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Natural Resource Stewardship and Science

Exotic Plant Inventories in Mount Rainier, North Cascades, and Olympic National Parks

Natural Resource Report NPS/NCCN/NRR—2016/1279

ON THE COVER

Photograph of reed canary grass (*Phalaris arundinacea*) on the edge of Ross Lake in Ross Lake National Recreation Area with Jack Mountain in the background, photo by Mignonne Bivin, North Cascades National Park Service Complex

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August 2016
U.S. Department of the Interior
National Park Service
Natural Resource Stewardship and Science
Fort Collins, Colorado

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This report received formal peer review by subject-matter experts who were not directly involved in the collection, analysis, or reporting of the data, and whose background and expertise put them on par technically and scientifically with the authors of the information.

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Please cite this publication as:

Rochefort, R. M., M. M. Bivin, L. Conquest, S. A. Acker, and L. Kurth. 2016. Exotic plant inventories in Mount Rainier, North Cascades, and Olympic National Parks. Natural Resource Report NPS/NCCN/NRR—2016/1279. National Park Service, Fort Collins, Colorado.

NPS 105/133825, 149/133825, August 2016

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Abstract

Non-native or exotic plant species threaten the integrity of natural ecosystems and pose a significant threat to the unique and rare botanical resources that we aspire to protect in national parks of the North Coast and Cascades Network (NCCN. In 2001 and 2002, exotic plant inventories were conducted in Mount Rainier (MORA), North Cascades (NOCA), and Olympic (OLYM) national parks. The objectives of our study were to: 1) document exotic plant species that occur in vulnerable habitats in each park, 2) describe distribution patterns of exotic plant species across vulnerable habitats, 3) identify habitats with the greatest exotic species richness, 4) identify patterns of exotic species richness with respect to elevation and distance from trailhead, and 5) identify priority (invasive) exotic species for control based on biological and management considerations. Susceptible habitats were defined as areas where soils and/or substrate are frequently disturbed, providing an opportunity for exotic species establishment. The four susceptible habitats surveyed for this report were: riparian areas, roadsides, trail corridors, and developed zones.

We surveyed 697 plots across the three parks and documented 112 exotic species in 348 (~50%) of the plots. We documented 42 exotic species in MORA, 64 at NOCA, and 81 in OLYM. At all three parks, exotic species richness was generally highest in plots located in roadsides or developed zones. Our study documented 8 species that were not on the parks' comprehensive online species lists (NP Species 2016): 2 at MORA and 6 at OLYM. Although we did not document any new species at NOCA, our study provided previously unavailable abundance information for that park.

We found that habitat (P=0.00000), canopy cover (P=0.0000444), and vegetation type (P=0.00000) were all statistically significantly associated with exotic percent cover. Slope, aspect, elevation, distance from trail, disturbance level, and location were not statistically significantly related to exotic percent cover. Exotic plant percent cover was higher in developed zones and roads than along trails or in riparian zones. Canopy cover was inversely related to percent cover and there was a significant influence of dominant vegetation type on exotic plant abundance. We recommend that our survey be repeated, but expanded to include undisturbed areas along transportation corridors and developed zones where shade tolerant introduced species may thrive.

Acknowledgments

Anne Braaten, Darin Swinney, and Roger Hoffman developed spatial databases to identify surveys sites and field maps to guide field crews. Natalya Antonova spent many hours completing data entry, quality control of the data, and developed all maps within this report.

Introduction

The National Park Service's primary mission is to conserve unimpaired the natural and cultural resources and values of the national park system for the enjoyment of present and future generations. In 1992, the National Park Service's (NPS) Inventory and Monitoring Program identified a list of candidate elements and processes for initial inventory in all natural resource parks; proposed the establishment of prototype inventory and monitoring parks; and outlined national implementation guidelines. The National Parks Omnibus Management Act of 1998 recognized the need for good scientific information to manage parks. The act mandated a "program of inventory and monitoring of National Park System resources to establish baseline information and to provide information on the long-term trends in the condition of National Park System resources".

Funding acquired through the Natural Resource Challenge (1999) provided the financial resources for National Park Service to initiate Species Inventory Programs focusing on vertebrates and vascular plants. The basic goal of this program was to provide park managers with comprehensive, scientifically-based information about the nature and status of selected biological resources occurring within park boundaries in a form that would be easily accessible and have utility for making management decisions, for scientific research, and for educating the public. The inventories would also lay the groundwork necessary for park managers to develop effective monitoring programs and to formulate strategies for resource management and protection. The North Coast and Cascades Network (NCCN) of parks developed a plan to inventory and document vertebrate and vascular plant species in the seven network parks (Figure 1) and initiated this program in 2001 (Rochefort et al. 2009). Vascular plant inventories were focused on two broad objectives: 1) complete verification of 90% of vascular plants expected to occur in all network parks and 2) develop quantitative assessments of exotic species and the habitats in which they occur.

Invasive non-native or exotic plant species threaten the integrity of natural ecosystems and pose a significant threat to the unique and rare botanical resources that we aspire to protect in the national parks of the NCCN. Often, presence/absence information is available for exotic species but more detailed information on abundance and distribution of these species and locations of susceptible habitats, where new invasions could occur, is needed to guide exotic plant management programs. When the NCCN Inventory Program was initiated, Mount Rainier National Park (MORA), North Cascades National Park Complex (NOCA), and Olympic National Park (OLYM) had nearly complete vascular plant lists, including exotic species, but often these data were simple species lists without abundance or distribution data.

In the NCCN Inventory Plan, Rochefort et al. (2009) proposed to conduct exotic plant surveys, at MORA, NOCA, and OLYM, only in areas most susceptible to exotic species invasions. Susceptible habitats were defined as areas where plant cover and substrates were frequently disturbed providing an opportunity for exotic species establishment such as travel-ways (i.e., edges of roads and trails), developed zones, and riparian areas (Forcella and Harvey 1983, Hobbs 1991, Tyser and Worley 1992, Lonsdale and Lane 1994, Lonsdale 1999, Morgan and Carnegie 2009, Stohlgren et al. 2013).

This report summarizes the exotic plant inventories that were conducted in MORA, NOCA, and OLYM parks during the field seasons of 2001 and 2002. The objectives for these inventories were to: 1) document exotic plant species that occur in susceptible habitats in each park, 2) describe distribution and abundance patterns of exotic plant species across vulnerable habitats, 3) identify habitats with the greatest exotic species richness, 4) identify patterns of exotic species richness with respect to elevation and distance from trailhead, and 5) identify priority exotic species for control based on biologic and management considerations.

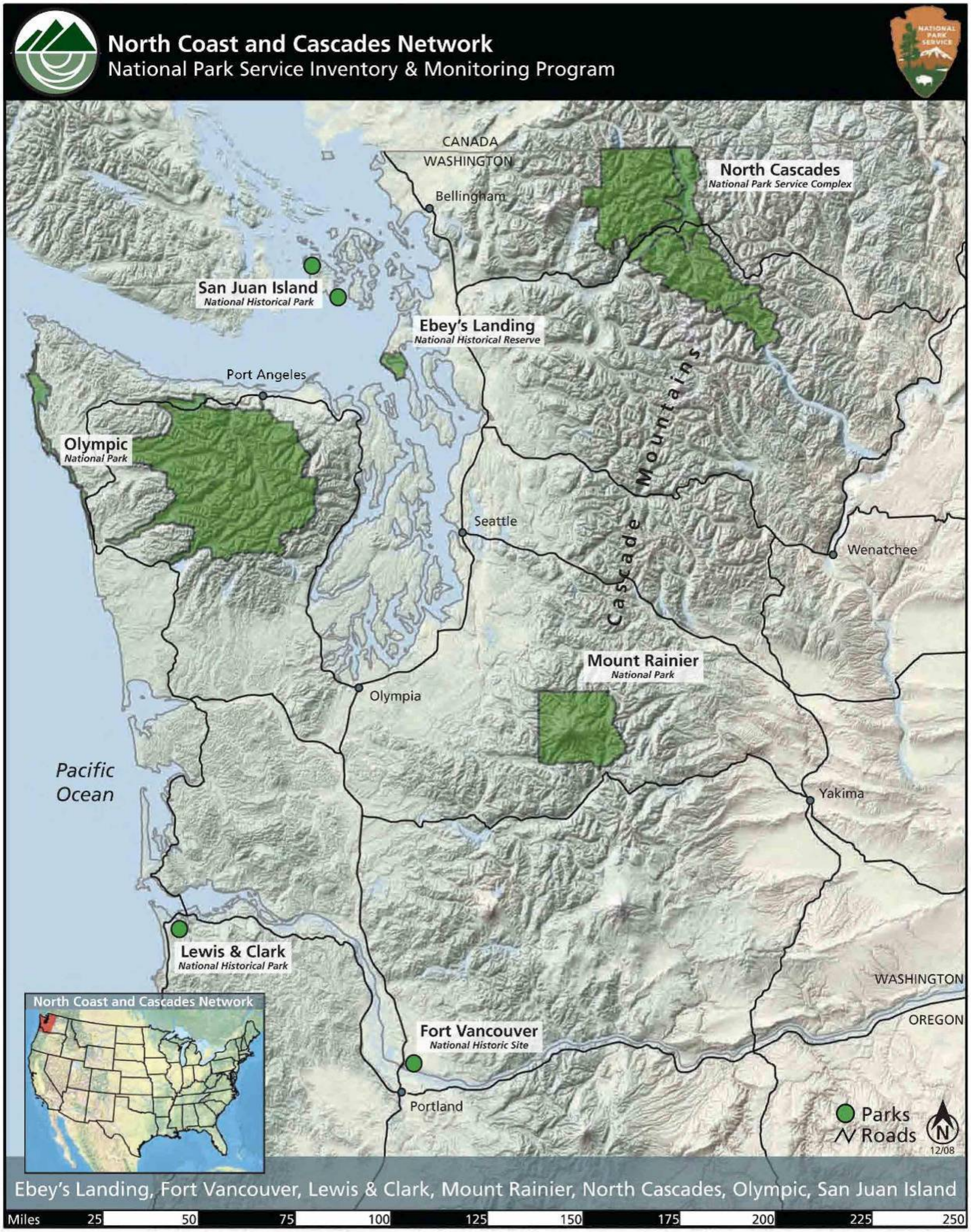

Figure 1. Map illustrating the location of park units within the North Coast and Cascades Network, Washington.

Methods

Field Methods

We focused our survey on habitats most susceptible to exotic plant invasion within the three parks. Susceptible habitats were defined as areas that provided both good substrates for exotic plant establishment and where there was a high probability of exotic seed dispersal. Using this definition, we identified four habitats for surveys: roads, trails, riparian areas (i.e., rivers), and developed zones. Although we recognized that avalanches, debris flows, fire, and other natural disturbances would also be susceptible to exotic establishment, we concentrated on areas that were regularly visited by people and stock (i.e., highly accessible) since human use is often a source of exotic species propagules (Stohlgren et al. 2013). We also chose to concentrate on backcountry trails rather than backcountry campsites because the trails are the corridors for spread of exotic plants.

We stratified our sampling among the four sensitive habitats: roads, trails, riparian areas and developed zones (Table 1, Figures 2, 3, 4). All four habitat types were identified in GIS. Within our four habitats, we included all developed zones on park owned land (i.e., no privately owned lands), all roads, all park maintained trails (i.e., no social or informal trails), and riparian areas with a slope ≤ 8% (safe access for field crews). Roads, trails, and riparian areas were considered to be linear features and were divided into segments along which subsamples (i.e., plots) were distributed. All segments were ≤ 5 miles in length and we generally used junctions with other trails, roads, or rivers to identify segments so that the segments could easily be identified in the field. Roads and trails had a minimum segment length of 0.5 miles and riparian areas had a minimum length of 1.0 miles. Segments were numbered within each strata and then randomly selected for sampling. After a random placement of the first plot within the first 0.5 miles of the randomly selected segment, plots were systematically distributed every mile within the road, trail, and riparian segments which had been randomly selected.

All plots or subsamples covered an area of 100 m^2 however, the dimensions and distribution of the plots varied depending on habitat type. Road and trail plots were 1m x 100 m and were established parallel to the road or trail. The first plot was located on the right or left side of the trail based on a coin toss and successive plots alternated sides. Riparian plots were also 100 m^2, but plot dimensions varied based on the terrain in order to locate the entire plot within the riparian zone. Crew members determined the plot dimensions when they arrived at the plot location. Frequently, plots were square (i.e., 10m x 10m), but when rectangular plots were used, they were oriented perpendicular to the river to capture variation in plant distribution within the riparian area. Developed zone plots were 10m x 10 m and were located relative to a random location generated in the GIS.

Surveys were conducted in Mount Rainier National Park in 2001 (Figure 2), in North Cascades in 2001 and 2002 (Figure 3), and in Olympic National Park in 2002(Figure 4). Initially, our target sample size was 400- 450 plots per year, targeting 200 plots per park evenly distributed within road, trail, and riparian areas in proportion to the total length of segments available for each habitat type. Following the first year of sampling, we revised our sampling scheme for OLYM based on the pilot data collected the previous season and aimed for a 10% precision of roads and developed zones, 5% for riparian areas, and 2% for trails (Table 1).

Data collected in each plot included general site characteristics: elevation, aspect, slope, location (collected with a GPS and recorded as Universal Trans Mercator or UTM coordinate), dominant overstory vegetation, and disturbance level (Table 2). Within each plot, overstory canopy cover, total percent cover of vascular plants and exotic plants, and cover of each exotic plant species were recorded. Overstory canopy cover was estimated to 1% using a spherical densiometer. Estimates were recorded at three locations within the plot (i.e., 25, 50 and 75-m) and the average of the three estimates was used as the canopy cover in all analyses. Ocular estimates of cover of individual species were recorded by classes: <1%, 1-5%, 6-25%, 26-50%, 51-75%, and 75-100%. Plant nomenclature followed the Washington Flora Checklist (http://biology.burke.washington.edu/herbarium/waflora/checklist.php).

Table 1. Distribution of sample plots within the four strata.

Habitat	Total Area Sampled	No. of Plots Sampled	% of Park Total Plots
MORA			
Roads	104 miles	31	15
Trails	286 miles	97	46
Riparian	127 miles	72	34
Developed Zones	476 acres	10	5
Total		**210**	**100**
NOCA			
Roads	96 miles	20	9
Trails	306 miles	102	45
Riparian/Reservoirs	340[1]	76	34
Developed Zones	189 acres	28	12
Total		**226**	**100**
OLYM			
Roads	122 miles	82	31
Trails	559 miles	31	12
Riparian	206 miles	31	12
Developed Zones	902 acres	118	45
Total		**262**	**100**

[1]238 miles of riparian areas along rivers and 102 miles along the edge of Ross Lake reservoir

Table 2. Disturbance levels recorded in each exotic plant survey plot.

Disturbance Level	Definition
Undisturbed	Ground is in stable condition
Low	If mechanical or animal disturbance, 5-20 percent of ground cover removed exposing bare soil and pavement; if fire, most fine fuels burned, some charring of 3+ in. fuels, woody plants scorched but not burned to the ground; uneven patch burning of duff and litter
Moderate	If mechanical or animal disturbance, 20-40 percent of ground cover removed exposing bare soil and pavement; if fire, nearly all fine fuels consumed, some consumption of 3+ in. fuels, some woody plants consumed; patch distribution of duff and litter consumption.
High	If mechanical or animal disturbance, 40-100 percent of ground cover removed exposing bare soil and pavement; if fire, many areas of exposed mineral soil, many woody plants consumed, most 3+ in. fuels charred and many consumed; fairly even distribution of duff and litter consumption.

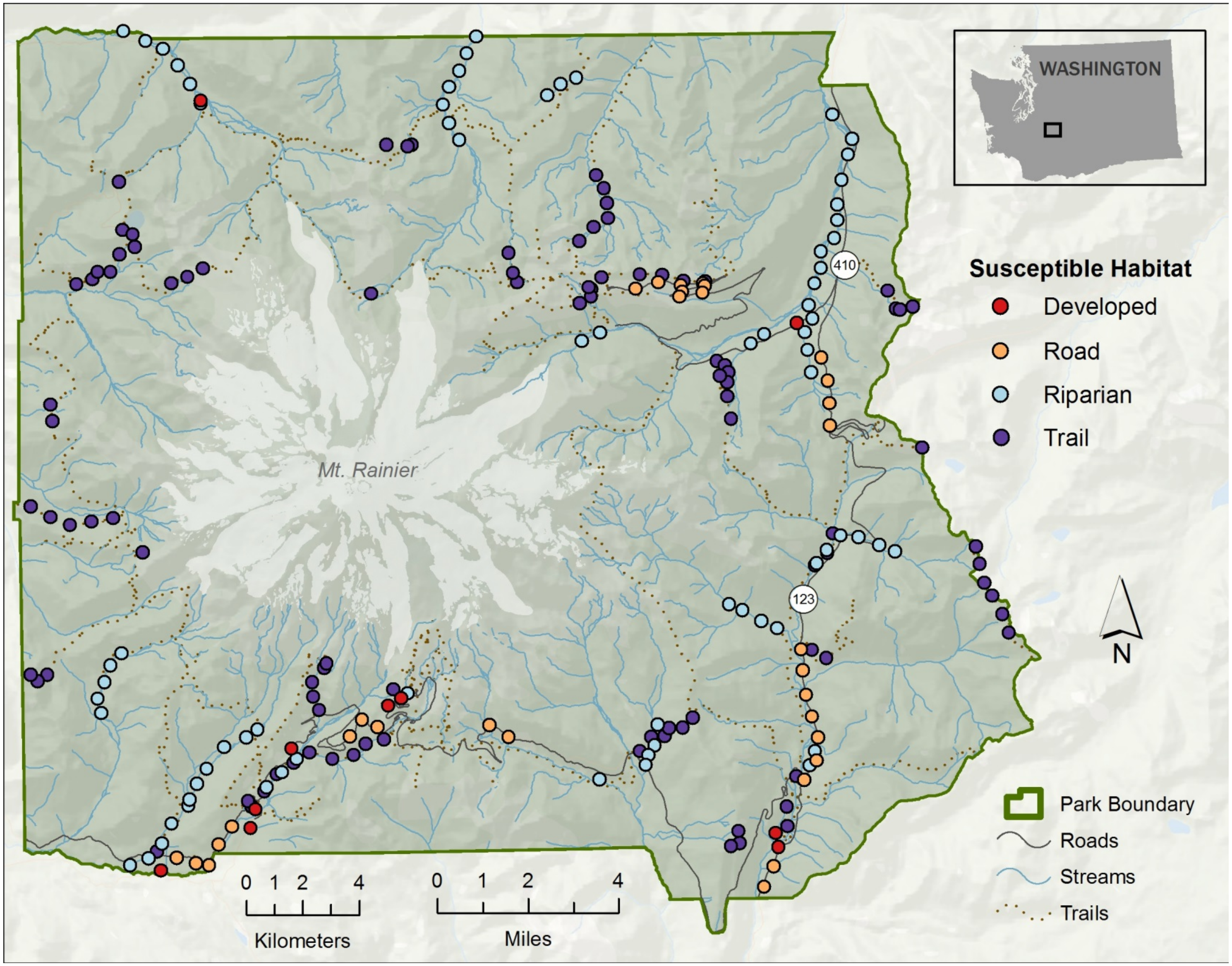

Figure 2. Locations of exotic inventory plots, by susceptible habitat type, in Mount Rainier National Park, Washington.

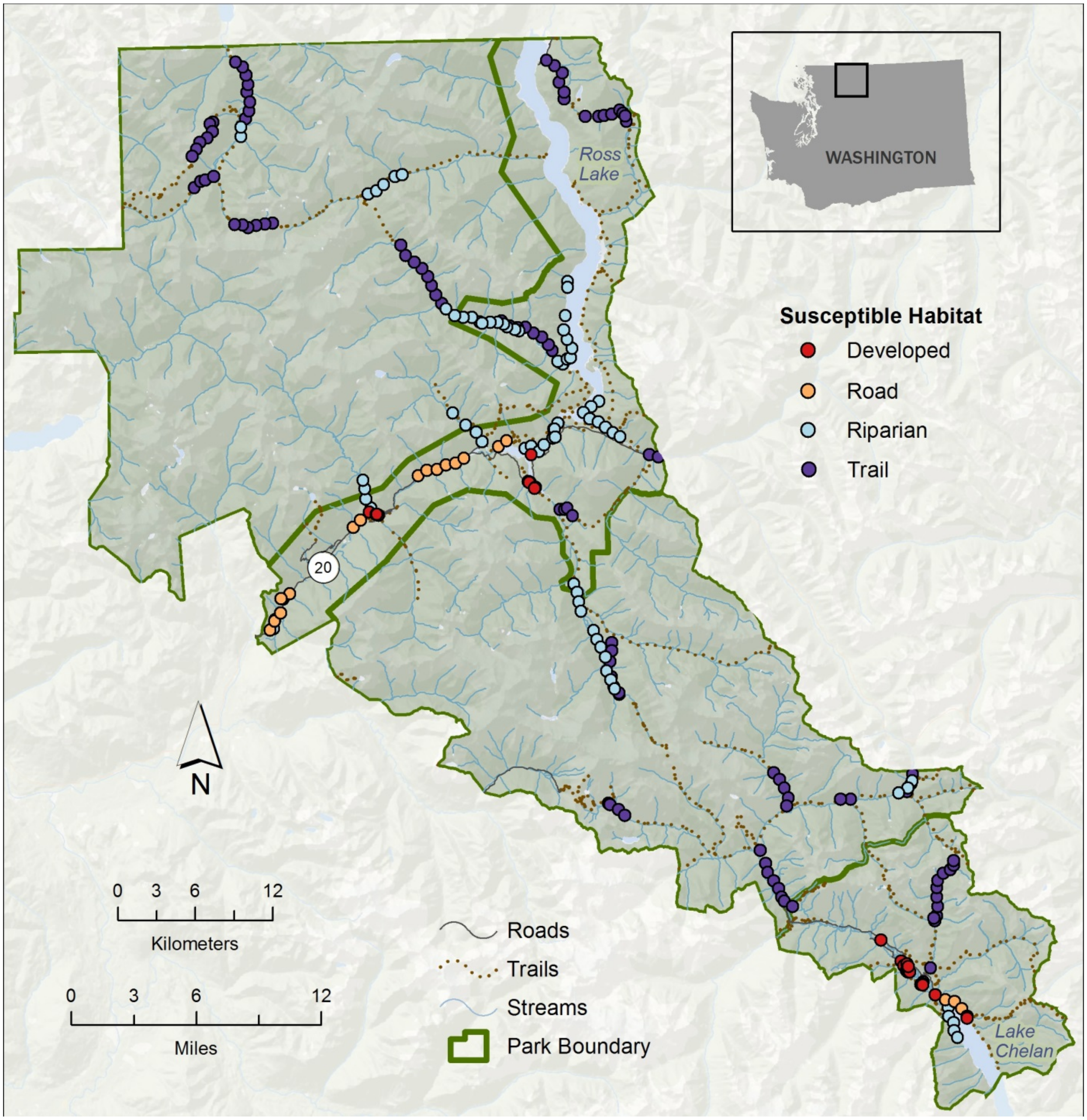

Figure 3. Locations of exotic inventory plots, by susceptible habitat type, in North Cascades National Park Service Complex, Washington.

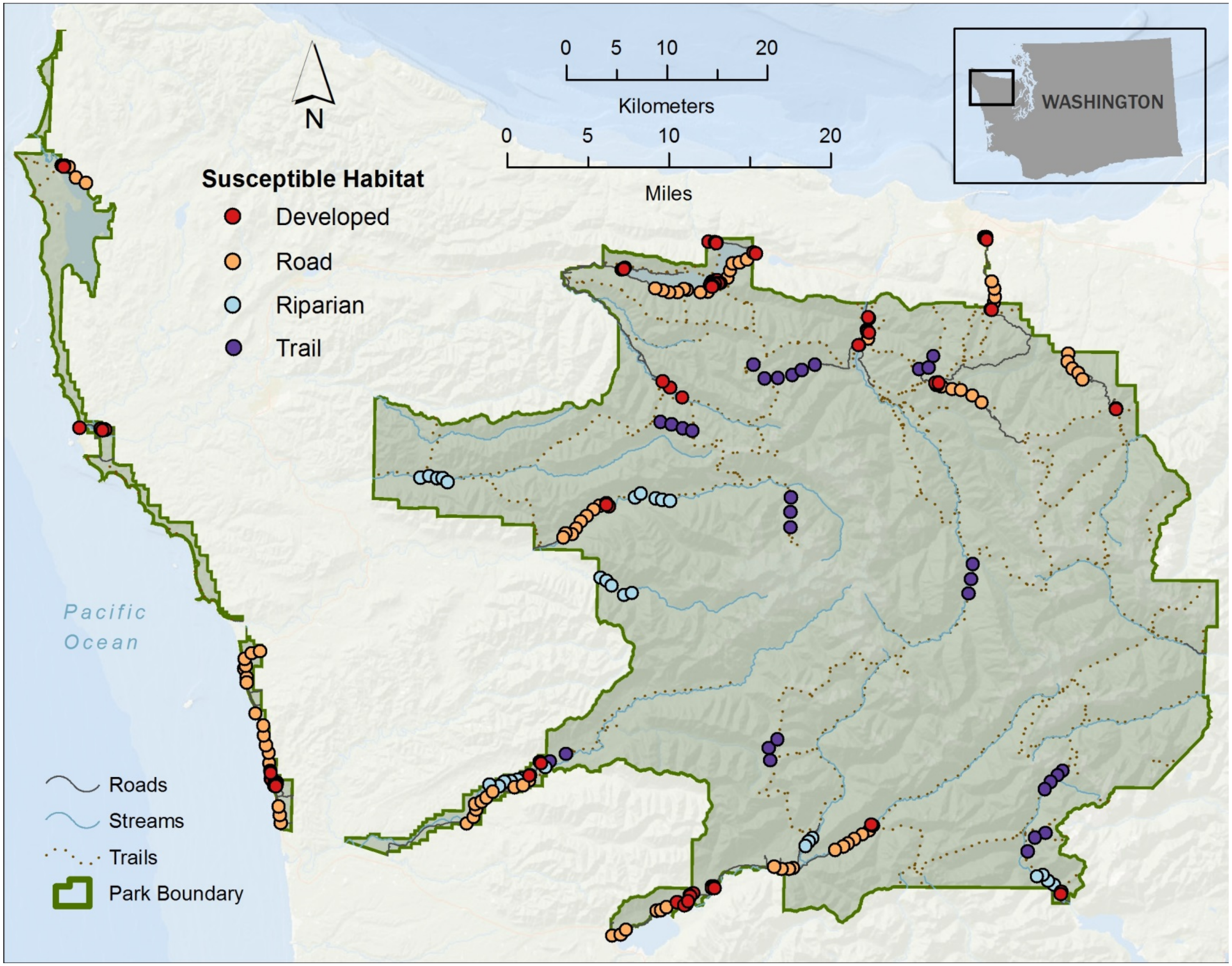

Figure 4. Locations of exotic inventory plots, by susceptible habitat type, in Olympic National Park, Washington.

Analysis

We used a generalized linear model to examine the effect of a set of categorical predictors on exotic plant cover: habitat type, slope, aspect, elevation, distance from trailhead, location (i.e., UTM easting and UTM northing), disturbance level, canopy cover, and vegetation type. Because the distribution of exotic percent cover was so right-skewed (with many zeroes), a generalized linear model with a quasi-Poisson likelihood was used. This allows for right skewed distributions (like the Poisson) but with a variance-to-mean ratio greater than 1.0 (1.0 being the value of the ratio for the standard Poisson distribution).

Vegetation types were initially based on the 27 forest communities defined in MORA (Franklin et al. 1988), but as field crews moved into NOCA and OLYM, the number of vegetation types increased to 50. Because using all 50 types would have resulted 1225 pairwise comparisons of means (i.e., (50 x 49)/2), the original list of 50 was reduced to the eight types that had at least 30 sample plots. The eight types were based on the dominant overstory species: *Abies amabilis* (Pacific silver fir or Abiama), *Abies lasiocarpa* (Subalpine fir or Abilas), *Alnus rubra* (Red alder or Alnrub), herbaceous (Herb), *Picea sitchensis* (Sitka spruce or Picsit), *Pseudotsuga menziesii* (Douglas fir or Psemen), *Thuja plicata* (Western red cedar or Thupli), and *Tsuga heterophylla* (Western hemlock or Tsuhet). After reducing the vegetation types, our analysis of the effect of habitat, slope, aspect, elevation, distance from trailhead, location, disturbance, canopy cover, and dominant vegetation was conducted on 635 of the total (697) vegetation plots. The distribution of plots within the reduced set of cover types among the three parks was: Abiama (133), Abilas (44), Alnrub (57), Herb (38), Picsit (52), Psemen (164), Thupli (31), and Tsuhet (116).

Categorical predictors which showed a statistically significant relationship with percent exotic cover were then subjected to multiple comparison tests to determine which categories were statistically different from each other. Because the response variable had a quasi-Poisson distribution and therefore was not normally distributed, it was not possible to use the standard Tukey HSD (Honestly Significant Difference) method of multiple comparisons of means. Rather, each pairwise comparison was done by seeing whether the regression coefficient in the generalized linear model representing the difference between the two means was significantly different from zero via a *t* test. Furthermore, because there were several of these tests being done (thus increasing the possibility of Type I errors), a standard Bonferroni approach was taken by multiplying the unadjusted P-value for each test by the number of tests being done (Miller 1981). This would assure that the overall level of significance would not exceed the stated level, here 0.05. For example, among the four habitats there would be six possible pairwise comparisons. Therefore, the P-value for each individual pairwise test comparing two habitat means was multiplied by 6.0. As part of the multiple comparison technique, the ordered means were listed and the Bonferroni-adjusted P-values noted. The multiple comparison procedure proceeds “from the outside in”—i.e., by comparing the largest to the smallest mean first, followed by comparing means that are closer together, until at the last step, adjacent means are compared. In reporting our results, any two means that are declared to be statistically not different are connected via an underline, and all means that occur between them are also considered not statistically different.

Results

Exotic Plant Species Documented by Park

We surveyed 697 plots across the three parks that were distributed across a wide elevation gradient extending from 3m in OLYM to 2,076m in MORA (Figure 5). We documented 112 exotic species in 348 (~50%) of the plots (Table 3, Appendix A).. Approximately 52% (58) of the species occurred in all three parks, 29% (33) were documented in two parks, and 19% (21) were only recorded in one park. Olympic National Park had the highest number of exotic species. Generally, at all three parks, exotic species richness was highest in plots located in roadside or developed zones (Table 3). Most of the exotic species encountered were herbaceous (80 spp. or 71%) or grasses (23 spp. or 21%). Vines (6 spp.); trees, (2) and shrubs (1) were limited. Twenty-four of the species observed are listed as noxious weeds by Washington State (Washington State 2015) (Table 4).

Table 3. Distribution of exotic plant species in the sample plots within the four strata.

Category	Total Number Plots Sampled	Number of Plots with Exotic Species[1]	Total Exotic Species Richness	Average Exotic Species Richness per Plot	% of Plots with Exotic Species
MORA					
Roads	31	29 (28)	39	7.9	94
Trails	97	17 (16)	14	2.0	18
Riparian	72	15 (14)	11	3.4	21
Developed Zones	10	4	11	4.0	40
Total	**210**	**65**	**42**		
NOCA					
Roads	20	20	58	12.7	100
Trails	102	18 (16)	12	1.6	18
Riparian/Reservoirs	75	36 (32)	23	2.0	47
Developed Zones	28	21 (20)	23	3.3	100
Total	**225**	**95**	**64**		
OLYM					
Roads	82	74	66	8.5	90
Trails	31	11 (10)	24	6.0	35
Riparian	31	29	23	4.3	94
Developed Zones	118	74	58	5.2	63
Total	**262**	**188**	**81**		

[1] (#) number of plots used in analysis of exotic species; some data sheets listed exotics present but did not identify the species

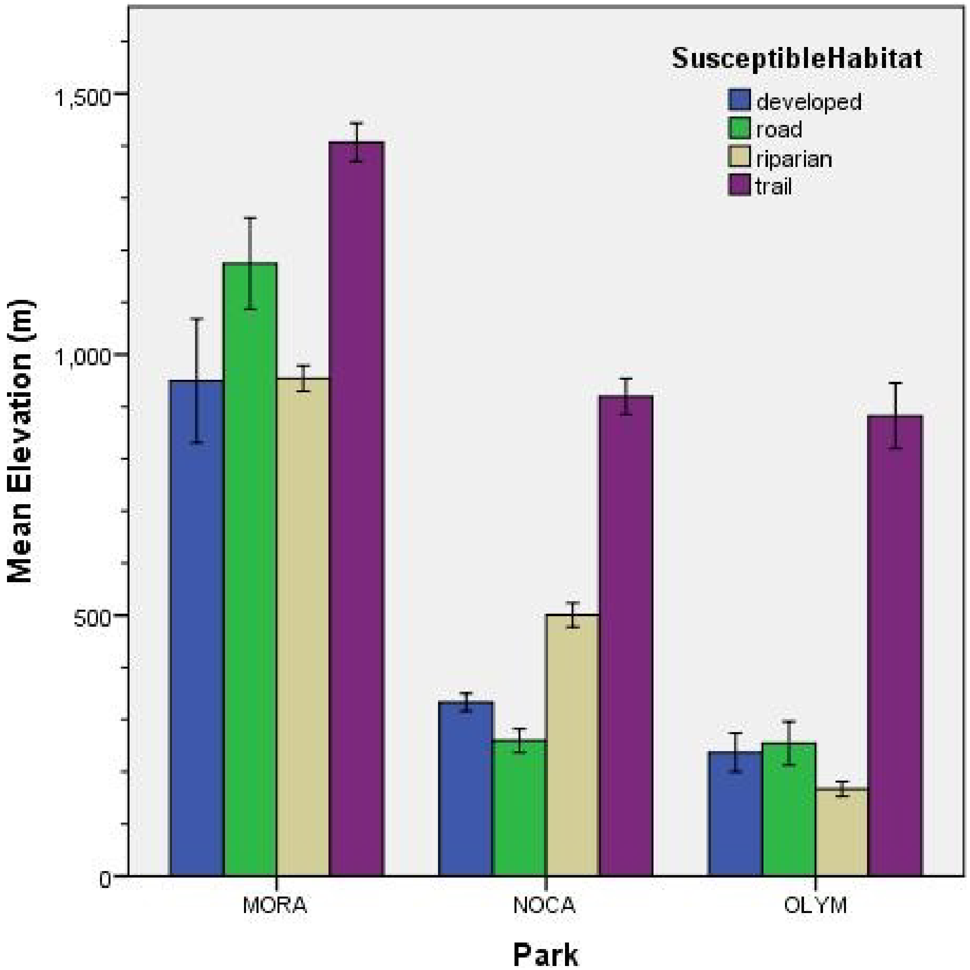

Figure 5. Mean elevation (±1 standard error of the mean or SEM) of survey plots within each susceptible habitat type, by park.

Table 4. Summary of exotic species documented most frequently in survey plots and all noxious weeds observed.

Species	Common Name	WA State Weed Class[1]	Number of Plots		
			MORA	NOCA	OLYM
Aira caryophyllea	Delicate hairgrass	--	0	18	10
Aira praecox	Silver hairgrass	--	1	0	20
Anthoxanthum odoratum	Sweet vernal grass	--	0	0	26
Artemesia absinthium	Absinth wormwood	C	0	1	0
Centaurea diffusa	Diffuse knapweed	B	0	1	8
Centaurea nigra	Black knapweed	B	2	0	0
Centaurea stoebe	Spotted knapweed	B	1	0	0
Cirsium arvense	Canada thistle	C	0	3	14
Cirsium vulgare	Bull thistle	C	3	7	20
Conium maculatum	Poison hemlock	B	0	0	1
Cytisus scoparius	Scot's broom	B	0	2	15
Dactylis glomerata	Orchard grass	--	12	28	28
Digitalis purpurea	Foxglove	--	1	3	35
Geranium robertianum	Herb Robert	B	0	4	23
Hedera helix	English ivy	C	0	0	5
Hieracium atratum	Polar hawkweed	B	2	0	0
Hieracium aurantiacum	Orange hawkweed	B	0	0	2
Hypericum perforatum	Klamath weed	C	10	21	8
Hypochaeris glabra	Smooth cat's ear	--	0	8	73
Hypochaeris radicata	Hairy cat's ear	C	29	8	73
Ilex aquifolium	English holly	Monitor	0	0	7
Lathyrus sylvestris	Flat pea	Monitor	0	1	10
Leucanthemum vulgare	Ox-eye daisy	C	19	15	28
Linaria dalmatica	Dalmatian toadflax	B	0	1	0
Lotus uliginosus	Large trefoil	--	0	0	34
Medicago lupulina	Black medic grass	--	0	0	25

[1]B = non-native species limited to portions of WA State; C = noxious weeds widespread in WA or special interest to agricultural; Monitor = species for which more information is needed because they are believed to pose a threat in Washington state (Washington State 2015).

Table 4 (continued). Summary of exotic species documented most frequently in survey plots and all noxious weeds observed.

Species	Common Name	WA State Weed Class[1]	Number of Plots		
			MORA	NOCA	OLYM
Mycelis muralis	Wall lettuce	Monitor	21	39	80
Phalaris arundinacea	Reed canary grass	C	0	13	8
Plantago lanceolata	English plantain	--	15	25	44
Plantago major	Common plantain	--	17	14	36
Poa trivialis	Rough-stalked bluegrass	--	13	6	11
Polygonum x bohemicum	Bohemian knotweed	B	0	0	1
Prunella vulgaris var. vulgaris	Self-heal	--	1	4	56
Ranunculus repens	Creeping buttercup	--	3	1	94
Rubus lacinatus	Evergreen blackberry	C	0	2	24
Rumex acetosella	Sheep sorrel	--	13	15	4
Rumex obtusifolius	Bitter dock	--	0	4	49
Senecio jacobaea	Tansy ragwort	B	0	0	19
Tanaecetum vulgare	Common tansy	C	1	20	0
Trifolium repens	White clover	--	24	26	58
Taraxacum officinale	Common dandelion	--	24	15	26

[1]B = non-native species limited to portions of WA State; C = noxious weeds widespread in WA or special interest to agricultural; Monitor = species for which more information is needed because they are believed to pose a threat in Washington state (Washington State 2015).

Patterns of Exotic Plant Species Distribution

Habitat (P=0.00000), canopy cover (P=0.0000444), and vegetation type (P=0.00000) were all statistically significantly associated with exotic plant percent cover. The other predictors (i.e., slope, aspect, elevation, distance from trailhead, location, and disturbance) were not statistically significantly related to percent exotic cover.

We examined the relationship between habitat and exotic plant cover via pairwise comparisons of means within a quasi-Poisson generalized linear model including habitat as a statistically significant predictor. Two distinct habitat groupings emerged from this analysis based the amount of exotic plant cover; 1) Developed Zones and Roads and 2) Riparian and Trail Habitats (Table 5, Figures 6, 7, 8, 9). Across the three parks, developed zones and roads had similarly high levels of exotic plant cover vs. lower levels along trails and riparian corridors. Taking a closer look, mean exotic plant cover of Developed and Road habitat types was substantially higher in NOCA and OLYM than MORA, whereas exotic plant cover in Trail habitats was much higher in OLYM than NOCA or MORA

(Figure 6). Canopy cover was inversely related to percent exotic plant cover (coefficient = -0.0021, S.E. = 0.00051, P =0.0000444).

Table 5. Percent exotic cover means, standard errors, and number of data points of the four habitats.

Habitat	Trail	Riparian	Developed	Road
Mean	3.78[a]	6.69[a]	20.85[b]	28.32[b]
s.e.	0.60	0.85	1.99	1.80
N	230	179	156	133

[a, b] denote means which are not statistically different from each other

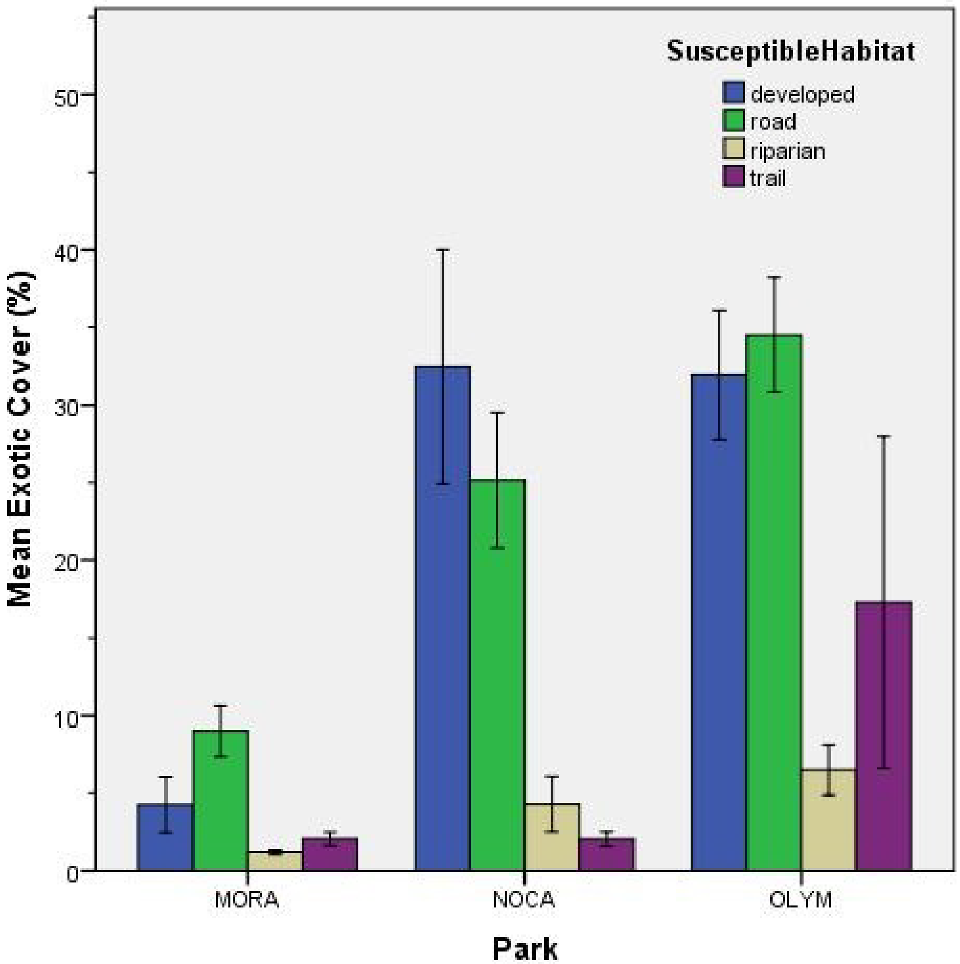

Figure 6. Mean exotic plant cover (±1 standard error of the mean or SEM) by park and susceptible habitat in plots where exotic plants were documented.

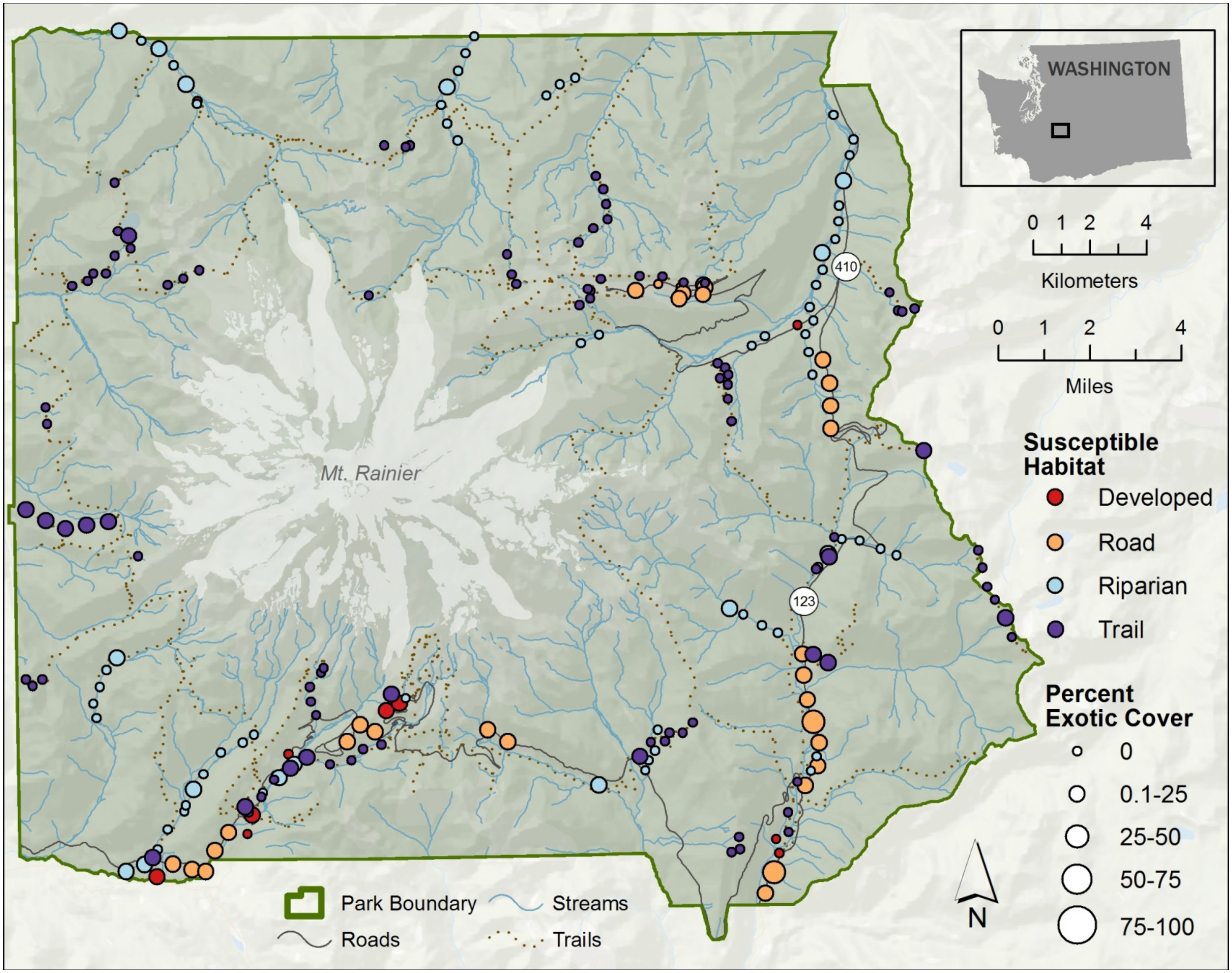

Figure 7. Exotic plant species cover categories shown by susceptible habitat type in Mount Rainier National Park, Washington.

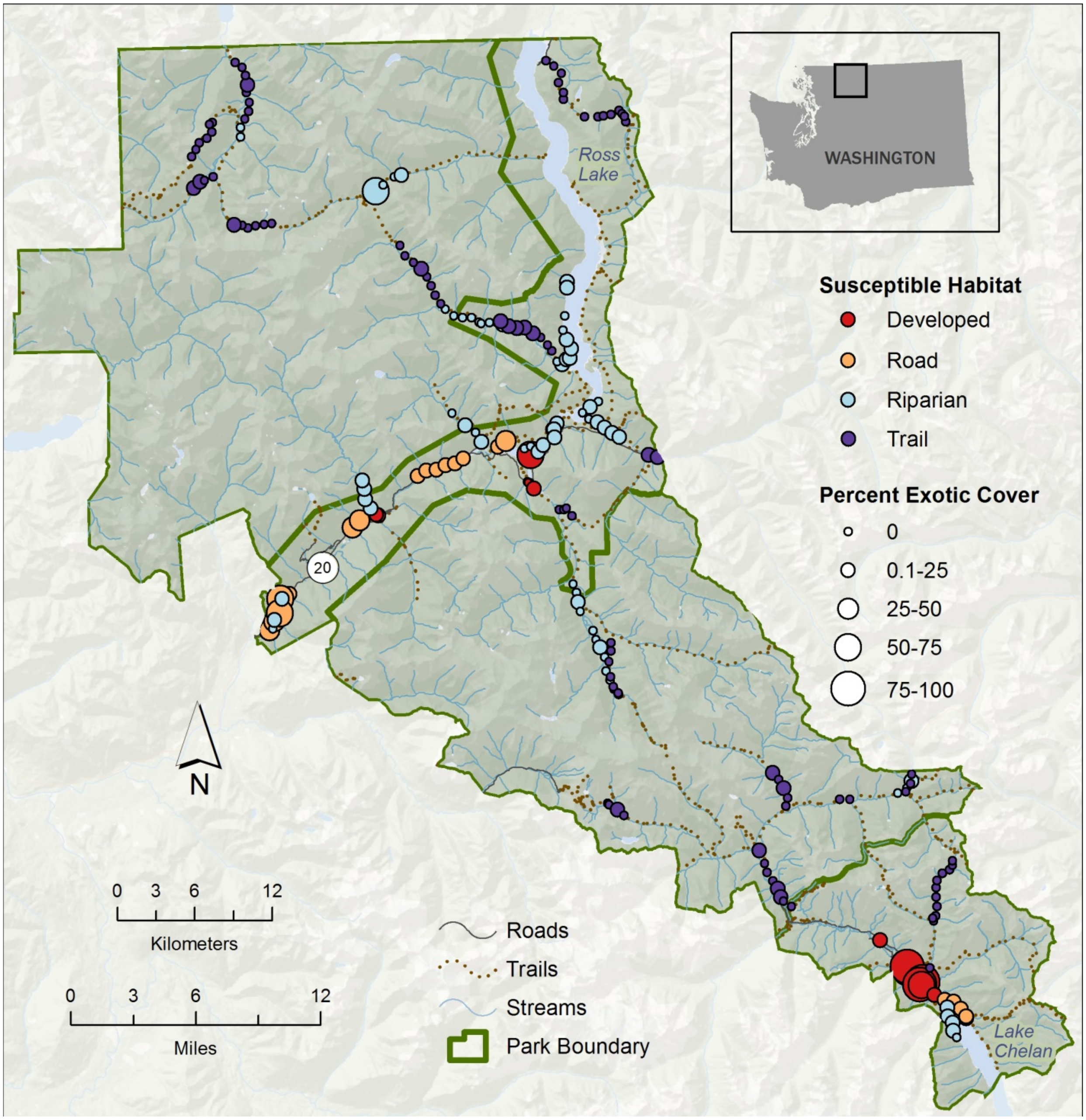

Figure 8. Exotic plant species cover categories shown by susceptible habitat type in North Cascades National Park Service Complex, Washington.

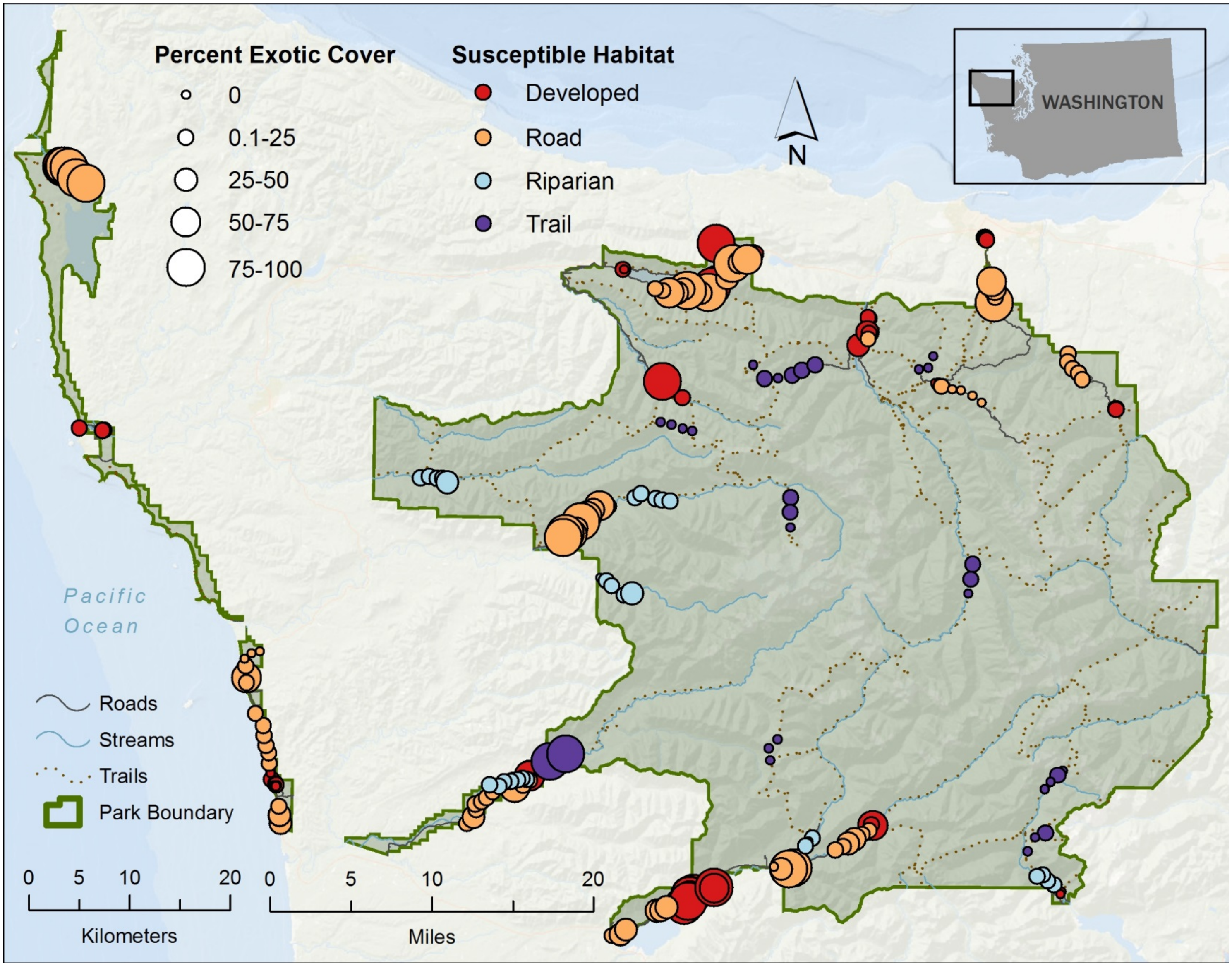

Figure 9. Exotic plant species cover categories shown by susceptible habitat type in Olympic National Park, Washington.

The influence of dominant vegetation type, examined through pairwise comparison ((8x7)/2 = 28 possible pairwise comparisons), are shown in Table 6. Here the groupings were not as distinguishable as those for the habitat categories, with many "overlaps" between pairwise comparisons that resulted in some vegetation types belonging to two or more groups. The groups in increasing order of exotic plant cover are: {Abilas, Abiama, Tsuhet}, {Tsuhet, Psemen, Thupli}, {Psemen, Thupli, Alnrub, Picsit}, {Thupli, Alnrub, Picsit, Herb}. In the language of multiple comparisons, "at least one Type II error is occurring here" (i.e., false negative: accepting what is false), and biological knowledge must be applied to further separate the groups.

Table 6. Percent exotic cover means, standard errors, and number of data points of eight dominant vegetation types.

Veg. Type	Abilas	Abiama	Tsuhet	Psemen	Thupli	Alnrub	Picsit	Herb
Mean	3.0	4.10[1]	8.59	14.15	14.35*	20.77	24.36	42.32
S.E.	0.74	0.74	1.26	1.53	3.10	2.99	3.12	4.26
N	44	133	116	164	31	57	52	38

[1]Bonferroni-adjusted P-value to compare Abiama vs. Thupli: P=0.060. Dashed underlines denote means which are not statistically different from each other via pairwise comparisons of means within a quasi-Poisson generalized linear model that included Domination Vegetation Type as a statistically significant predictor.

Discussion

Our sample design was built on the field observations that exotic plants tend to be most abundant in susceptible areas where dispersal vectors (people or stock) and disturbances were frequent. Based on this, we sampled roads, trails, and developed zones where we presumed to find high abundance and richness of exotic species in MORA, NOCA, and OLYM. We expected that exotic plant cover would decrease both with increasing distance from trailheads and increasing elevation. We also sampled riparian zones because they are frequently disturbed by natural water flow, however we were uncertain we if exotic species cover or species richness might be high in this zone.

We found that roads and developed zones had significantly higher exotic cover than trails and streams. Habitat type, canopy cover, and forest type (dominant tree cover) were significantly associated with exotic plant abundance, but in contrast to our prior expectations, elevation and distance from trailhead were not (Figures, 6-8, Tables 5, 6). Although elevation was not a statistically significant predictor of exotic plant cover, it may influence some of the patterns we found between parks and between forest types. Exotic plant cover was higher in the low elevation forest types of Psemen, Thupli, Alnrub, Picsit than in the mid to high elevation forests dominated by Abilas, Abiama, Tsuhet. MORA had the lowest exotic plant cover; surveys sites at this Park were generally higher in elevation than NOCA or OLYM (Figures 5 and 6). The lower exotic plant cover at all MORA sites and in mid to high elevations forest types across parks may both reflect the harsher environmental conditions of higher elevation sites to which native species are better adapted (Pauchard et al. 2009).

Visual inspection of percent cover maps (Figures 6-8) illustrates that higher percent cover of exotic plants occurs along roads and developed zones and along trail segments closer to access points. Road edges are frequently mowed and sand is often applied in the winter, both practices maintain an open road edge environment that can easily be invaded by new seeds. Additionally, in the past, many roads and developed zones were seeded with introduced species in an effort to maintain low ground cover that could be mowed and increase sight lines along roads and ornamentals were often planted in developed zones. Earlier studies in Glacier National Park (Tyser and Worley 1992) and Mount Rainier National Park (Wakefield 1966) documented the abundance of exotic species along roads and trails and the predominance of species used in road edge mixes or pasture grasses. We also found that the most abundant species were those associated with road edge seeding and common perennial pasture grasses (Table 5).

In our surveys we documented 112 exotic plant species. Our study added new species to MORA and OLYM's list of exotic species and more importantly provided new information about the distribution and abundance of exotic species in all three parks. We compared the species that we documented in each park to species lists in NPSpecies (2016). NPSpecies documents species presence and abundance for each park. Species are listed as present in the park if there is documentation: scientific studies, curated plant specimens, or photographs. Abundance of each species is recorded in categories: abundant, common, uncommon, rare, occasional or unknown.

Prior to our study, Mount Rainier National Park documented 145 species of exotic plants as present in the park; North Cascades National Park Complex listed 219 species; and Olympic National Park 95 species (NPSpecies 2016). Of MORA's 145 known exotic plant species, abundance was known for all but 9 species. In our survey we documented 42 exotic species, 2 of which were not on the current species list and 1 species (*Centaurea nigra*) was listed as present by Wakefield (1966) but not present by Biek (2000) so, additional surveys for this species may warranted. NOCA listed 219 species as present within the park complex, but abundances were only recorded for 4 species based on observations in developed zones. Our surveys provided abundances for 64 additional species. OLYM lists 95 exotic species as present in the park; we documented 27 species that were previously listed as probably present in OLYM and 6 species that were not on the current list.

The National Park Service defines exotic species as species that occupy park lands as a result of deliberate or accidental human actions. All exotic species are of concern because they "…did not evolve in concert with the species native to the place, the exotic species is not a natural component of the natural ecosystem at that place." (NPS 2006). Because it is not practical for national parks to control all exotic species, management efforts are prioritized by species. High priority species for control are those that have both the potential to substantially impact park ecosystems and that can be successfully controlled (NPS 2006). Currently, the species of highest management concern in terms of abundance and difficulty to control in OLYM are herb Robert, reed canarygrass, Canada thistle, blackberry species, Scot's broom, and knotweed species. Additionally, cheatgrass and yellow toadflax are relatively localized species that are being controlled (pers. comm. Dan Campbell). In MORA, they are herb Robert, Ox-eye Daisy, Bohemian knotweed, Canada thistle, fox glove, butter and eggs (*Linaria vulgaris*), and the hawkweeds. In NOCA, the highest species of concern are cheat grass, reed canary grass, Herb Robert, sweet clover, toad flax, knapweeds, hawkweeds, and rush skeleton weed. Several of these species were not found during our surveys or documented in a limited number of. For example, herb Robert and Bohemian knotweed were not documented in MORA during our surveys although they had been the focus of control efforts since the late 1990s. In the case of these two species, it may be because they were localized in their distribution and our sampling strategy just missed them. However, it may be that some species have spread since the time of our surveys. Herb Robert was only found in four locations along road edges in NOCA and at the time of this writing has sizeable populations in several campgrounds (developed zones) which were probably not established or much smaller at the time of our surveys. MORA has the most active exotic plant management program of the three parks and the low distributions there may also be indicative of their program's success in controlling these species.

Conclusions

This work constitutes an important benchmark for three globally-significant natural areas, Mount Rainier, North Cascades, and Olympic National Parks. Our study documented distinct, and expected, patterns of exotic plant species distribution. Exotic plants were most abundant along roads and in developed zones. At the same time, the distribution and abundance of exotic species is rapidly evolving, so repeating the exotic plant inventory reported here would be of value for park management, the scientific community, and the public. Future inventories should include areas deemed less susceptible to invasion both to confirm our current understanding of the distribution of exotic plants, and to enable early detection of spread of exotic plants due to climate change and other factors (Jones et al. 2010).

The design of our study was not designed to reveal the extent of shade tolerant species such as herb Robert, so we recommend expanding our study to include surveys of undisturbed habitat along road, trails, and developed zones (Martin et al. 2009). The threat of increased flooding with climate change and the need to bring in more road fill to repair flood damaged roads may increase the importation of exotic seeds in road fill and therefore increase the spread into areas adjacent to the immediate transportation corridor. With warming climates, snowpack and duration of snow cover are projected to decrease (Elsner et al.2010). These changes may both allow people to access higher elevations earlier (carrying weed seeds) and create milder conditions facilitating the survival and spread of exotic species (Pauchard et al. 2009). Based on these projections, surveys should be continued in the four susceptible habitats and expanded to adjacent undisturbed areas in these parks.

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Appendix A. Exotic species documented in study plots by park

Species	Common Name	WA State Weed Class[1]	MORA	NOCA	OLYM	Life Form[2]
Agrostis capillaris	Colonial bentgrass	--	--	--	X	G
Agrostis gigantea	Black bentgrass	--	X	X	X[3]	G
Aira caryophyllea	Delicate hairgrass	--	--	X	X	G
Aira praecox	Silver hairgrass	--	X	--	X	G
Anthoxanthum odoratum	Sweet vernal grass	--	--	--	X	F
Arabidopsis thaliana	Mouse-ear cress	--	--	X	--	F
Arctium minus	Common burdock	--	--	X	X	F
Arenaria serpyllifolia	Thyme-leaved sandwort	--	X	--	--	F
Arrhenatherum elatius var.elatius	Tall oatgrass	--	--	--	X[3]	G
Artemesia absinthium	Absinth wormwood	C	X[4]	X	--	F
Barbarea vulgaris	Bitter winter cress	--	--	--	X	F
Bellis perennis	English daisy	--	--	--	X	F
Bromus commutatus	Meadow brome	--	X	--	X	G
Bromus inermis	Smooth brome	--	X	X	--	G
Bromus tectorum	Cheat grass	--		X	X	G
Campanula perscifolia	Peach-leaf bellflower	--	X	--	--	F
Centaurea diffusa	Diffuse knapweed	B		X	X	F
Centaurea nigra	Black knapweed	B	X[4]	--	--	F
Centaurea stoebe	Spotted knapweed	B	X	--	--	F
Cerastium fontanum	Common chickweed	--	X	X	X	F
Cerastrium glomeratum	Sticky mouse-ear chickweed	--	--	X	X[3]	F
Cirsium arvense	Canada thistle	C	--	X	X	F
Cirsium vulgare	Bull thistle	C	X	X	X	F
Convolvulus arvensis	Field bind-weed	--	--	--	X[3]	V
Conium maculatum	Poison hemlock	B	--	--	X[3]	F
Crepis capillaris	Smooth hawksbeard		X	X	X[3]	F
Cynosurus cristatus	Crested dogtail	--	--	--	X	G
Cytisus scoparius	Scot's broom	B	--	X	X	S
Dactylis glomerata	Orchard grass	--	X	X	X	G
Daucus carota	Queen Annes' lace	C	--	X	X[3]	F
Dianthus armeria	Deptford pink	--	--	--	X	F
Dianthus barbatus	Sweet William	--	--	--	X[3]	F
Digitalis purpurea	Foxglove	--	X	X	X3	F
Draba verna	Spring whitlow-grass	--	--	--	X3	F
Echinochloa crus-galli	Barnyard grass	--	--	X	--	G
Echium vulgare	Common vipers-bugloss	--	--	--	X	F
Festuca pratensis	Meadow fescue	--	--	--	X[3]	G
Geranium robertianum	Herb Robert	B	--	X	X	F
Glechoma hederacea	Creeping Charlie		--	--	X[3]	V
Hedera helix	English ivy	C	--	--	X	V
Hieracium atratum	Polar hawkweed	B	--	--	X[4]	F
Hieracium aurantiacum	Orange hawkweed	B	X	--	--	F

Species	Common Name	WA State Weed Class[1]	MORA	NOCA	OLYM	Life Form[2]
Holcus lanatus	Velvet grass	--	--	X	X	G
Hypochaeris glabra	Smooth cat's ear	--	--	--	X[3]	F
Hypochaeris radicata	Hairy cat's ear	C	X	X	X	F
Hypericum perforatum	Klamath weed	C	X	X	X	F
Ilex aquifolium	English holly	Monitor	--	--	X	T
Lapsana communis	Nipplewort	--	--	X	X	F
Lathyrus sylvestris	Flat pea	Monitor		X[4]	X[3]	V
Leontodon saxatilis	Lesser hawkbit	--	--	--	X[4]	F
Leucanthemum vulgare	Ox-eye daisy	C	X	X	X	F
Linaria dalmatica	Dalmatian toadflax	B	--	--	X[3]	F
Lolium multiflorum	Annual ryegrass	--	X	--	--	G
Lolium perenne	Perennial ryegrass	--	X	--	X	G
Lotus corniculatus	Birds-foot trefoil	--	X	--	--	F
Lotus uliginosus	Large trefoil	--	--	--	X[4]	F
Malus x domestica	Cultivated apple	--	--	--	X[4]	T
Matricaria matricaroides	Pineapple weed	--	--	X	--	F
Medicago lupulina	Black medicgrass	--	--		X[3]	F
Medicago sativa	Alfalfa	--	--	X	--	F
Melilotus alba	White sweet clover	--	--	X	--	F
Mycelis muralis	Wall lettuce	Monitor	X	X	X	F
Myosotis discolor	Yellow and blue forget-me-not	--	--	--	X	F
Myosotis sylvatica	Woodland forget-me-not	--	--	X[4]	--	F
Oenothera biennis	Evening primrose	--	--	X[4]	--	F
Phalaris arundinacea	Reed canary grass	C	--	X	X	G
Phleum pretense	Common Timothy	--	X	X	X	G
Plantago lanceolata	English plantain	--	X	X	X[3]	F
Plantago major	Common plantain	--	X	X	X	F
Poa annua	Annual bluegrass	--	X	X	X	G
Poa compressa	Flat-stem blue grass	--	--	--	X	G
Poa pratensis	Kentucky bluegrass	--	--	X	X	G
Poa trivialis	Rough-stalked bluegrass	--	X	X	X	G
Polygonum aviculare	Doorweed	--	X	X	--	F
Polygonum x bohemicum	Bohemian knotweed	B	--	--	X	F
Polygonum maculosa	Spotted lady's-thumb	--	--	--	X[4]	F
Prunella vulgaris var. vulgaris	Self-heal	--	X	X	X	F
Ranunculus acris	Meadow buttercup	--		X	X[4]	F
Ranunculus repens	Creeping buttercup	--	X	X	X	F
Rubus discolor	Himalayan blackberry	--	--	X	X	V
Rubus lacinatus	Evergreen blackberry	C	--	X	X	V
Rumex acetosella	Sheep sorrel	--	X	X	X	F
Rumex crispus	Curly dock	--	--	X	X	F
Rumex obtusifolius	Bitter dock	--	--	X	X	F
Sagina procumbens	Bird-eye pearlwort	--	X	--	--	F

Species	Common Name	WA State Weed Class[1]	MORA	NOCA	OLYM	Life Form[2]
Schedonorus arundiaceus	Tall fescue	--	--	--	X	G
Senecio jacobaea	Tansy ragwort	B	--	--	X[3]	F
Senecio sylvaticus	Wood groundsel	--	--	--	X[3]	F
Silene latifolia	White campion	--	--	X	--	F
Silene noctiflora	Night-flowering campion	--	--	X	--	F
Silene vulgaris	Bladder campion	--	X	X		F
Sonchus asper	Prickly sow-thistle	--	--	X	X[3]	F
Sonchus oleraceus	Common sow-thistle	--	--	--	X[3]	F
Spergula arvensis	Stickwort	--	--	--	X[3]	F
Spergularia rubra	Red sandspurry	--	X	--	X	F
Stellaria media	Chickweed	--	--	--	X	F
Tanaecetum vulgare	Common tansy	C	X	X	--	F
Taraxacum officinale	Common dandelion	--	X	X	X	F
Tragopogon porrifolius	Salsify	--	--	X	--	F
Trifolium arvense	Rabbit-foot clover	--	--	X	--	F
Trifolium dubium	Least hop clover	--	X	--	--	F
Trifolium hybridum	Alsike clover	--		X	--	F
Trifolium pratense	Red clover	--	X	X	X[3]	F
Trifolium repens	White clover	--	X	X	X	F
Veronica arvensis	Wall speedwell	--			X	F
Veronica officinalis	Common speedwell	--	X	X	--	F
Veronica serpyllifolia var. serpyllifolia	Thyme-leaved speedwell	--	X	--	X	F
Verbascum thapsus	Common mullein	--	X	X	--	F
Vicia hirsuta	Hairy vetch	--	--	X	X	F
Vicia sativa var. sativa	Common vetch	--	--	X	--	F
Vicia tetrasperma	Slender vetch	--	--	X	--	F
Vulpia bromoides	Brome six-weeks grass	--	--	--	X	G

[1] A = non-native species whose distribution in Washington is still limited, eradication of Class A plants is required by law; B = non-native species presently limited to portions of the State; C = noxious weeds that are typically widespread in WA or are of special interest to the state's agricultural industry; Monitor indicates species for which more information is needed because they are believed to pose a threat in Washington state (Washington State 2015).

[2] F= forb, G = grass, S = shrub, T = tree, V = vine

[3] Species that are listed as Probably Present in NPSpecies.

[4] Species that are not listed as Present in Park in NPSpecies.

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NPS 105/133825, 149/133825, August 2016

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