**
Terminal 5 N	1.26	--	0.36	--	--	**1.62**
Terminal 5 SE	0.13	0.24	0.06	--	--	**0.43**
Terminal 91	0.67	--	0.91	3.47	2.50	**7.55**
Total by Habitat (tC/yr)	**12.57**	**10.48**	**4.50**	**3.57**	**2.62**	**33.74**

4.3 Discussion

As with traditional HEA valuation, those sites with the largest acreage, such as Terminal 91, Terminal 117, Terminal 25 South, and Terminal 107, contribute most to carbon sequestration. Sites with the highest carbon sequestration rate per unit area are those with the highest percentage of riparian and marsh habitat relative to other habitat types.

The total sequestration rate of 33.74 tC/year for PORTfolio projects is enough to approximately offset 124 tCO_2 emitted per year, which equates to roughly 13,953 gallons of gasoline.[1]

Emissions equivalent to carbon sequestered annually by PORTfolio projects, measured in ton-miles (transport of one ton of freight one mile):

- 846,705 ton-miles via truck
- 5,120,000 ton-miles via train
- 2,060,000 ton-miles via ship
- 94,010 ton-miles via plane

(Based on EPA calculations: https://www.epa.gov/sites/production/files/2015-12/documents/emission-factors_nov_2015.pdf)

[1] Based on EPA conversions: https://www.epa.gov/energy/greenhouse-gases-equivalencies-calculator-calculations-and-references#gasoline

5 Conclusions, Limitations, and Recommendations

This report provides an overview of the current understanding of carbon sequestration rates of estuarine and riparian habitats, as they relate to existing and anticipated restored conditions in the LDR and Elliott Bay, and applies those rates to the restored conditions of PORTfolio projects. Based on this assessment, estuarine habitat restoration is expected to contribute to the Port's Century Agenda goal of reducing net carbon emissions to be carbon neutral by the year 2050.

This review does not represent a site-specific, empirically based carbon sequestration analysis of PORTfolio projects in the LDR and Elliott Bay. Values extracted from the literature reflect a wide range of environmental contexts that may significantly influence carbon sequestration rates.

Scientific understanding of carbon sequestration in estuarine, marine, and other aquatic habitats, also known as blue carbon, is continuing to develop, particularly in the Pacific Northwest. At least one multi-year study in early phases will collect significant regional carbon sequestration data (J. Apple, pers. comm. October 20, 2017). The results of this study and others in the region will help the Port refine the applicability and accuracy of its calculations and contribute to understanding and accounting for the carbon sequestration benefits resulting from PORTfolio projects.

Many of the carbon sequestration values presented in this review are driven primarily by sediment accumulation rates. In order to confirm and refine sequestration benefits of habitat projects once they are constructed, the Port should incorporate measurement of sediment accretion, and possibly soil or sediment carbon density, into its monitoring protocol for PORTfolio projects.

Habitat restoration is one component of a broad suite of strategies the Port may employ to reduce overall greenhouse gas emissions over time. An additional potential strategy for emissions reduction is through the buying and selling of carbon "credits" in the global carbon market. Carbon credits may be generated by projects, including habitat restoration projects, that reduce atmospheric greenhouse gas concentrations. Before use in carbon markets, projects must be certified by the Verified Carbon Standard (VCS) Program using specified methodology to calculate project-specific greenhouse gas reductions. Recently, the VCS Program certified a procedure for estimating reductions from coastal wetland and seagrass restoration projects (Restore America's Estuaries and Silvestrum 2015). The procedure requires life-cycle analysis of project-related emissions, but focuses on the same fundamental mechanisms driving carbon benefits as discussed in this report. Together with site-specific measurements and additional analyses, the literature-derived numbers in this report could be used in applying VCS methodology to certify PORTfolio projects for use in carbon markets.

In addition to benefits from carbon sequestration to help offset carbon emissions, Portfolio projects may provide other potential climate change mitigation benefits, includingenhanced protection from storm surge and sea level rise, and local buffering of the effects of ocean acidification. Ocean acidification driven by increasing atmospheric carbon is a significant threat to Washington's coastal ecosystems and economies. As described in this report, kelp and eelgrass, may help buffer pH locally, providing better growing conditions for shellfish, plankton, and other marine calcifiers. In its 2017 report, the Washington Marine Resources Advisory Council identified kelp and eelgrass restoration, along with further research, as strategies to adapt to and remediate the impacts of ocean acidification in Washington (WA MRAC 2017). PORTfolio projects that incorporate large-scale kelp and eelgrass restoration may provide opportunities for improving understanding of the significance of these habitats related to ocean acidification. As scientific understanding of these benefits grows, ocean acidification could be incorporated into a broader climate effects analysis and overall decision-making calculus for habitat restoration by the Port.

This review focuses on one small portion of Port-owned property. Other natural or restored areas owned and managed by the Port likely provide additional carbon sequestration and climate change mitigation potential that should be quantified to factor into the net carbon emissions and climate-related outcomes of all Port activities.

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