NATURAL RESOURCES

Technical Report

Mapping Puget Sound's Artificial Reefs

Report prepared for DNR Aquatic Lands Restoration Team

August 16, 2023

WASHINGTON STATE DEPARTMENT OF NATURAL RESOURCES

Cover Photo: Tires entangled in wooden barge at Tolmie State Park, WA. Photo by DNR dive team.

Mapping Puget Sound's Artificial Reefs: Identifying Automobile Tires for Removal

August 16, 2023

Aquatic Assessment and Monitoring Team
Aquatic Resources GIS Team
Aquatic Lands Restoration Program

WASHINGTON STATE DEPARTMENT OF
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Acknowledgements

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The following document was produced in collaboration with the DNR's Aquatic Lands Restoration Team. There were a number of individuals who played a critical role in the collection and processing of different datasets. These people include Tyler Cowdrey, Niki Alden, Alena Reynolds, Tim Teets, Cassidy Johnson, Melissa Petrich, and Tom Martin along with the entire DNR dive team. The information we present in this paper would not be possible without the assistance from these individuals.

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EXECUTIVE SUMMARY

The Washington State Department of Natural Resources (DNR) manages 2.6 million acres of state-owned aquatic lands for the benefit of current and future citizens of Washington State. In addition to the protection of certain habitats and native species, DNR's stewardship responsibilities include the restoration of estuaries, shorelines, and bedlands. In the 1970s and 80s thousands of surplus automobile tires were placed on the bottom of Puget Sound with the intention of attracting reef fish in order to provide more recreational fishing opportunities. Unfortunately, these scrap tires have not provided the valuable habitat that was intended and instead have the potential to cause more harm than benefit. For this reason, DNR's Aquatic Lands Restoration Program has collaborated with the Aquatic Assessment and Monitoring Team to learn more about the disposition of these tire reefs with the eventual goal of removing them and restoring the benthos back to its natural state. From 2020 to 2021 DNR mapped 20 suspected tire reef sites with a multibeam sonar. Features found in sonar data were confirmed with a towed video camera.

Key Findings:

1. The largest tire reefs in Puget Sound have up to 22,000 tires bundled together with polypropylene rope into groups of up to 24 tires each. Comparatively, the smallest reef surveyed consists of approximately 166 tires bundled into groups of eight tires each.

2. Tire reefs can be spread across the seafloor to varying degrees. The largest site covered an area of approximately 7 acres and the smallest covered an area of approximately 1 acre.

3. The depth at which tires were found varied based on the slope and shape of the surrounding area.

   a) Middle Sound sites were more often located on steeper slopes, and so had a greater range of depths across the reef.
   b) South Sound sites in general had gentler sloping bathymetry, and so tire features could be found within a narrow band of depths that remained relatively shallow.

4. Tires were found bundled with polypropylene line and buried at different depths. Tires were in varying stages of decomposition based on the site.

   a) South Sound sites tended to have tire features that were buried deeper in fine sediment. Tires at those sites were up to 90% buried, and it is likely that there are additional tires that were not detected and remain completely buried.
   b) Middle Sound sites tended to be buried to a lesser extent, which could be due in part to a greater prevalence of sand and cobble bottom types among sites.

1 Introduction

1.1 Background and Project Description

Many large artificial reefs were constructed for fishing in Puget Sound between the 1970s and 80s. These reefs were built by different government and non-governmental organizations to enhance bottom-fishing opportunities in the face of curtailed salmon fishing limits for sport enthusiasts (Williams et. al 2010). During the 70s, salmon allocation issues, combined with more restrictive salmon conservation measures, created an increased interest in recreational bottom fishing - particularly for rockfish (*Sebastus* spp.) and lingcod (*Ophiodon elongatus*). Unfortunately, these reef species have life history characteristics that make them vulnerable to overfishing, and they were rapidly depleted from the few rocky outcroppings in Puget Sound that naturally supported them (Buckley 1982).

To ameliorate the demand for local bottom fish reef fishing, metropolitan centers such as Seattle, Tacoma, Des Moines, and Edmonds constructed public fishing piers on their waterfronts with funding from the Washington State legislature (Williams et. al 2010). Additionally, over a 15-year period starting in 1975, the Washington Department of Fisheries (WDF)[1] spearheaded the planning for, and construction of, large artificial reefs adjacent to many of these fishing piers to attract reef species for fishing enthusiasts (Figure 1, map of the reefs planned for and installed by the WDF Marine Fisheries Enhancement Division). To create artificial reefs, WDF dropped concrete structures and rubble obtained from anthropogenic demolition sites along with natural materials (e.g. quarry boulders and cobble) onto low rugosity sea beds with the intent to increase seabed complexity and attract reef dwelling fish (Stone 1974, Hueckel 1982).

During the same period of time in which these large installments were being placed near metropolitan centers, many smaller artificial reefs were installed in the nearshore environment throughout Puget Sound to improve bottom fishing opportunities for boating anglers and for the enjoyment of recreational scuba divers (Buckley 1982). For some of these reefs, the parties responsible for their construction could not be determined. Those were likely placed by local “poggie” clubs, scuba clubs, or private beachfront property owners (Larry Leclair 2023, pers. comm., June 2). Some reefs were installed by the DNR for fish habitat enhancement (Buckley 1982, Greg Hueckel 2022, pers. comm., Feb. 4).

[1] Now, the Washington Department of Fish and Wildlife.

Over the decades, a wide range of materials have been used to construct artificial reefs in Puget Sound, but early on they were primarily built out of used automobile tires, scrap concrete, and quarry rock. Quarry rock and scrap concrete add substantial rugosity and interstitial space to the seabed and thus bear some resemblance to naturally occurring rocky reefs. In addition to adding rugosity, the inherently hollow enclosures formed by tires were presumed to be of added benefit to cryptic and shelter seeking fish and invertebrates. Artificial reefs also provided a convenient and inexpensive means to dispose of waste tires (Sherman and Spieler 2006).

Tires were often bundled together into modules of different sizes and shapes (Figures 4 & 5). Modules were typically bound with propylene rope of various lengths and diameters. In the 1970s, the DNR used a compression, banding, and cutting machine to bail tires into "barrel" stacks (Figure 3) whereby 5 to 8 tires were stacked and compressed together with steel bands. Each tire stack was then secured with polypropylene rope. Afterward, the steel bands were cut, allowing the tire stack to "relax" into an overall form, which increased the available surface area and crevasses for reef dwelling species. Finally, tires were sliced to allow for air escapement while the tire modules sank to the bottom. Later, the WDF borrowed the compression and banding equipment from DNR for their reef construction efforts DNR (Hueckel, G. J. 2022. Personal communication February 4, 2022).

Barrel stacks were often banded together to build larger reef features such as pyramid shapes (Figure 3). Tires were also banded together in the center to form daisy formations or tied into loose, jumbled formations. In some cases, the bottom row of tires in these modules may have been filled with cement to keep the entire bundled feature anchored in place (Figure 3). While ballasting tires and tire reefs in this fashion has occurred in other parts of the world, the practice has not been confirmed in Puget Sound.

Many reefs that included automobile tires were constructed in Puget Sound during a short period. By 1982, tires were no longer the preferred material due to increasing costs, so the WDF switched to using scrap concrete and quarry rock exclusively. Scrap concrete from demolished bridges and buildings were cheaper to source and less labor intensive to construct than tire modules. In addition, reports were received that tires snagged more fishing gear than concrete reefs (Department of Army 1983).

There have been growing concerns over the environmental impacts of tires utilized for reef construction (Sherman and Spieler 2006). The first and most evident of these impacts has to do with the longevity of the materials used to hold the tires together in modules. Over time, the marine environment causes the material to degrade and modules break apart. The Osborne tire reef near Fort Lauderdale, FL is a famous example of a site where this has occurred. In 1967, nearly 2 million banded automobile tires were placed over 35 acres of an otherwise featureless sandy bottom in the nearshore environment. Over time, the nylon rope and steel clips holding tires together broke. This allowed the tires to be dispersed over great distances during tropical storms, destroying fragile coral habitats in their paths (Sherman and Spieler 2006). Once tires have broken apart from their modules, they become increasingly difficult and expensive to locate and remove. To date, only 165,000 tires have been removed from the Osbourne Reef site at a cost of over 1.6 million dollars (Fleshler 2015). Due to the increase in size of the reef footprint, the cost to coalesce tires and remove them by barge and diver have dramatically increased.

In Puget Sound, individual tires that have broken from their modules are also at risk of being dispersed. While their dispersal does not pose a destructive threat to fragile hard corals, it does pose a risk to benthic plants and animals native to Puget Sound. Further, when moved by currents and storm surge they are at greater risk of settling in positions and at locations that make them more susceptible to becoming completely buried, adding substantially to the cost of finding and removing them. Due to their lack of structural complexity, individual tires lying flat on the bottom, particularly when they are partially buried, provide little or no habitat value to fish. Loose tires are also less likely to allow for attached plant and invertebrate growth due to constant or periodic agitation with the seabed (Guidelines 2020). Moreover, single tires can move into different depth zones and detrimentally affect other habitats such as shallow water eelgrass and deep water sea whip beds. A study in Japan found that single tires trapped and killed hermit crabs, similar to how derelict fishing gear or lost fishing nets continue to trap species for long periods of time (Sogabe 2021).

Single tires are also more likely to wash up on shore during storms. Under these conditions, strewn tires can increase the overall tire reef footprint, and are more susceptible to weathering. The physical breakdown of tires into smaller pieces increases surface area and allows noxious chemicals to leach at higher rates (Aleksandrov et al. 2002). Leachates such as formaldehyde and petroleum-based chemicals released from pieces of weathered tires have been measured over six times greater than the standard permissible maximum limit (PML, Aleksandrov et al. 2002). Other studies have found that in high salinity environments (compared to freshwater); there are no acute toxicological risks to resident organisms due to leaching of chemicals (Hartwell et al. 1998). However, those studies do not account for whether long-term bioaccumulation of certain chemicals might be harmful to the same organisms.

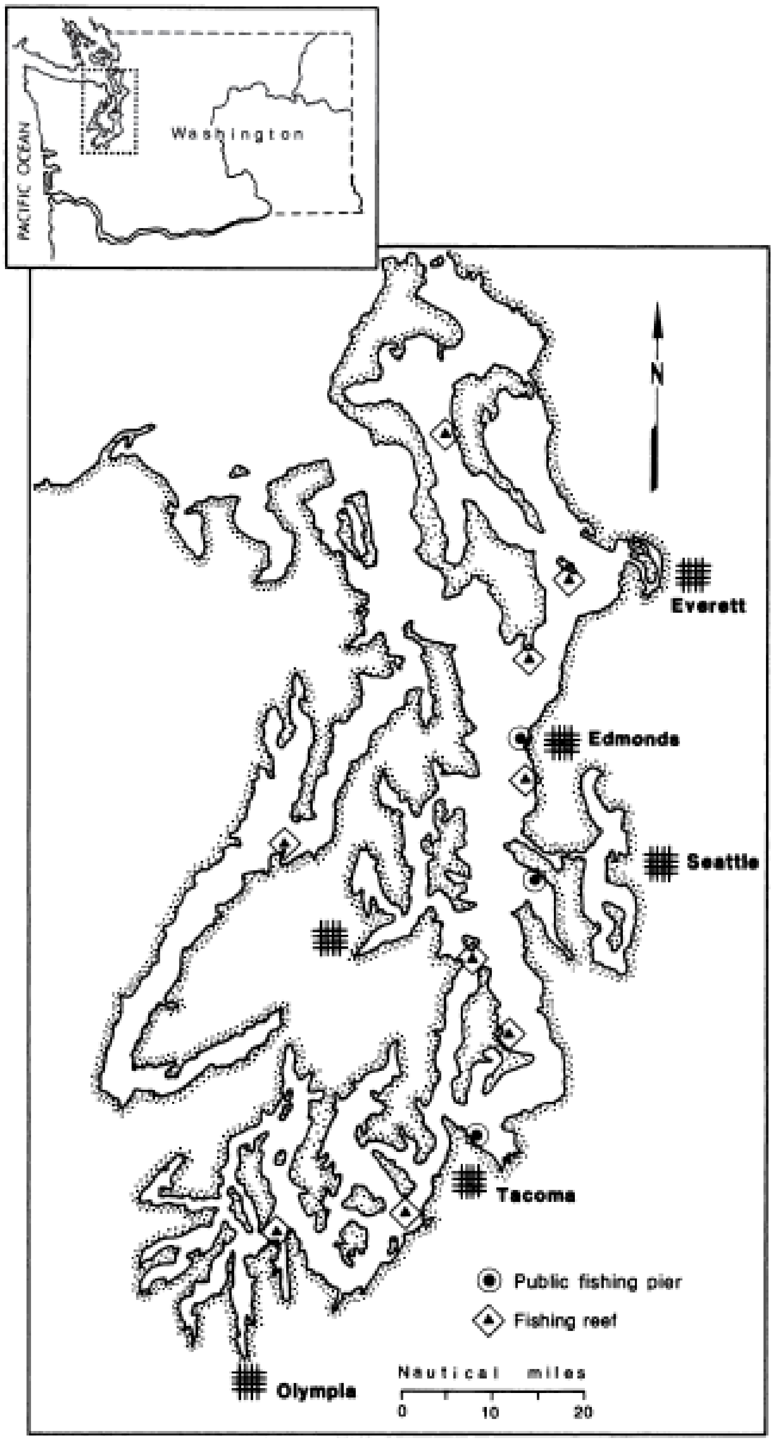

Figure 1. Image from Buckley (1982) showing locations of 12 reefs installed by the Department of Fisheries' Washington Marine Fisheries Enhancement Division. Not all of the reefs in this map include tires.

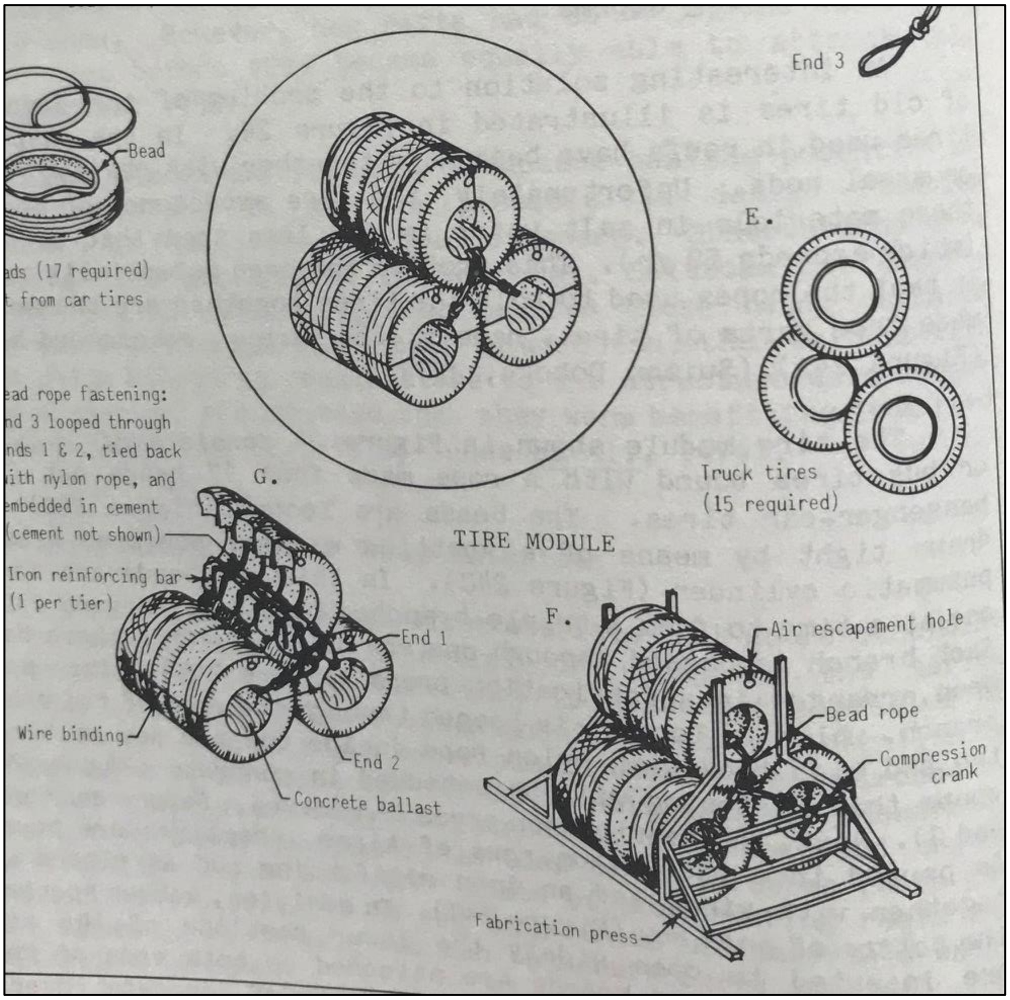

Figure 2. Bundles of tires ready to be deployed at the Blake Island reef. Photo date unknown.

Figure 3. An example of a tire module banding jig which could be rented from the Bridgestone Tire Company (D'itri, 2018). Tires barrel joined and secured in pyramid formations like these were found in many reefs mapped for this project.

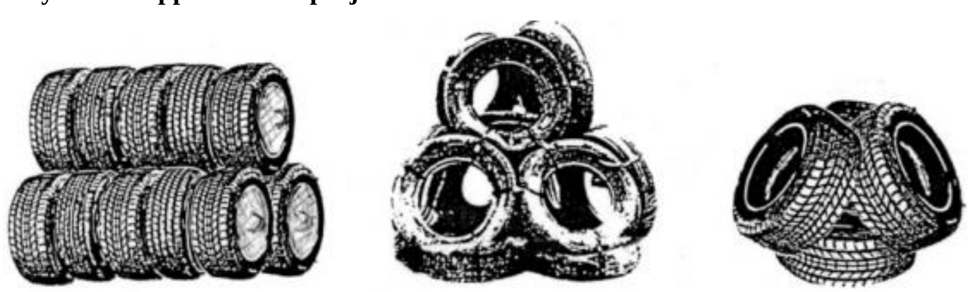

Figure 4. Different types of tire modules utilized to enhance structural complexity.

1.2 *Specific Objective*

In the last several years, DNR's Aquatic Lands Restoration Team (ALRT) has received reports of an increasing number of automobile tires washing ashore at sites near known tire reef locations, suggesting that the reefs are breaking apart (Figure 5). With the current understanding regarding negative effects that tires have in the marine environment, and to remain consistent with the Agency's own habitat stewardship measures, the removal of automobile tires at reef sites on State Owned Aquatic Land (SOAL) in Puget Sound has become a priority for DNR's ALRT.

Many of the reefs in Puget Sound constructed after 1982 with scrap concrete, quarry rock, or other non – tire materials are well-known fishing and diving locations that provide abundant marine habitat and recreational opportunities. Some of these quarry or concrete composed reefs are the product of 30-year lease agreements between the DNR and the WDFW. For most of the artificial reefs, and particularly for tire reefs constructed prior to 1982, there is minimal information about their location, shape, size, or the materials used when they were constructed. This information, including the precise location and size of the reefs was not well documented, and confirmation is crucial for planning efforts to remove them. While detailed information for many of the early artificial reefs in Puget Sound is not available, the WDFW has maintained an account of the coordinates for most tire reefs that are known to exist. These coordinates are based on staff knowledge, nautical charts, and information from the recreational fishing and scuba diving community (Table 1).

In the first phase of DNR's Tire Reef Mapping Pilot, (2019 to 2021), the ALRT worked with DNR's Aquatic Assessment and Monitoring Team (AAMT) to initiate a comprehensive survey and mapping effort for twenty different priority tire reef sites (Figure 6Figure 6). The ALRT identified these locations as priority sites based on WDFW information that suggested they were built of tires, their placement on SOAL, and their proximity to adjacent state, city, or county owned uplands.

The primary objective of this study was to first confirm whether tires are present at each priority site. Additional information that was collected included the quantity of tires present and their precise locations, the type and condition of tire modules (bundled, broken or intact), whether banding material was present (rope, chain, steel strap etc.), the level of tire decomposition, the extent of burial into natural sediments, and the identification of other non-tire materials that comprise the reefs. Table 2 outlines the specific attributes that DNR desired to establish for each reef. Sites where bundles have broken apart and allowed individual tires to drift from main aggregations should receive higher priority for removal than reefs that remain intact. Individual tires are much more difficult to find and remove as they often lay on their sides and are buried with little visual evidence of their existence. A comprehensive understanding of the tire reef characteristics in Puget Sound based on the information above will allow DNR's ALRT to select sites as pilot studies for automobile tire removal.

Table 1. Preliminary Washington Department of Fish and Wildlife provided coordinates and site descriptions.

Location	Region	Latitude	Longitude	Comments
Driftwood County Park	North Puget Sound	48.163	-122.637	There is a substantial tire reef at this location.
Fort Worden Pier	North Puget Sound	48.1354	-122.761	There is a small tire reef just south of the Marine Life Center Pier
Mukilteo Oil Dock	North Puget Sound	47.8113	-122.39	Adjacent to private tidelands
Edmonds	North Puget Sound	47.8122	-122.387	Primarily south of the ferry dock and north of the pipeline, reports from local divers of tires also located near and under the public fishing pier.
Seattle Public Fishing Pier	Central Puget Sound	47.6257	-122.373	Tire bundles located near and under the pier.
Illahee State Park	Central Puget Sound	47.6126	-122.594	This reef is noted on the nautical charts as a fish haven obstruction just south of the town of Illahee.
West Seattle Artificial Reef	Central Puget Sound	47.557	-122.407	There are a substantial number of tire bundles inshore of the quarry rock reef.
Tramp Harbor	Central Puget Sound	47.4062	-122.429	This reef is noted on the nautical charts as a fish haven obstruction on the south shore of Tramp Harbor on Maury Island.
Des Moines Public Fishing Pier	Central Puget Sound	47.4031	-122.334	This reef is located just west of the offshore end of the pier.
Saltwater State Park	Central Puget Sound	47.3731	-122.328	Many of the tire bundles were recently removed in connection with the new artificial reef construction; however, recent dives confirm that there are many remaining.
Old Town Dock	Central Puget Sound	47.2779	-122.465	Local divers report several tire bundles adjacent to the dock.
Carr Inlet	South Puget Sound	47.3094	-122.692	This reef is noted on the nautical charts as a fish haven obstruction near Kopachuck State Park south of Cutts Island.
Solo Point	South Puget Sound	47.1379	-122.636	Tire bundles were reportedly placed at this location by DNR in the seventies
Tolmie State Park	South Puget Sound	47.1249	-122.772	Local divers report several tire bundles near the sunken barges.
Case Inlet	South Puget Sound	47.2603	-122.863	This reef is noted on the nautical charts as a fish haven obstruction just north of McMicken Island.
Budd Inlet	South Puget Sound	47.1224	-122.903	This reef is noted on the nautical charts as a fish haven obstruction on the east shore of Budd Inlet south of Burfoot County Park.

Burfoot County Park	South Puget Sound	47.1311	-122.907	Tire bundles were reportedly placed at this location by DNR in the late seventies or early eighties. Anecdotal accounts from local divers would indicate that the tires are still there.
Frye Cove County Park	South Puget Sound	47.117	-122.961	This reef is noted on the nautical charts as a fish haven obstruction north of Flapjack Point near Frye Cove County Park on the west shore of Eld Inlet.
East Eld Inlet	South Puget Sound	47.107	-122.942	No Comments

Figure 5. Pile of tires that have washed ashore from failed reef bundles in Budd Inlet just south of the Burfoot County Park Reef. These tires have slices through the sidewall similar to tires found in other reefs. The cuts are made to promote air escapement, which allows them to sink during placement.

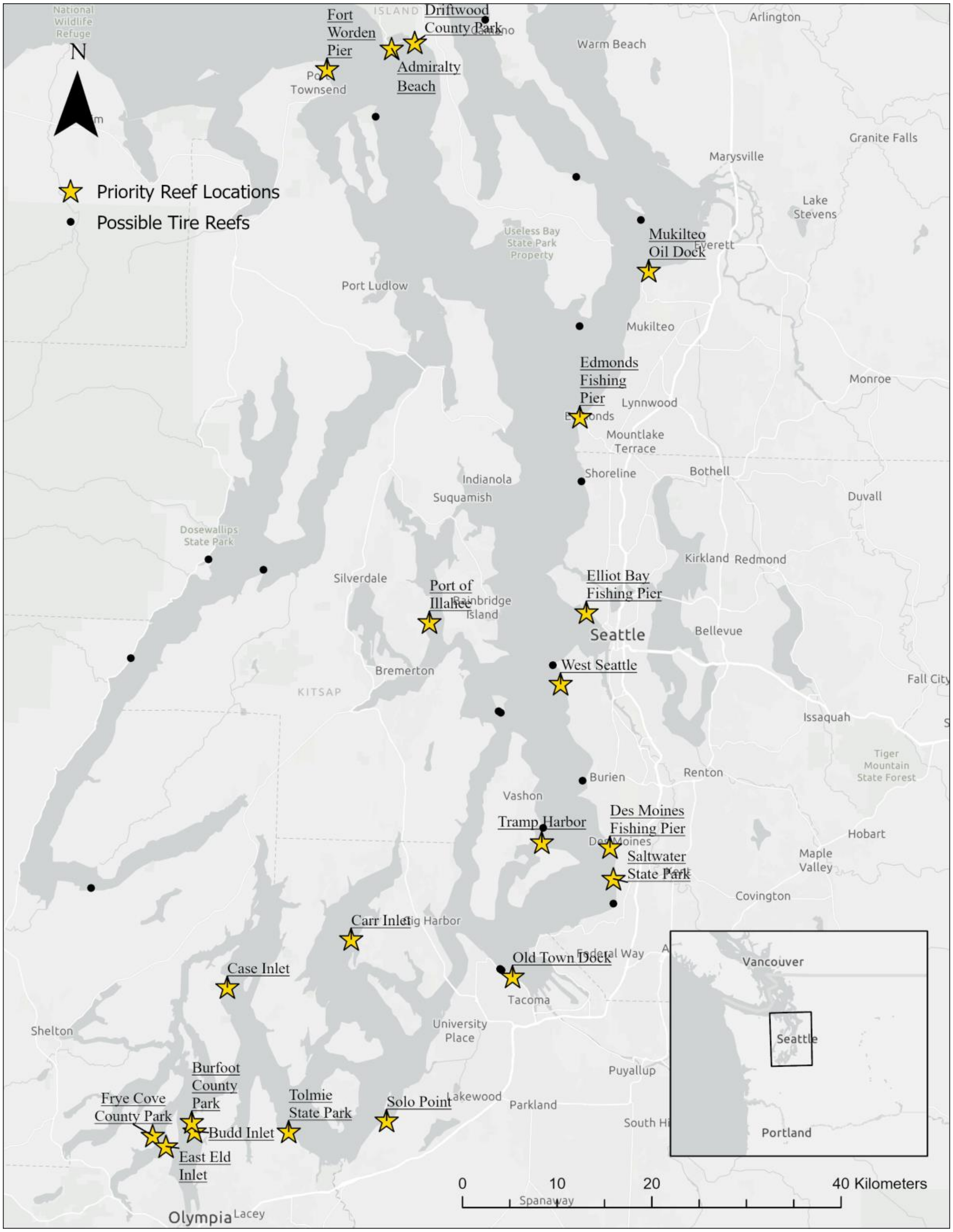

Figure 6. DNR surveyed 20 priority sites from a list of 40 known coordinates for this study. Original point coordinate data compiled and provided by the Washington Department of Fish and Wildlife.

2 Methods

2.1 Priority Reef Attributes

In 2019, AAMT began an effort to accurately locate and map twenty artificial reefs in Puget Sound. These reefs were prioritized based on their location on subtidal SOAL and for their believed proximity to state or other publicly owned uplands including county, city, or port property.

AAMT utilized several advanced data collection tools including a multibeam sonar, underwater towed video camera, and an underwater remotely operated vehicle (ROV) equipped with a front facing camera to map and identify features within each artificial reef. Using these data, the team was then able to estimate the number of tires, approximate their mass, and create maps and figures identifying tires and the type and location of other reef features. Table 2 shows the various reef attributes that were established, and method(s) used to collect them.

Table 2. Desired Attributes collecting using sonar, towed video, or ROV footage.

	Multibeam Sonar	Video	ROV
Reef location	+	+	
Reef volume	+		
Reef height	+		
Reef depth	+		
Tire reef area	+		
Materials present (metal strapping/tires/concrete)		+	+
Tire feature types		+	+
Number of tires (total estimate)	+		
Condition of materials present		+	+

2.2 Field Collection: Hydrographic Survey

For all 20 WDFW priority coordinates, a five-hundred-meter square survey area was mapped with sonar around each point center. DNR's twenty-two-foot-long research vessel (R/V *Neap*), equipped with an R2Sonic, Inc. 2020 multibeam sonar system and integrated navigation system was used for reef mapping (R2Sonic 2021).

The 2020 sonar is a small flat-array multibeam unit that combines a transmitter and receiver into a single instrument. This design has several advantages; along with its small size it also acts as a single reference point for both the transmit and receive nodes, which simplifies the number of calculations required by the navigation software (R2Sonic 2021). The 2020 system has an onboard surface computer and navigation system - position, heading, pitch, yaw, and roll are all recorded with an Applanix Inertial Motion Unit (IMU) and Trimble GNSS positioning system. Applanix POS PAC software (Applanix Corporation 2011) is used to post process raw motion and heading data collected in the field.

We collected hydrographic data at 400 kHz, with a beam width of 130 degrees. Care was taken to maintain an absorption spectrum across beam angles between 50 and 90 percent, and to maintain 50 to 100 percent data overlap between passes. Surveys were planned and carried out with QPS QINSY software. Continuous surface sound speeds were collected using an AML Micro X Sound velocity sensor attached at the sonar head, and full water column casts were taken every 2 hours with a Son-tek Castaway CTD. At the end of each survey, a patch test was completed.

Figure 7. Close-up of R2Sonic 2020 multibeam sonar head (bottom, grey) and Applanix IMU (top, black) with mount (blue).

Figure 8. R/V Neap with R2Sonic 2020 multibeam sonar system.

2.3 Post Processed Bathymetric Surface

Bathymetric data was cleaned and processed with QPS Qimera software. A processed position and motion file was created with Applanix PosPac software and applied to correct raw bathymetric files. Patch tests from field-collected data were also applied within Qimera.

A dynamic surface was calculated using the Combined Uncertainty and Bathymetric Estimator (CUBE) algorithm within Qimera, from which all point surface data anomalies were edited by hand (Calder and Wells 2006). The surface was then exported as a Bathymetric Attributed Grid (BAG) file. BAG files are a raster format, with each grid cell assigned a specific depth calculated as an average of the point surface. BAGs were exported in the NAVD88 (m) vertical datum (NAD 83 (m) horizontal datum) with a resolution of $0.25m^2$. BAGs for each survey were imported into Arc GIS where topographical slope and hill-shade files were created (Costa et. al. 2009). The slope layer assigns a value from zero to ninety degrees which represents the maximum rate of change from a cell to its neighbors - it is a useful metric for identifying features raised from a flat surface (ESRI 2021).

Video Collection

A Sea Viewer brand Sea-Drop 950 towable camera with a Trimble brand Global Navigation Satellite System (GNSS) antennae (positions every second) was used to validate features identified in the sonar survey.

Raw GNSS data was differentially corrected in GPS Pathfinder office based on the nearest reliable base station. Corrected point files were converted to ASCII text files, for which comma separated value (.csv) files were created and used for video processing in VLC Media Player. DNR staff recorded the presence/absence of both tires and non-tire reef structure, the estimated number of tires, tire burial extent, sediment type, and the presence and absence of submerged marine vegetation. This information was converted to Geographic Information Systems (GIS) feature class formats to be overlaid on BAG surfaces in ArcGIS. Processed video feature classes were used to more accurately delineate reef extents and to inform BAG surface feature identity.

2.4 Diver Surveys

For four reefs in South Puget Sound (Tolmie State Park, Burfoot County Park, Solo Point, and Frye Cove County Park), divers from the DNR's geoduck compliance program collected measurements (length, width, height), and automobile tire counts for tire modules. The measurements that were collected were later georeferenced onto BAG surfaces which helped to refine tire density per unit area and to establish more accurate estimates of tire quantity for these sites. In addition, divers collected GoPro video footage and photographs of tire modules at these reefs.

2.5 Determining Reef Metrics from Field-Collected Data

Estimates for reef size and shape were determined from delineations of reef features within cleaned multi-beam BAG surfaces. Once features were identified in BAGs, various attributes were calculated from the volume and footprint area of these features. These attributes included estimates for reef depth, footprint size, tire number, and tire mass (Table 2).

2.5.1 Distinguishing Automobile Tires from Other Non-Tire Features in Bathymetric Data

Many reefs were composed of a mix of automobile tires and other debris - it was important to identify both tires as well as all types of debris incorporated into each reef.
The natural substrate among tire reef locations ranged from soft silt to coarse sand-gravel mix with large erratic boulders, and the first step in estimating reef metrics was to differentiate tires from these other features.

Where towed video data was available, it was used to ground truth tire features and delineate them from other reef materials. In this way it informed our knowledge of site-specific features (i.e., likelihood of fallen boulders from nearby railroad grade, jetty or natural presence), vs. the likelihood of it being a tire module.

Once identified from visual inspection of the BAG imagery, tire and rock features were separately demarcated in ArcGIS by manually placing nodes over them (Figure 9, Figure 10). Nodes were placed no more than 1.5m apart. When towed video was not sufficient to determine a feature, a "potential tire" feature class node was used.

Non-tire features that had hard (linear) sides such as concrete blocks, outfalls, concrete pilings, wood pilings, and submerged barges, were traced into a separate "linear feature" polygon feature class.

2.5.2 Tire Feature Volume (Minimum Value)

A volume-based calculation to determine an estimate of the minimum number of tires at a site. To estimate the volume of tires in a reef, the tire node feature class was buffered and dissolved by 1, 1.5, and 2 m using the buffer tool in ArcGIS Pro with the dissolve tool. The resulting buffer-footprint covered all identified tire features within the reef (Figure 10). This same process was carried out for potential tire nodes.

A "reef footprint" feature class was next manually delineated to surround the 1.5m tire node footprint and any part of the potential buffer footprint that also appeared to contribute to the main reef (Figure 11). In some cases, the total reef footprint included other non- tire features such as wooden barges that were intentionally placed at the site to create reef habitat.

The tire node feature classes and total reef footprint were fed into a python scripted Arc GIS tool, which calculated the total volume of tires at a site. This tool creates a blank interpolated version of the BAG surface by cutting out all features within the 1.5m tire node buffer. The voids are then interpolated with the elevation void-fill function. Next, the tool subtracts the flat surface from the original unaltered BAG surface, a process by which reveals the total volume of tires above sediment level. Detailed documentation about this ArcPro tool is available in supplemental materials (WA DNR, 2020). The average volume produced from 1, 1.5, and 2 m buffers was used in the following steps to calculate tire quantity from volume.

Tire Estimate from Volume of Tires Above Sediment Level

To calculate the number of tires from volume, volume was multiplied by the estimated tire density. Guidelines by the California Waste Tire Estimator Program were followed (Table 3) (CalRecycle 2021). The density of tires per unit volume from CalRecycle is based on the method of stacking (barrel, or loose) and the total pile height for tires greater than 15 years old (Table 3). Field measurements were used in place of the CalRecycle estimate for four South Sound reefs where DNR divers collected accurate density estimates.

Loose stacked formations are those where loosely piled tires are placed in an unorganized mound. Tires within this mound are often bound with polypropylene line. Barrel stacked tires, on the other hand, are those banded with strapping (usually polypropylene line) into a machine-assisted cylinder shape. Figure 13 shows barrel stacking for tires stacked upright. Barrel formations within tire reefs were dropped by boat and are usually laying parallel to the sediment surface - they can be grouped in barrels of three or more to create pyramid shaped features. Because tires are neatly stacked next to one another in a barrel stack, the number of tires per unit area is higher than for loose stacking (Table 3).

The volumetric based tire estimate produced through these methods is considered a minimum estimate. This is because it does not account for any volume of the tires buried in sediments. To provide a more accurate range of tires in any reef, a maximum extent was also established.

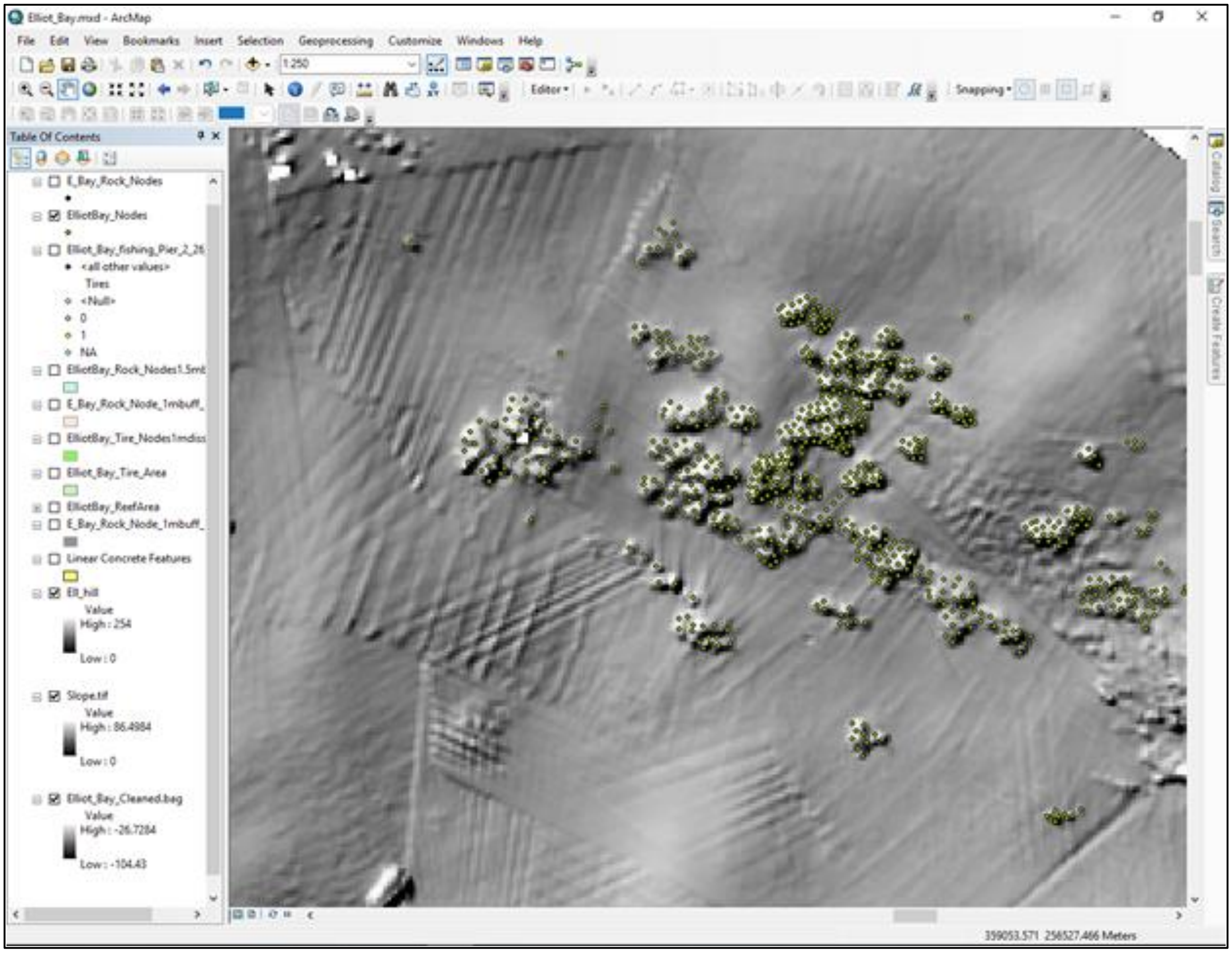

Figure 9. Tire nodes placed over tire reef features at the Elliott Bay Fishing Pier reef. Nodes are manually placed within 1.5 m of eachother.

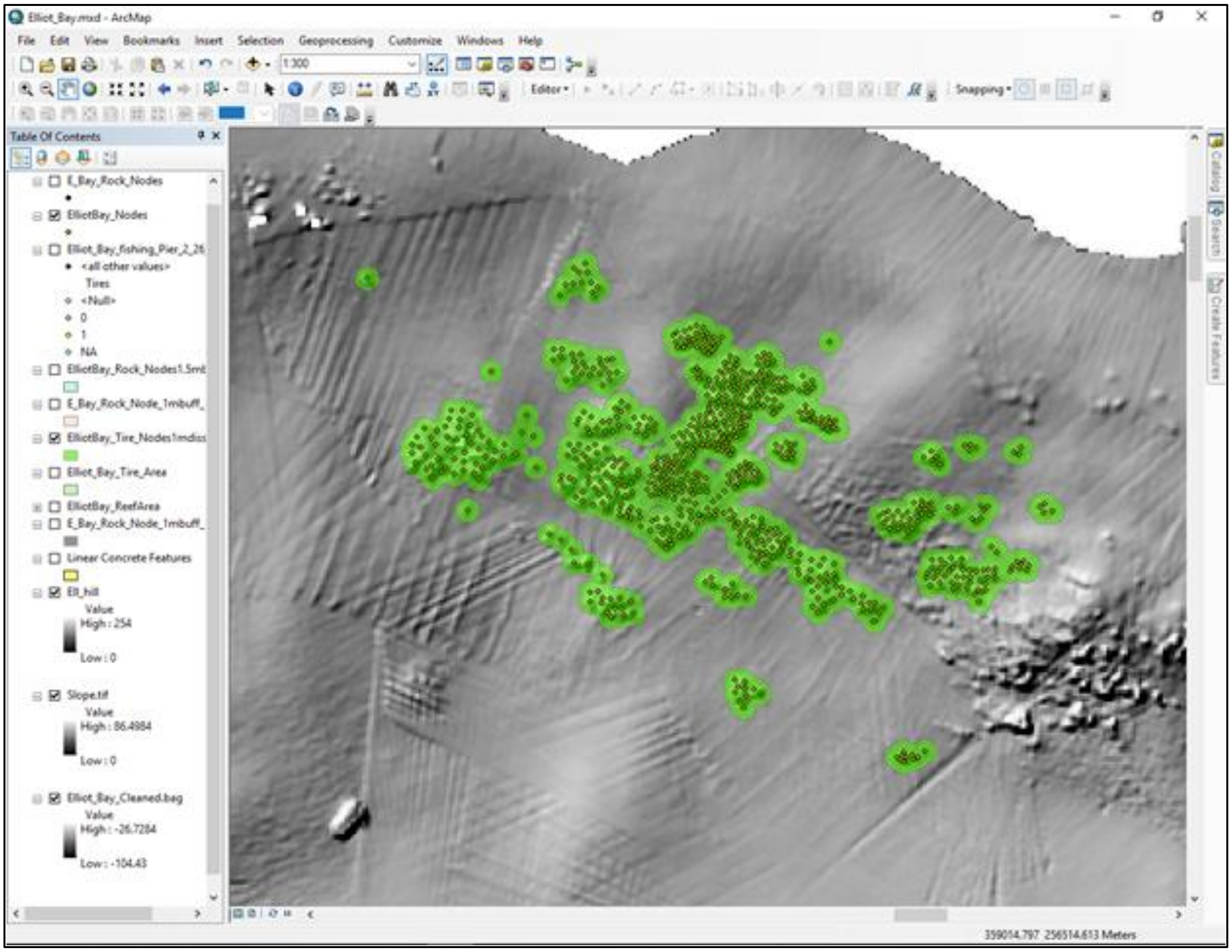

Figure 10. Tire Nodes with 1.5m buffer placed on tire features at the Elliott Bay Fishing Pier tire reef.

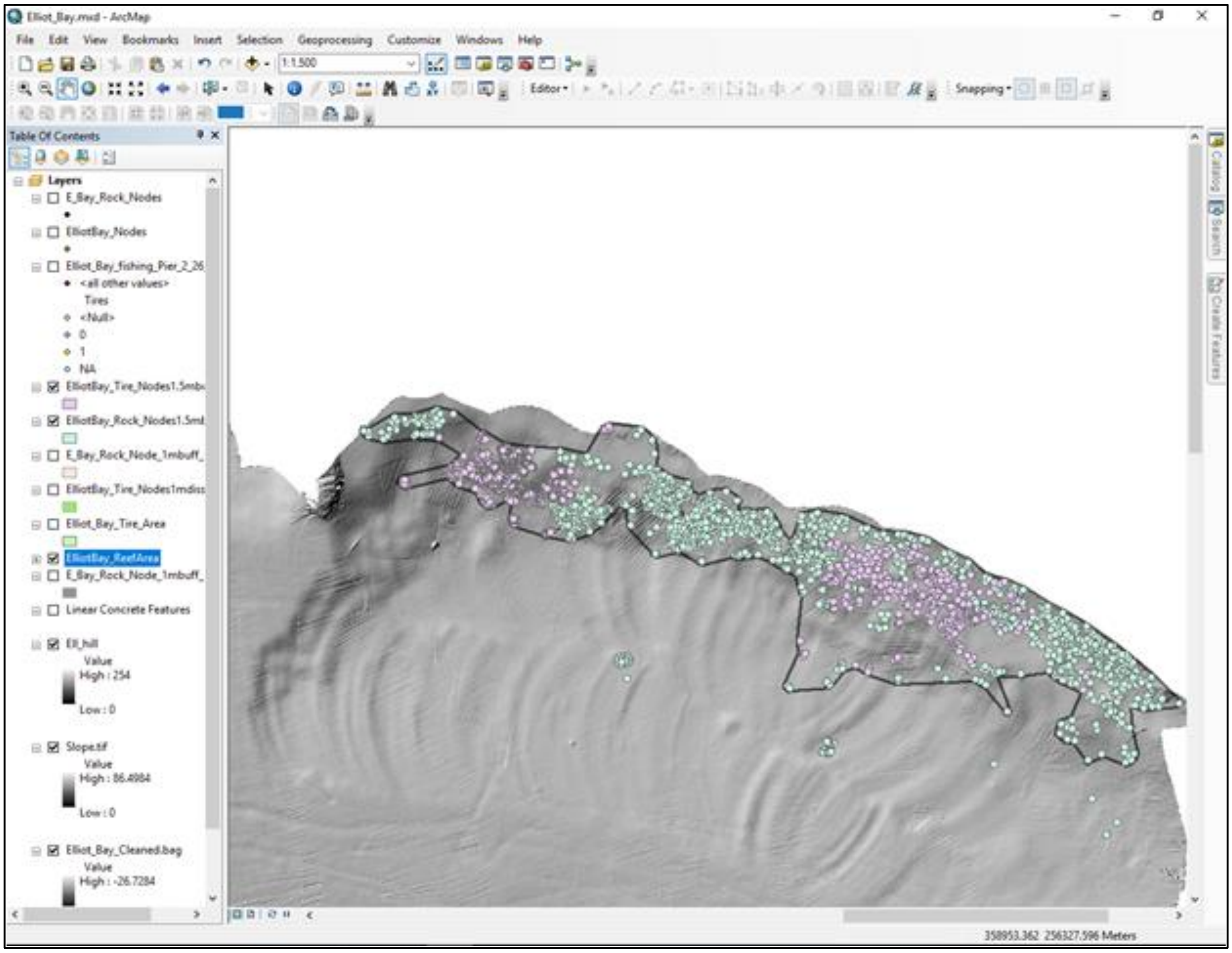

Figure 11. Reef footprint showing the general shape of the Elliott Bay Fishing Pier tire reef. Blue points indicate tire nodes, and pink points are rock nodes. The black polygon is a footprint of the main reef's horizontal extent and dispersion.

Table 3. Passenger and truck tire density estimates per m³ for tires stored 15 years or longer based on the height of pile (Calrecycle 2021). Tires were stacked less than three m high and were either barrel laced or loose stacked at all sites.

Storage Type	Height of Pile		
	< 3 m	**3 – 4.6 m**	**> 4.6 m**
Loose Stacking	15.72	18.34	20.96
Barrel Stacking	18.34	20.96	23.58

Figure 12. An example of loose tire stacking. Image from Calrecycle.gov.

Figure 13. An example of barrel stacking. Image from Calrecycle.gov.

2.5.3 Tire Estimate from 1.5m Buffer (Maximum Value)

A maximum estimate of tires was established by multiplying the 1.5m tire node buffer feature class by an estimated density per unit area (m^2) in the reef. The estimated density per unit area was determined by sampling three tire modules coinciding with video data within the 1.5 m tire node buffer. Tires for each module were counted in video footage, and module dimensions were measured from the BAG surface. The number of tires per unit area in the 1.5m buffer selection was then calculated. For four South Sound reefs where DNR divers measured tire modules, diver dimensions were used in place of this methodology. Tire density is multiplied by the total area of the 1.5m tire node buffer feature:

$$A_b * D_t = Maximum\ Tire\ Estimate$$

Where:

$A_b = total\ m^2\ of\ 1.5m\ node\ buffer$
$Dt = density\ of\ tires\ established\ from\ video\ analysis$

This maximum value accounts for the buried portions of tires missed in volumetric analysis but likely overestimates the actual number of tires present at any site. This overestimate is extrapolated when it is used for sites where tires are not buried, and where a volumetric analysis is more appropriate. Standard error is reported from the tire quantities calculated from three different tire densities.

2.5.4 Minimum and Maximum Tire Mass Estimates

Estimates of tire mass were calculated by multiplying the tire estimates from both volume and 1.5m buffer calculations by the approximate mass of a standard passenger vehicle tire (20 lbs.) (CalRecycle 2021).

2.5.5 Minimum and Maximum Distance from Shore

Cross-shore distance from the beach to reef edges were measured in the GIS from the beach/ upland interface to the shallowest reef feature (minimum distance) and deepest (maximum distance) reef feature.

2.5.6 Minimum and Maximum Reef Depth

Average minimum and maximum reef depths were established for both the shallow and deep sides of the reef. Three measurements from both end of the reef as well as the middle point were taken to calculate this value.

2.5.7 Reef Footprint

A total reef footprint was created by hand delineating a boundary around all reef features in GIS (1.5m tire node buffer, linear features etc.) (Figure 11). All features within a reasonable distance to the main reef were included in this footprint. Potential features which were separate from the majority of features at a site were likely not part of the intended reef and were not included in this polygon.

2.5.8 Estimated Number of Bundles

The number of bundles for a site was estimated by dividing the average number of tires per bundle (estimated through either diving surveys or video footage) by the maximum tire value.

3 Results

3.1 General Survey Findings

Reef structure was found at 16 of 20 surveyed reefs (Figure 14), and tires were confirmed or suspected at 14 of these sites. The two sites where no tires were found within reef structure were the West Seattle and the Mukilteo Oil Dock sites. Only large riprap boulders were found at the West Seattle site, whereas creosote pilings left over from removed dock structure were found at the Mukilteo Oil Dock. Table 4 is a summary of the materials found at each reef location. No reef structure was found at East Eld Inlet, Budd Inlet, Tramp Harbor, or Admiralty Beach sites. The majority (64%) of sites with confirmed automobile tires had other reef materials present. Depending on the site, this “other” structure could include concrete blocks, wooden pilings, wooden barges, large rip-rap boulders, and miscellaneous metal structure or other refuse. While no tires were captured in video footage at the Driftwood County Park and Fort Worden sites, features we found in multibeam data which suggest the presence of tires.

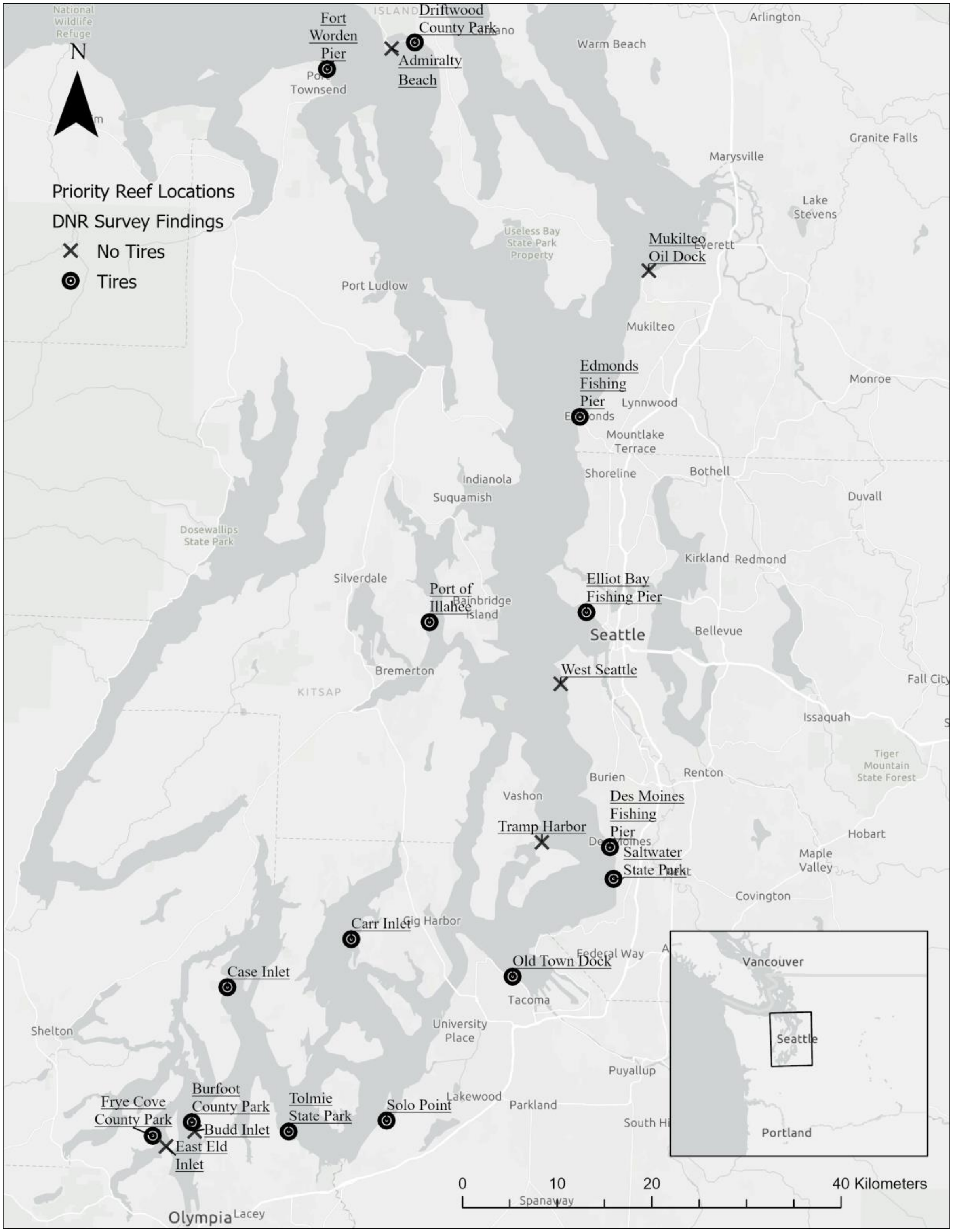

Figure 14. Tire presence and absence for reefs that were surveyed by DNR.

Table 4. Qualitative survey attributes for DNR surveyed sites.

Site	Tires Found	Banding Material	Banding Condition	Materials Present
Driftwood County Park (Whidbey Island)	Yes	Polypropylene line	NA	Video unavailable, tires suspected, pilings
Port Townsend (Fort Worden)	Yes	Polypropylene line	NA	Concrete, tires suspected
Edmonds Fishing Pier	Yes	Polypropylene line	Medium	Tire, concrete, chain
Elliott Bay Fishing Pier	Yes	Polypropylene line	Medium	Tire and boulder
Illahee	Yes	Polypropylene line	Good	Tires
Des Moines	Yes	Polypropylene line	Good	Tires, concrete, metal, boulder, other
Salt Water State Park	Yes	Polypropylene line	Poor	Tires, concrete, wooden pilings, boulder, wooden barge
Old Town Dock	Yes	Polypropylene line	Good	Tires, metal, chain, concrete, wooden pilings, cinderblocks, electric scooters
Carr Inlet (Kopachuck State Park)	Yes	Polypropylene line	Good	Tires, wooden barge
Case Inlet (Harstine Island State Park)	Yes	Polypropylene line	Good	Tires
Solo Point	Yes	Polypropylene line	Poor	Tires
Tolmie State Park	Yes	Polypropylene line	Medium	Tires, wooden barge
Burfoot County Park (Budd Inlet)	Yes	Polypropylene line	Poor	Tires
Frye Cove County Park (Eld Inlet)	Yes	Polypropylene line	Poor	Tires
Tramp Harbor (Vashon)	No	NA	NA	No reef found
West Seattle (Alki)	No	NA	NA	Boulder
Mukilteo Oil Dock	No	NA	NA	Pilings
East Eld Inlet	No	NA	NA	No reef found
Budd Inlet	No	NA	NA	Tires found north of site at Burfoot County Park
Admiralty Beach (Whidbey)	No	NA	NA	No reef found

3.2 Minimum and Maximum Reef Depths

The depth at which tire reefs existed varied based on their location, bathymetry of the nearby area, and reef size (Figure 15). In general, North and Middle Sound sites extended to greater depths than South Sound sites did, with many of them at depths exceeding 60 ft. NAVD88. Some sites were found to cover narrow bands of depth (Carr Inlet, Frye Cove, Illahee), whereas other sites (Elliott Bay, Des Moines, and Burfoot County Park) had tire features spread over a greater range of depths. Both the slope profile and the reef's overall footprint size played an important role in how variable depths were at a site. Sites that were steeply sloped (Burfoot County Park, Elliott Bay Fishing Pier) tended to have tires spread over a greater range of depths even though they may not have had the largest footprint. Many of the sites in South Sound can attribute a constricted range of depths to low slope profiles when compared to the sites in North or Middle Sound. At other sites, the footprint size of a reef was most important for whether tires could be found at variable depths. Solo Point covered a footprint so large that while most of the reef was at relatively shallow depths (< 30 ft.), a few tire features were found at 60 - 70 ft. NAVD88. Suggesting, that over time tire bundles have moved off the expansive shallow shelf from where they had been placed initially. Des Moines is another example of a reef with so large a footprint that tires could be found at nearly 80 ft. (NAVD88) of water.

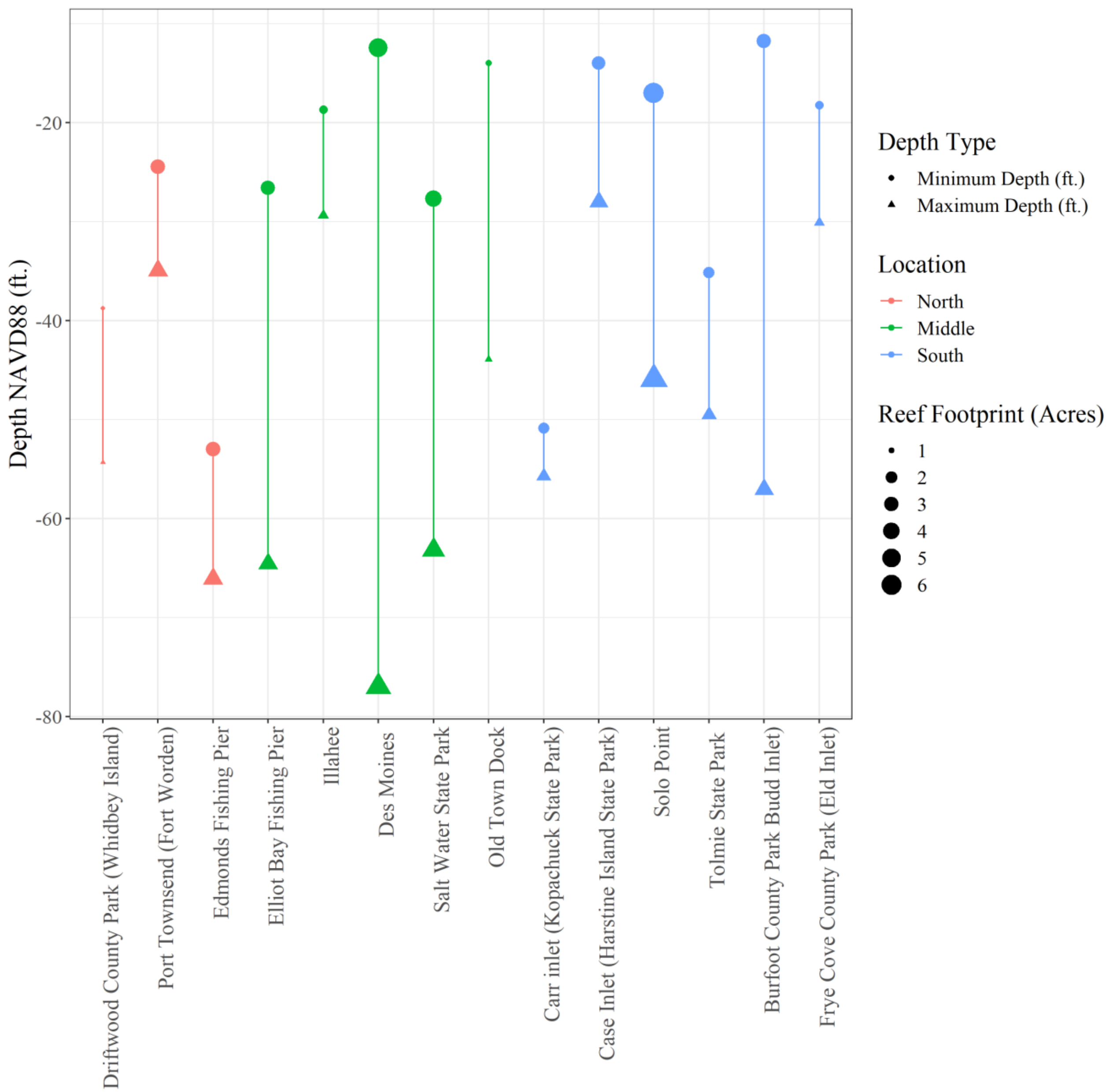

Figure 15. Average minimum and maximum depths for DNR surveyed tire reefs. The size of depth indicators is representative of the reefs' footprint size, whereas the color indicates its general location. Sites are organized from left to right by latitude (North to South).

3.3 Reef Footprint

The overall reef footprint varied extensively by site. It was apparent that the footprint covered by any particular reef had direct ties to how it was placed and for what purpose. For some of the sites, tire features had been intentionally focused around nearby fishing piers. At these sites, tire features were specifically intended to increase the productivity of fishing nearby fishing piers. Elliott Bay, Edmonds, and Illahee reefs are examples of reefs with modest footprints (3.23, 3.43, and 1.34 acres) that are focused nearby dock and fishing pier structure. While these footprints were not the largest, we do estimate them to hold more tires than most sites (Figure 16). This is because these sites (along with the larger Des Moines reef) are estimated to have higher densities of tires per acre compared to other sites (Figure 18). The Des Moines tire reef is spread over the second largest footprint (5.67 acres) and has high density tire bundles around the fishing pier there (Figure 18). Comparatively, the Solo Point tire reef had the largest reef footprint, but was on the lower end of estimated tires per acre (Figure 18). Tire bundles at Solo Point site were haphazardly strewn about the 6.75-acre footprint and look to have been thrown out of a drifting vessel in an unorganized fashion. Strong currents at the Solo Pt. site appear to have pulled tire bundles deeper than their original placement – effectively increasing the reef footprint of the site. We know that for three sites (Frye Cove, Saltwater State Park, and Burfoot County Park) the footprint we have mapped is smaller than the area the reef extends, and for these sites, we expect more tires to be found over a greater area than what is represented in this report.

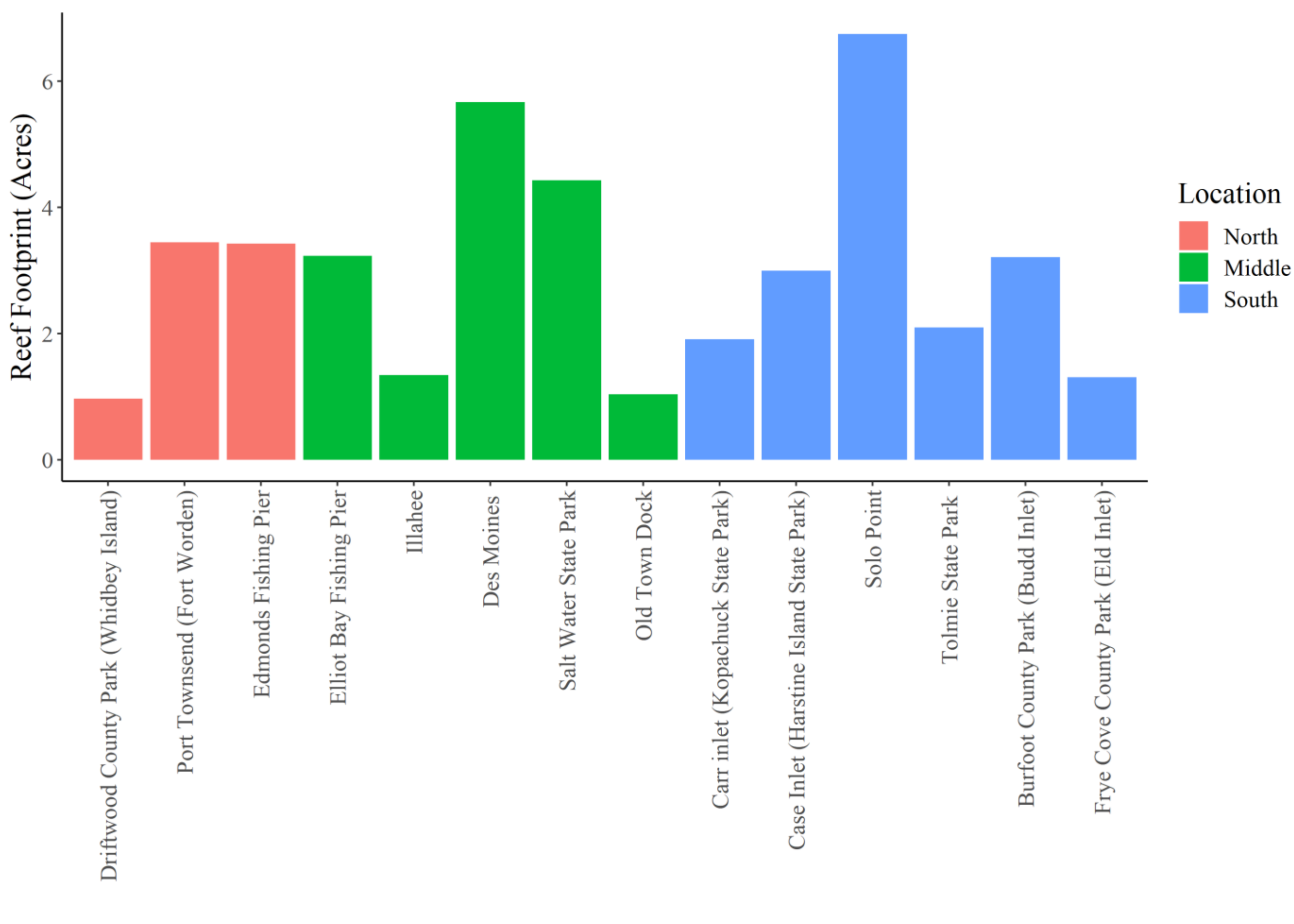

Figure 16. Footprint sizes of all mapped reefs.

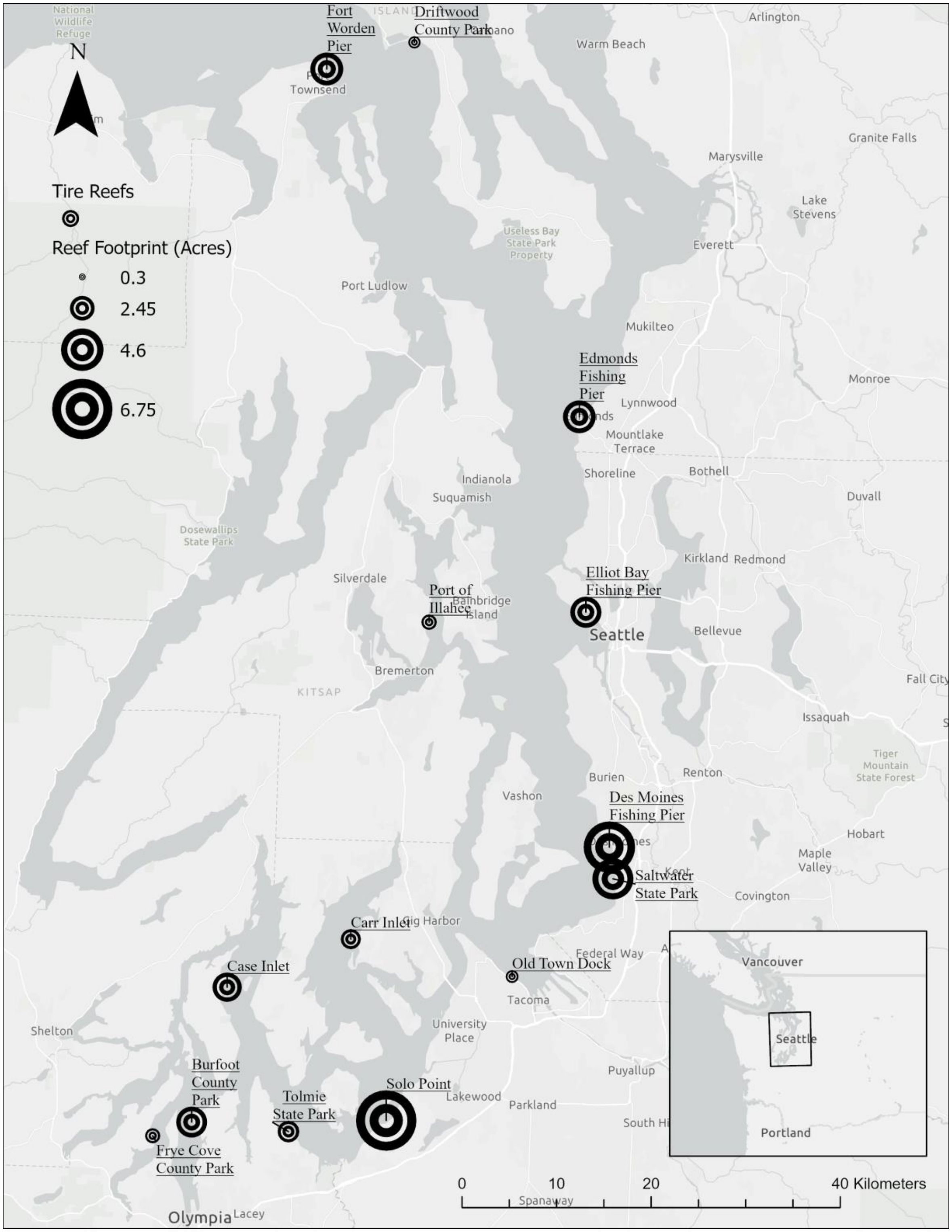

Figure 17. Tire reefs symbolized by footprint size in acres.

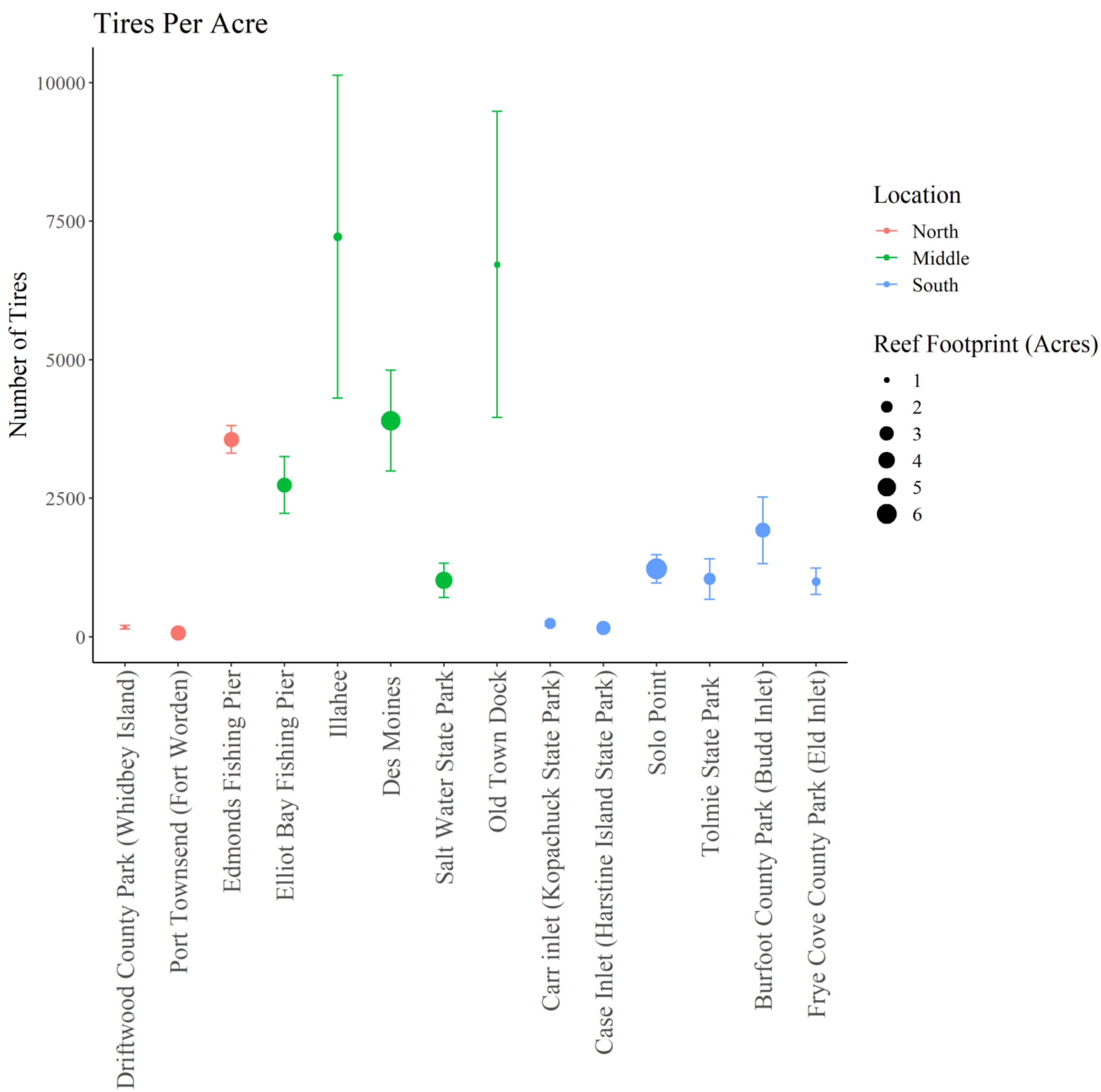

Figure 18. Number of tires per acre. A high estimate (density-based calculation) was used to establish these values. Error bars indicate standard error.

3.4 Tire Burial

Tires were buried into the sediment at different depths across the 12 mapped reefs (Figure 19). For North and Middle Sound reefs, moderate to low burial was found. Apart from a few sites in these zones where fine sediment was found covering the bottom row tire features up to 50% (Illahee and Edmonds), the substrate was generally harder and composed of coarser sand, gravel or cobble. With harder substrates like these, tires do not sink into surface sediments as they have at other sites.

Deeply buried tires were found at three of four South Sound sites (Frye Cove, Burfoot County Park, and Solo Point) where slow tidal currents and heavy sedimentation are common. Some tire modules at these sites are completely covered and are not represented in our estimates for tire quantity, mass, or bundle number since we were unable to detect them. Tires that are most buried (greater than 50%), are expected to cost more to remove based on the increased time needed to free them and the additional weight they will carry from sediment.

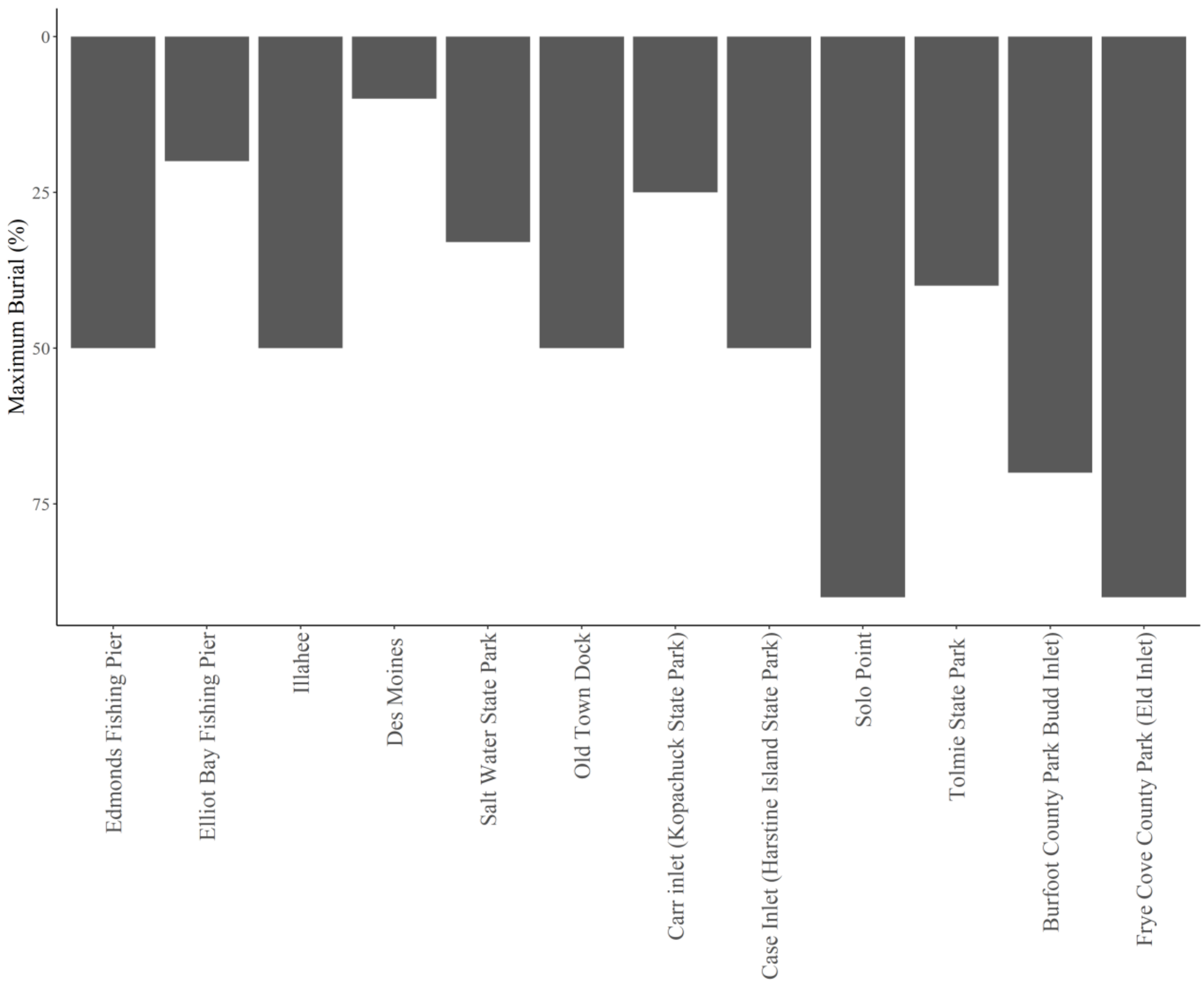

Figure 19. Maximum burial of the lowest layer of tires observed from video and diver surveys. Driftwood County Park and Fort Worden sites were not included. There was no confirmatory video collected for either of these sites.

3.5 Minimum and Maximum Tire Estimate

Minimum and maximum estimates for tires followed similar patterns over the 14 confirmed tire reefs (Figure 19 and Figure 20). Like footprint size, the number of tires in any one reef was tied to its specific purpose and location.

Middle Sound reefs had more tires in them than those located in the South Sound. Bundle type was a driving factor for this trend, with more tires per bundle (or many small bundles grouped together into bigger formations) at Middle Sound Sites compared to single barrel-row bundles characteristic of South Sound sites. Like footprint size, we found more tires in Middle Sound reefs that were focused around fishing piers or docks. The Des Moines, Edmonds, Elliott Bay, and Illahee reefs fell into this category with maximum estimates of 22,117 ± 5,153 (SE), 12,219 ± 861 (SE), 8,848 ± 1,643 (SE), and 9,674 ± 3903 (SE) tires each. Reefs such as Edmonds and Elliott Bay that were implemented by the Marine Fisheries Enhancement Division of the WDF tend of have more densely designed tire features and more overall tires.

Comparatively, small reefs tended to be those in front of County or State run parks and include Driftwood County Park (166 ± 34 (SE) tires), Carr Inlet (454 ± 81 (SE) tires), and Case Inlet (481 ± 130 (SE) tires). Two South Sound sites yielded larger tire number estimates than the others - Burfoot County Park and Solo Point. These sites were simply larger in footprint than the other sites and had more bundled tire features deployed at them. It is important to also point out that the Saltwater State Park, Burfoot County Park, and Frye Cove reefs were not fully mapped in DNR surveys and the maximum number of tires as well as the overall footprint for these sites is larger than stated here.

The minimum tire estimate produced from tire volume estimated on average only 30% of the tires that our estimate from the 1.5m buffer determined. This discrepancy can be partially explained by the extent to which tires were buried. For sites with the softest sediment and most extensive burial, the ratio for minimum to maximum estimates was lower. This was true for the Burfoot County Park and Frye Cove reefs where this ratio is 13% and 11% respectively. Tire features at these sites were generally one row of eight tires bundled into a barrel formation - some of which were buried up to 90%. Because the minimum estimate is based on volume, we can assume that it is capturing only the portion of tire features that are exposed. For sites where there was limited burial of the bottom row of tires (Des Moines, Elliott Bay, and Saltwater State Park), the minimum/maximum ratio was higher. These exhibited minimum estimate/maximum estimate ratios of 57%, 44%, and 28% respectively.

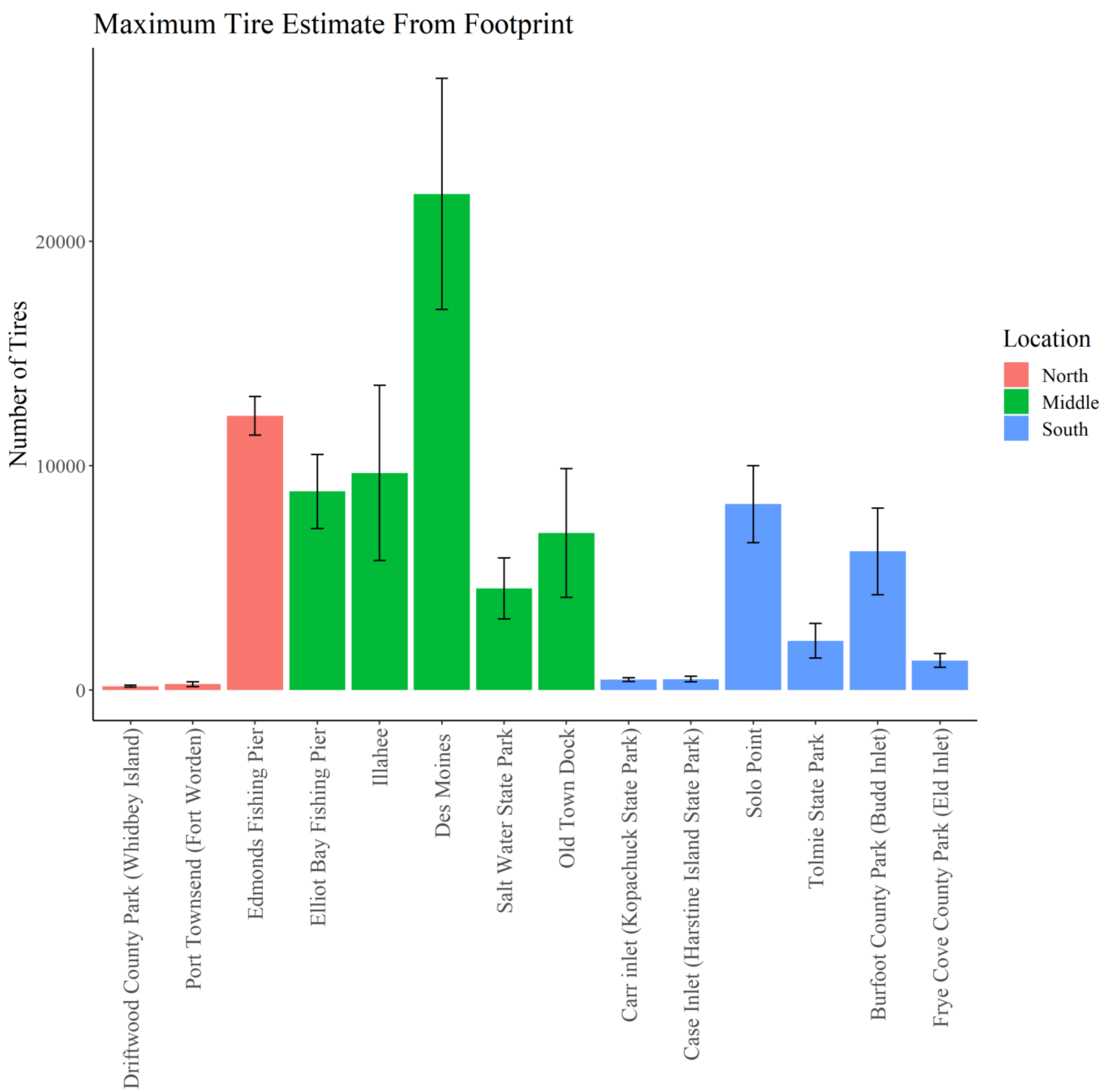

Figure 20. Total number of tires estimated from maximum estimate (footprint - density method). Error bars indicate standard error. Note: only a fraction of the Frye Cove County park site was mapped in DNR surveys (realized after the fact), and it is likely that many more tires exist there. This is also the case for Saltwater State Park. Sites with extensive burial may also have additional tire features that are not represented by these estimates.

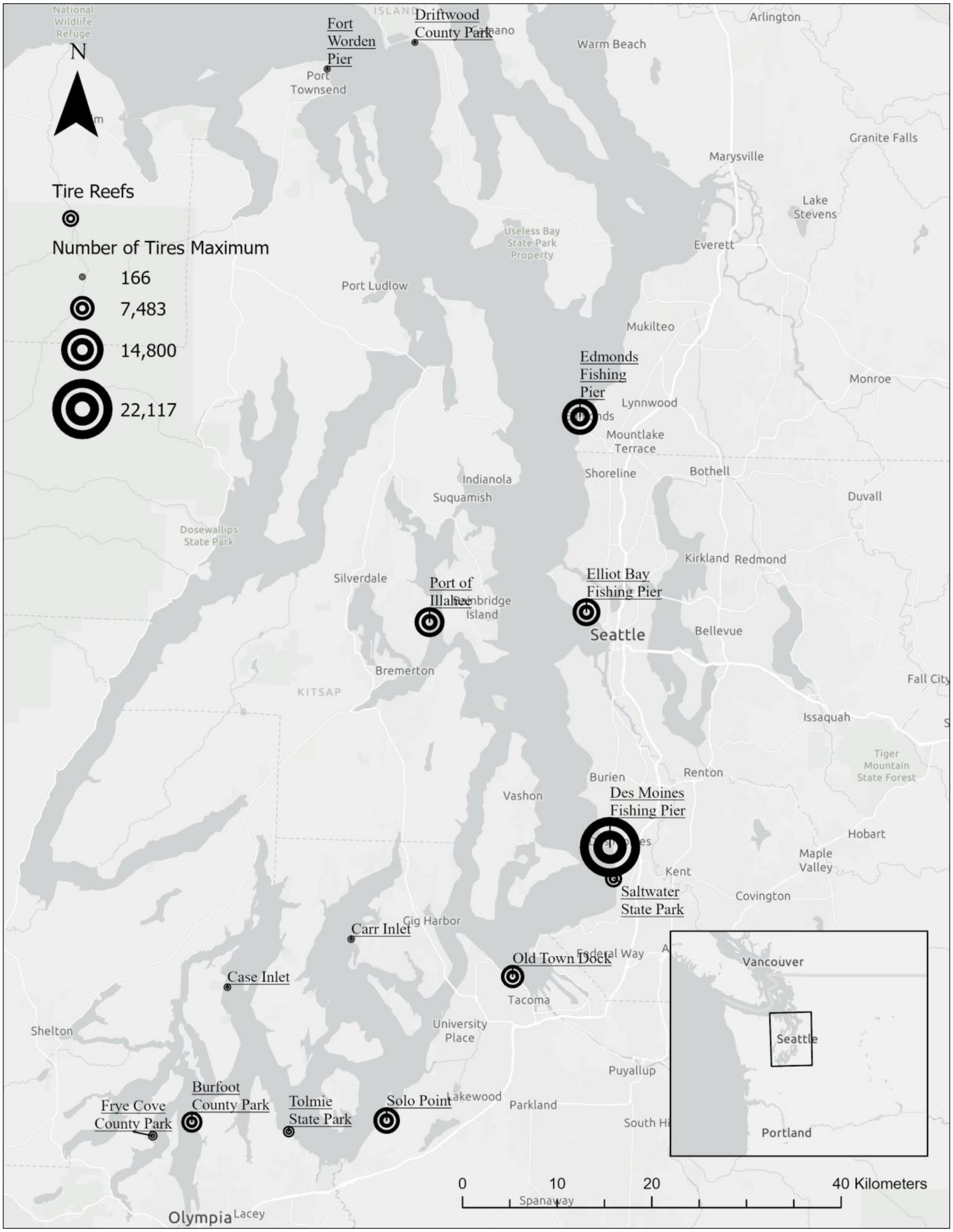

Figure 21. Map of the maximum number of tires that were found. The size of the tire reef symbol is an indicator for the maximum number of tires at a reef.

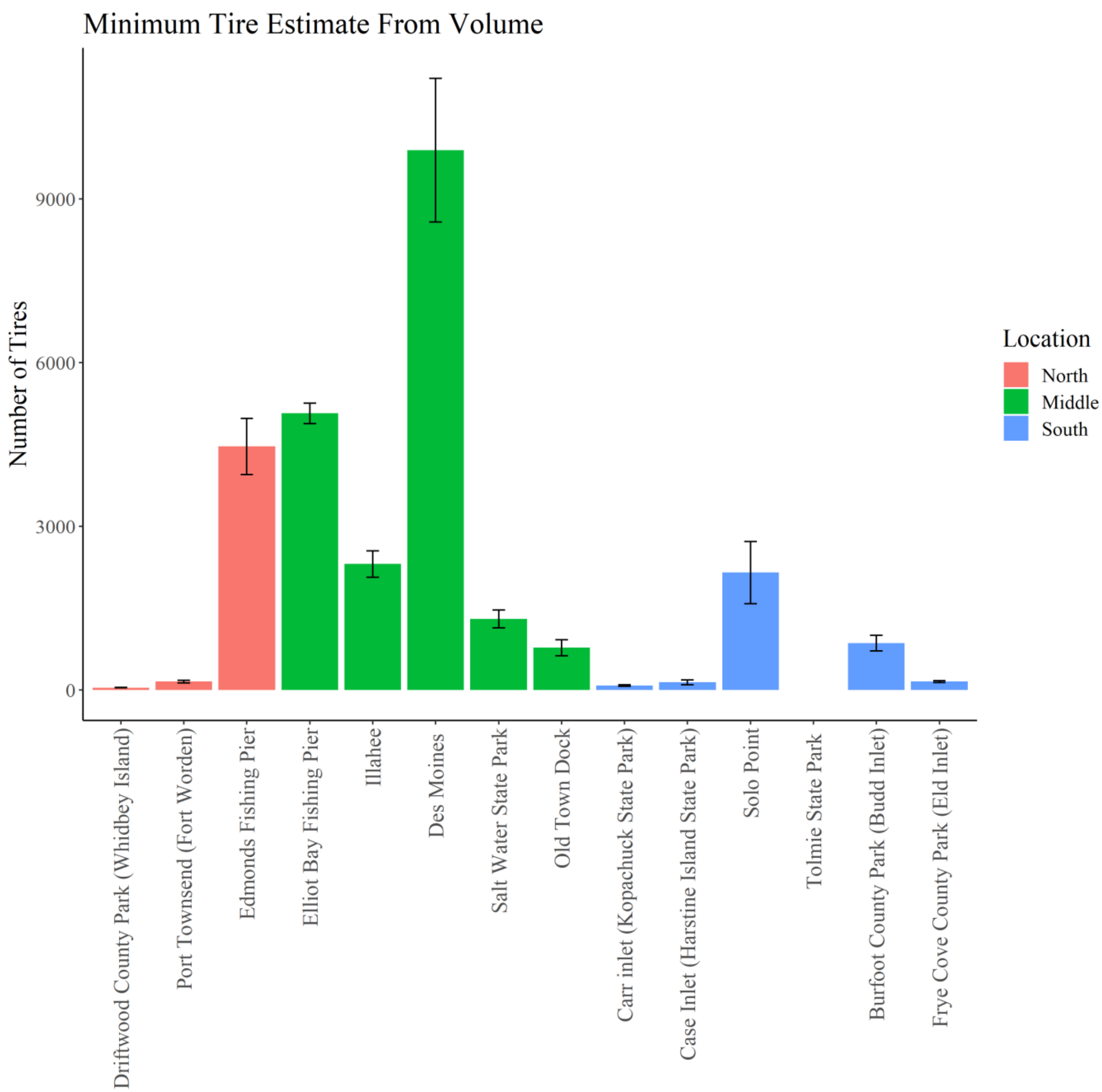

Figure 22. Total number of tires estimated from low estimate (volume method). Error bars indicate standard error. Note: only a fraction of the Frye Cove County park site was mapped in DNR surveys (realized after the fact), and it is likely that many more tires exist there. This is also the case for the Saltwater State Park site. Sites with extensive burial may also have additional tire features that are not represented by these estimates. Due to errors during the processing of the Tolmie State Park survey, a minimum tire estimate by volume is not producible and is not shown here.

3.6 Minimum and Maximum Mass of Tires

The minimum and maximum mass of tires for each reef is a direct extrapolation from the number of tires we have estimated for each site. The trends therefore are the same for mass as they are for the estimates of tires described above. Specific values for estimated mass can be found in the attached supplementary reports for each surveyed site.

3.7 Number of tire Bundles/Features

The number of bundles within a reef was dependent on the estimated number of tires in a reef and the average bundle size found there determined through video imagery or DNR diver surveys. Like other tire reef metrics, we found that bundle size was dependent on the original purpose of a reef and who constructed it. We found that for some reefs like Des Moines or Elliott Bay the number of tires per tire reef feature was large (24 to 21). Both of these reefs were installed around public fishing piers and include large tire features built of multiple smaller bundled groupings of tires. Larger features like these were intended to boost the abundance of fish by creating more cavernous structure for individuals to hide. For others (Old Town Dock or Illahee) the number of tires per bundle was found to be extremely small. The smallest bundles at these sites are expected to hold only three tires. Because of this, Old Town Dock and Illahee sites are estimated to have the highest number of tire bundles for all sites surveyed (Figure 23, Figure 24).

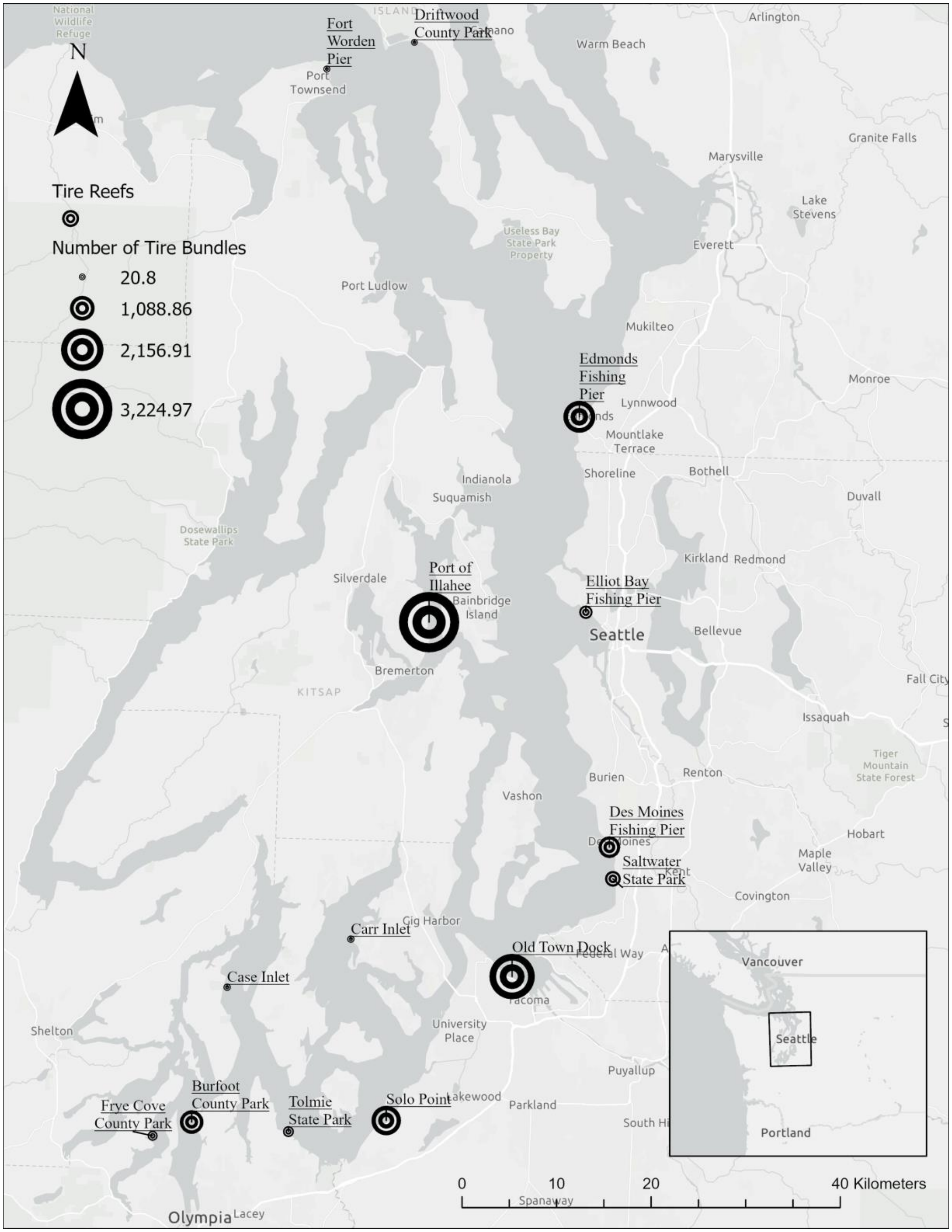

Figure 23. Map of reef sites that are expected to have automobile tires. The size of each tire reef symbol represents the number of tire bundles that are expected to be there.

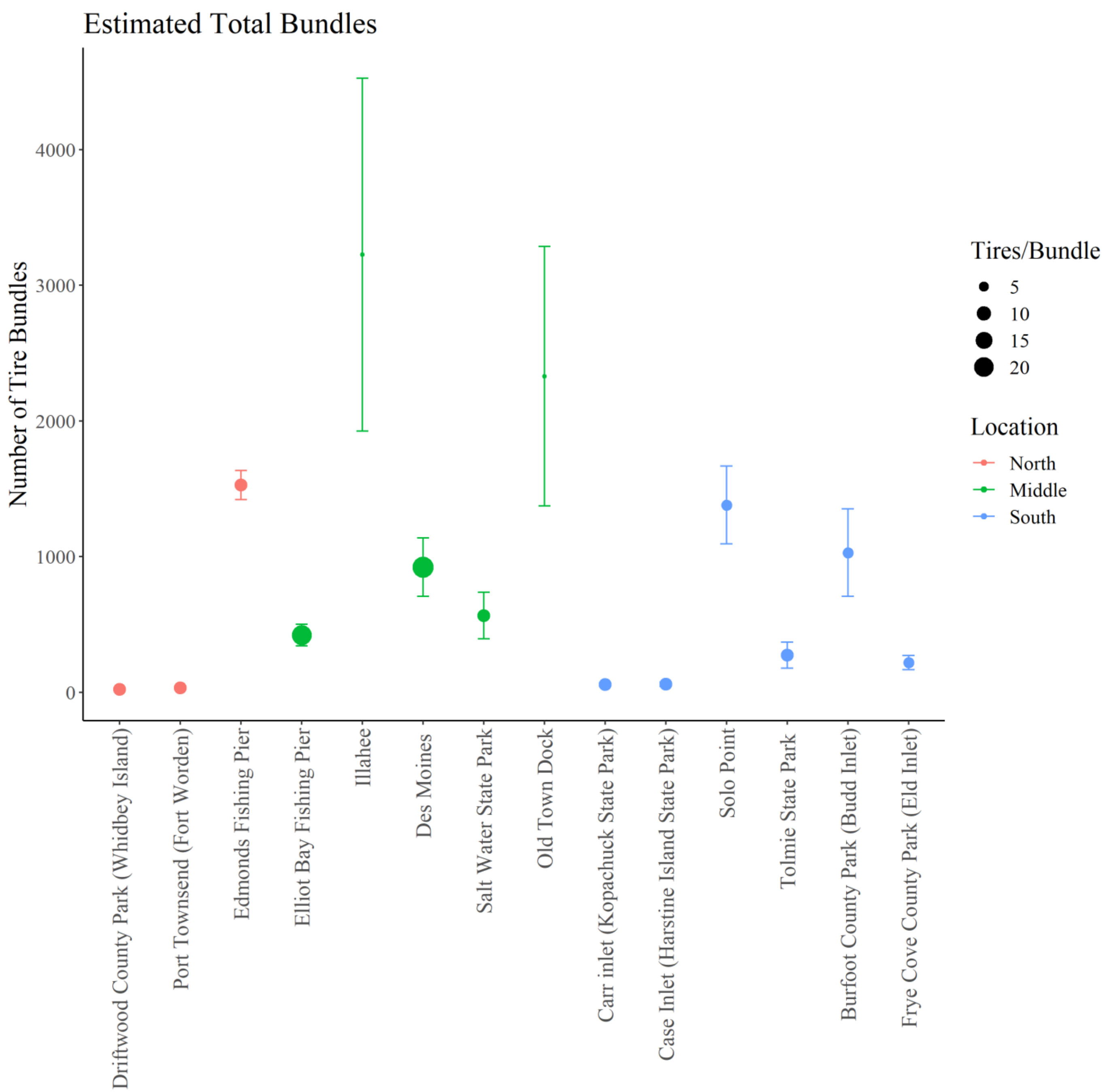

Figure 24. Number of bundles estimated from the number of tires per bundle. The high estimate (density based) total tire value was used for each site. Error bars indicate standard error.

4 Discussion

The reefs mapped in this study reveal that the number of tires, depth, total footprint, extent of burial, bundle type and size, and other materials present varies throughout Puget Sound. Due to the unique structure of each reef, a variety of specific challenges regarding their removal will influence the procedures and cost for each site.

Tire removal can occur with different techniques based on the specific attributes of a reef. Because removal is diving reliant, the cost associated with tire removal is largely driven by the hours of dive time. Large tire removal projects like those at the Osbourne Tire Reef in Fort Lauderdale Florida have employed the services of U.S. Navy diver salvage teams who utilized the opportunity as training exercises. In the case of the Osbourne reef, the strapping holding tire modules together had completely failed, forcing divers to collect and string together every tire that has been removed. Divers would string a metal cable through 50 tires at a time. Grouped tires were then lifted to the surface with 4,000-pound capacity lift bags. Once these bags surfaced, a crane operator would hook into the metal cable stringing tires, and lift them onto a floating barge (U.S. Navy 2008). In 2008, tires at the Osbourne reef were removed at a cost of two dollars per tire (U.S. Navy 2008).

A smaller removal project that occurred at the Les Davies Pier in Tacoma provides an example of how tire reefs can be removed in Puget Sound. In 2015, 2,855 tires were removed offshore from the Les Davies Pier in Tacoma, WA. Tire removal at this site was carried out by the Nisqually Indian Tribe's Marine Services Division, who bundled the tires with synthetic rope and lifted them to the surface with a boat-mounted crane. In all, 57 individual tire bundles were removed from the site at a total cost of ten dollars per tire.

4.1 Considerations for the Removal of Tires from Puget Sound

Differences in the attributes we found at certain reefs will provide challenges of varying degree when tires are removed. Sites that have tires at greater depths (i.e., Des Moines, Saltwater, Elliott Bay, Edmonds, and Burfoot County Park) will take more time and require more divers than those that are generally shallower. Similarly, reefs which have less tire features per unit area will be costlier per tire to remove, since divers will have to spend more time searching for tires. In this case, the costs are inflated due to the time that will be needed for divers or boat operators to move and find tires that would otherwise be obvious at sites with higher density tires per acre.

Additionally, tires that are buried in sediment to greater extents will take additional effort to remove. We found that at certain locations, some tires and tire features are nearly buried (up to 90%) or completely buried in fine sediment. These sites may require additional effort from diving personnel to find and free buried bundles before they are cable joined and lifted to the surface. A related unknown will be the total mass of these buried tire features once they are freed from the sediment. While we do not anticipate there being negative ballast like concrete filling the tires, they will surely be filled with sediment, and covered in plumose anemones or other fouling organisms. This additional mass should be considered and included when calculating weight limits and equipment capacities.

Bundle size is an important consideration as well. It is unlikely that the polypropylene line still grouping tires into tire features is robust enough to hold the weight of the tires as they are lifted to the surface. Divers will likely need to thread a line or cable through the middle of tire bundles to lift them. Based on the specific conditions at a site, bundles may then either be attached to a high-capacity float bag or lifted directly by crane onto a floating barge. For sites with tires that are banded into larger formations and have more tires per group (21 to 24 tires), costs would be lower due to the reduced number of times a diver would need to descend to connect a feature compared to sites that have less tires per bundle (some as low as 3 tires).

Failed banding was found at several sites where individual tires were distributed across the seafloor and where polypropylene line had visibly worn through. These sites will require more dive time per unit area than sites with intact bundles since divers will need to manually thread cable or line through individual tires.

Finally, it is important to highlight the presence of other material that may complicate the removal of tires from these sites. Many of the surveyed sites contain non-tire material mixed in with tires and tire modules. This ranges from concrete blocks and pilings to creosote pilings and wooden barge debris, which were found on top of or mixed in with tires. Over decades of fishing, many of the reefs nearby fishing piers have accumulated derelict gear. Des Moines, for example is known to have high quantities of broken monofilament fishing line, which is is nearly invisible to the human eye and presents a hazard for entangling divers (Leclair, L. Personal communication May 11, 2023). When planning for the removal of tires at these sites, it will be important to factor in the removal or movement of these other materials that may impede tire extraction or are a hazard for human health.

The removal of tires from the largest sites will need to be carefully coordinated with the Washington Department of Ecology to ensure there is space and a location for the proper disposal of material that is brought to the surface. Because of the marine life growing on them, the condition of the tires, and recent links to Coho salmon mortality (*Oncorhynchus kisutch*) from 6PPD-quinone in roadway runoff, it is not likely that they will be good candidates for a tire recycling program such as one that would turn them into turf (Tian et al. 2020). Instead, they will need to be transported to and placed in a landfill. Other items such as the lithium battery powered electric scooters found at the Old Town Dock Reef in Tacoma, or the creosote pilings at a few sites will require additional disposal strategies.

4.2 Removal Priority Indicators

An important indicator that DNR's Aquatic Lands Restoration Team will use to prioritize removal is the condition of tire module banding. Sites where we observed evidence of breaking or already broken bundles include Saltwater State Park, Solo Point, Burfoot County Park, and Frye Cove County Park. Once tire module banding has failed, tires will separate from their initial grouping and be more difficult to clean up. At some sites, tires that have separated from broken modules have washed ashore where they break into smaller crumb pieces. Alternatively, individually separated tires may be pushed to deeper depths by sub-surface currents where they are even costlier to find and remove. To prevent the further spread of tires from these reefs, sites with the poorest condition of banding will be prioritized for removal.

4.3 Next Steps and Additional Monitoring

The Washington Department of Natural Resources Aquatic Lands Restoration Team will review data collected at the 14 different confirmed tire reefs and identify one site as a pilot removal project. This site will be selected to cover a wide range of attributes with the intent to provide accurate information on the actual removal cost for different types of tire reef. This information will be used to efficiently and cost effectively plan for the removal of tires at the remaining 13 sites.

DNR's Aquatic Assessment and Monitoring Team plans to collaborate with the Department of Fish and Wildlife to monitor the pilot removal site and two other project sites for restoration effectiveness. Some of the data that may be collected in this monitoring effort will be additional sonar surveys, grain size, turbidity, and information on subtidal vegetation distribution.

5 Appendix

Barrel Stacked: A common technique of banding multiple tires together. Tires are banded with strapping (usually polypropylene line) into a cylinder shape. Figure 8B shows barrel stacking for tires stacked upright without banding. Barrel stacked formations within tire reefs are usually laying parallel to the sediment surface and are often in groups of three “barrels” which form a pyramid.

Pyramid Formation: A stack of three barrel stacked groupings. Figure 3 is a demonstration of this tire feature. Many tire reefs within Puget Sound use pyramid formations.

Loose Stacked: A pile form found in tire reefs. In these formations, tires are loosely piled on top of one another in an unorganized mound. The tires within the mound are usually bound with polypropylene line.

Tire Nodes: Spatial point features that are placed manually over a bathymetrically calculated hill shade or slope layer within ArcGIS to demarcate where confirmed tire features exist within a reef.

Potential Tire Nodes: Point features that are placed manually over a bathymetrically calculated hill shade or slope layer within ArcGIS to demarcate where potential tires may be. These are placed on mounded features that are too far from the bulk of a tire reef to likely be placed tires, but have not been confirmed otherwise by video.

Linear Features: Reef Features that are not mound shaped in multibeam data (not rock or tire). These can include concrete pilings, sunken barges, concrete blocks, wooden logs, chain, metal sheets, and other materials that were placed within reefs to attract fish.

1.5 meter Tire Node Buffer Area: An area created from the Tire Node data. This polygon feature class is created by a 1.5 meter (m) buffer with dissolve function of the tire node feature class. It represents the approximate area of tire reef features.

1.5m Potential Feature Buffer Area:
This polygon feature class is created by a 1.5 meter (m) buffer with dissolve function of the potential node feature class. This area may include potential features such as boulders or other mound like features are too far from the main portion of the reef to likely be tires, but cannot be confirmed otherwise.

Reef Footprint: A hand delineated area inclusive of all reef features (both confirmed and potential in the immediate vicinity of the main reef). This is likely an overestimate; however, it provides a general reef shape for comparison and is used for the volume estimate tool.

Bathymetry Attributed Grid (BAG): A two-band raster dataset generated from cleaned and processed multibeam data. The file includes and elevation layer and an uncertainty, both measured in m. A hill shade and slope layer are created from this layer.

Reef Feature: Any reef feature that was intentionally placed and not naturally present.

Tire Feature/ Module: Any grouping or banding of more than one tire. The terms feature/module are used interchangeably

Tire Condition: A scale from "good" to "poor" based on the visual integrity of tires at the reef site. Good tires are not distorted or torn and are relatively clear of barnacles/ other fouling organisms. A detailed tire condition description is within each site report.

NAVD88: The North American Vertical Datum of 1988. A vertical survey datum that serves as the vertical control datum for North America. It is in m above the fixed-height of the primary tidal benchmark at Father Point/Rimouski Quebec, Canada.

MLLW: Mean Lower Low Water (tidal datum). Measurements in feet. This datum is based on observations that are calculated and referenced to an 18-year tidal cycle. It is the average height of the lower of the two diurnal low tides each da

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