

Final Report

Title of Study: Assessing biodiversity and connectivity of cold-adapted alpine insects in the Skagit River Watershed

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Photos of *Nebria vandykei* (above) and *Grylloblatta* (below).



I. Introduction

Montane habitats, covering approximately 10% of the global land surface, provide critical environmental services to adjacent ecosystems and human communities, including clean water, carbon storage, and a wealth of natural resources (Spehn and Körner 2005). These habitats are also biodiversity hotspots that are particularly susceptible to species loss in a changing climate due to their high level of endemism (Körner and Spehn 2002). In western North America, montane regions are considered “globally outstanding” when measured for their biological distinctiveness (Ricketts et al. 1999), and at the same time “exceptionally at risk” of biodiversity loss due to climate change (La Sorte and Jetz 2010). Although natural reserves encompass many western mountains, recent studies have documented upslope range shifts and population declines in protected plant and animal taxa (Lenoir et al. 2008, Moritz et al. 2008).

A number of climate change assessments have been developed for the Pacific Northwest focusing on threatened plant and vertebrate species with good presence/absence data (e.g. Carroll et al. 2010, Johnston et al. 2012). However, baseline data is largely lacking for the North Cascades ecoregion (existing data is reviewed in: Raymond et al. 2013), particularly standardized data suitable for assessing changes in abundance and diversity of climate sensitive taxa. This study focused on a group of cold-adapted insects, including ground beetles in the genus *Nebria* (Coleoptera: Carabidae) and ice-crawlers in the genus *Grylloblatta* (Grylloblattodea: Grylloblattidae), because they are highly diverse, responsive to environmental change on short timescales, and dependent on snow-field and montane riparian habitats, therefore directly susceptible to projected reductions in snow cover in the Pacific Northwest (Nolin and Daly 2006, Minder 2010). As an ecological guild, these insects serve as a multi-species index to measure the effect of changing precipitation in the North Cascades.

The specific objectives in this research project were to 1) determine the diversity and abundance of *Nebria* and *Grylloblatta* species in the North Cascades ecoregion, 2) estimate genetic connectivity among populations in this region for several species, and 3) train graduate and undergraduate students in alpine biodiversity studies and genetics. I set out to test two hypotheses, first that diversity and abundance change across the Cascades Range, specifically with a reduction in diversity and abundance at sites with less topographic relief, and second, that populations of alpine insects comprise multiple management units that consist of discrete genetic groups within the North Cascades ecosystem. If abundance and diversity varies, and populations consist of isolated genetic groups across the North Cascades, then my research will demonstrate that climate change could drive populations extinct in peripheral areas or areas lacking high elevation retreats. The outcome of this research on cold-adapted insects in the Skagit Watershed provides baseline data for continued assessment and resource management decision-making on montane riparian and snowfield habitats.

II. Methods

Permits, Study organisms and Surveys:

Scientific collecting permits were obtained from Mt. Rainier National Park (#MORA-2014-SCI-0006), North Cascades National Park (#NCCO-2014-SCI-0005), and the State of Washington (#14-116). Additionally, I received a special use permit covering sites in Mt. Baker-Snoqualmie National Forest.

Ground beetles in the genus *Nebria* are locally abundant and highly diverse across all major mountain ranges in western North America (Kavanaugh 1978, Kavanaugh and Schoville 2009), with up to 13 species occupying distinct altitudinal zones on individual mountains in the

North Cascades. These beetles directly depend on winter snowpack to buffer their microhabitats, as well as stable sources of cold water to maintain the temperature and humidity of these microhabitats (Kavanaugh 1988). Ice-crawlers (*Grylloblatta* spp.), although less well known, are even more sensitive physiologically to snowpack conditions on talus slopes (Schoville et al. 2015) and are extremely poor dispersers (Schoville and Graening 2013).

Sixteen sites were visited during this study in June-August 2013-2015 (see Figure 1), including eight focal sites in the North Cascades/Skagit watershed. Abundance surveys focused primarily on high elevation regions and were successfully completed at ten sites, as poor weather conditions rendered abundance estimates at six sites unreliable, though these sites were included

as presence/absence surveys and for genetic sampling. Distribution data of *Nebria* and *Grylloblatta* are available for Mt. Rainier from a period in the late 1970s (Kavanaugh 1978, Mann et al. 1980). Transect surveys were conducted to mimic these previous surveys, and so were conducted during the peak nocturnal foraging period of these insects, 2-3 hours after sunset (Mann et al. 1980). Transects of 100 meters length, repeated as frequently as every 100m elevation and up to a range of 500-1000m elevation per night, were centered 5 meters from riparian zones or snowfield boundaries (where talus is exposed), as insects emerge from these habitats during foraging bouts. Abundance counts noted each individual within 5 meters to the left and right of the transect line, in order to calculate the number of individuals encountered per meter-squared of habitat at each elevation. In most cases, replicate transects were made at each elevation, and the average across transects for each elevation zone is presented. The abundance counts per m² at each elevation are the basis for estimating each species range extent and the abundance weighted average of the range at each site.

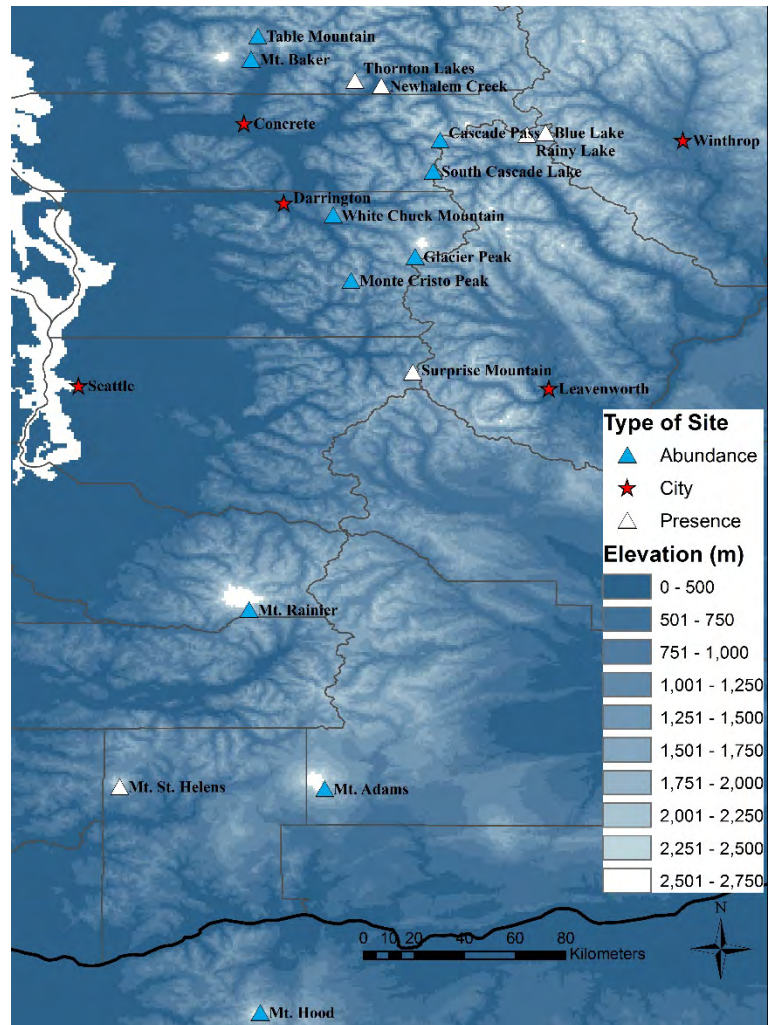


Figure 1. Map of sites visited for presence (white triangles) and abundance surveys (blue triangles).

Topographic Relief and Hypothesis Testing:

To calculate the relative topographic relief of each site, I obtained the Washington 10 meter resolution Digital Elevation Model (<http://gis.ess.washington.edu>), which is derived from

7.5-minute United States Geological Survey topographic maps. Terrain roughness per raster cell was calculated using neighboring cell values (10x10) as the difference in mean elevation minus minimum elevation, divided the difference in maximum elevation minus minimum elevation. The mean roughness per sample site was then calculated as the average per cell roughness within a buffer of 1 and 10km², to reflect site-specific and regional aspects of topographic change. Using a Pearson correlation coefficient (r), I examined the relationship between the presence of each *Nebria* and *Grylloblatta* species and terrain roughness, as well as range size.

Genetic Analyses:

Genetic data are increasingly used to infer demographic processes on landscapes and to assess potential impacts of climate change (Manel and Holderegger 2013). In particular, these data provide estimates of genetic diversity within and among populations, which is proportional to a long-term average of population size, and the frequency of gene exchange among populations. In prior studies, I've used genetic data to understand how interconnected *Nebria* and *Grylloblatta* populations are in the Sierra Nevada Mountains of California (Schoville and Roderick 2010, Schoville et al. 2012). In this study, preliminary genetic analyses focus on two high elevation *Nebria* species, *N. paradisi* and *N. vandykei*, and one riparian montane species, *N. meanyi*. Additionally, I examine the genetic diversity of high elevation populations of *Grylloblatta*. The genetic sampling presented here includes one mitochondrial gene (the COI locus for *Nebria*, and the COII locus for *Grylloblatta*). Population genetic differentiation was measured as pairwise sequence divergence (number of nucleotide differences among sequences), as well as pairwise difference corrected for within population variation using the F_{ST} statistic. The significance of F_{ST} was calculated using permutation tests. Both statistics were measured in the software ARLEQUIN v3.5 (Excoffier et al. 2005). In addition, for *Grylloblatta*, a neighbor-joining tree based on Jukes-Cantor corrected nucleotide distances was calculated in the software GENEIOUS (Biomatters Ltd.). Sampling of nuclear genes is on-going and will provide the basis for detailed connectivity analyses in an upcoming publication.

III. Results

Species Diversity and Abundance:

Sixteen sites were surveyed for beetles in the genus *Nebria* and ice-crawlers in the genus *Grylloblatta*. Thirteen species of *Nebria* (including the closely related genus *Nippononebria*) were found across the region (see **Table 1**), in accordance with prior studies (Kavanaugh 1988). However, some notable discoveries were made, including the presence of the rare beetle, *Nippononebria campbelli*, at sites throughout the North Cascades and at Mt. Rainier (it was previously only known from Table Mountain). Additionally, *Grylloblatta* was found at all survey sites, with new discoveries at Mt. Baker, Thornton Lakes, Rainy Lake, Cascade Pass, Glacier Peak, Surprise Mountain, and Mt. Adams. Other range extensions include nearly all records of *Nebria* from the North Cascades region, which had not been surveyed specifically for these beetles. The diversity of *Nebria* varied among the study sites, from the most diverse community at Mt. Rainier, to the least diverse community at Mt. St. Helens. Within the North Cascades, sites such as Cascade Pass, Glacier Peak, and Monte Cristo had the most diverse *Nebria* communities. Sites along the Highway 20 corridor (Thornton Lakes, Blue Lake, and Rainy Lake) had few species of *Nebria*. Despite appropriate habitat, some sites (e.g. Mt. Baker) lacked high elevation *Nebria* species such as *N. paradisi* and *N. vandykei*, while others only had one of these species (e.g. White Chuck Mountain).

Table 1. Presence (+), absence (-), or unknown presence (?) of *Nebria* and *Grylloblatta* species at sample sites.

Species	Table Mountain	Mt. Baker	Thornton Lakes	Newhalem Creek	Blue Lake	Rainy Lake	Cascade Pass	South Cascade Lake	White Chuck Mountain	Glacier Peak	Monte Cristo Peak	Surprise Mountain	Mt. Rainier	Mt. St. Helens	Mt. Adams	Mt. Hood
<i>Nebria paradisi</i>	-	-	-	-	-	-	+	+	+	+	+	-	+	+	+	+
<i>N. crassicornis</i>	-	+	+	-	?	+	+	+	+	+	-	-	+	-	?	-
<i>N. vandykei</i>	+	-	-	-	+	+	+	+	-	+	+	-	+	+	?	+
<i>N. meanyi</i>	+	+	+	-	?	+	+	+	+	+	+	-	+	-	?	+
<i>N. kincaidi</i>	-	-	-	-	-	-	-	-	-	-	-	+	?	-	?	+
<i>N. gebleri</i>	+	+	+	+	?	?	+	+	?	+	+	+	+	?	+	+
<i>N. acuta</i>	+	+	?	-	?	?	+	+	?	+	+	?	+	?	?	+
<i>N. piperi</i>	-	-	-	-	-	-	-	+	-	-	-	?	+	-	-	-
<i>N. sahlbergii</i>	+	-	-	+	-	-	-	-	-	-	+	-	+	+	+	+
<i>N. metallica</i>	+	-	-	+	-	-	+	-	-	-	-	-	+	?	-	-
<i>N. mannerheimii</i>	+	-	-	+	-	-	-	-	-	-	-	-	+	?	?	+
<i>N. eschscholtzii</i>	-	-	-	-	-	-	-	-	-	-	-	?	+	+	+	+
<i>Nipp. campbelli</i>	+	-	+	-	-	+	+	-	-	-	-	-	+	-	-	-
<i>Grylloblatta sp.</i>	+	+	+	-	+	+	+	+	+	+	+	+	+	+	+	+

The altitudinal distribution of *Nebria* and *Grylloblatta* also varied among sites (**Figure 2**), with all species occupying lower elevations in the North Cascades. The range size is also compressed in the North Cascades, which is not only reflected by the smaller range size but also the abundance weighted average of the range. The abundance data is provided as an appendix to this report (see **Section VIII**).

Topographic Relief, Diversity and Range Size:

Measurements of terrain roughness were estimated from digital elevation models to use as proxy measures of topographic relief (**Table 2**), at a scale of 10km² and 1km². The larger scale reflects regional changes in topography surrounding each site, which might influence species diversity and abundance through a ‘neighborhood effect’ of surrounding topographically complex sites. The smaller scale reflects local, site specific influences of topography, which likely impact local populations directly and relate to structural environmental features that differ among sites. Correlation coefficients of insect presence across these two scales of roughness suggests that several species are responsive ($r > \pm 0.5$) to these conditions. At a large scale, the riparian species *N. meanyi*, *N. acuta* and *N. kincaidi* exhibit a large correlation, while at a local scale the high elevation, snowfield specialists *N. paradisi* and *N. vandykei* have a high correlation. *Nippononebria campbelli* and *Grylloblatta* also are responsive to roughness at a large scale.

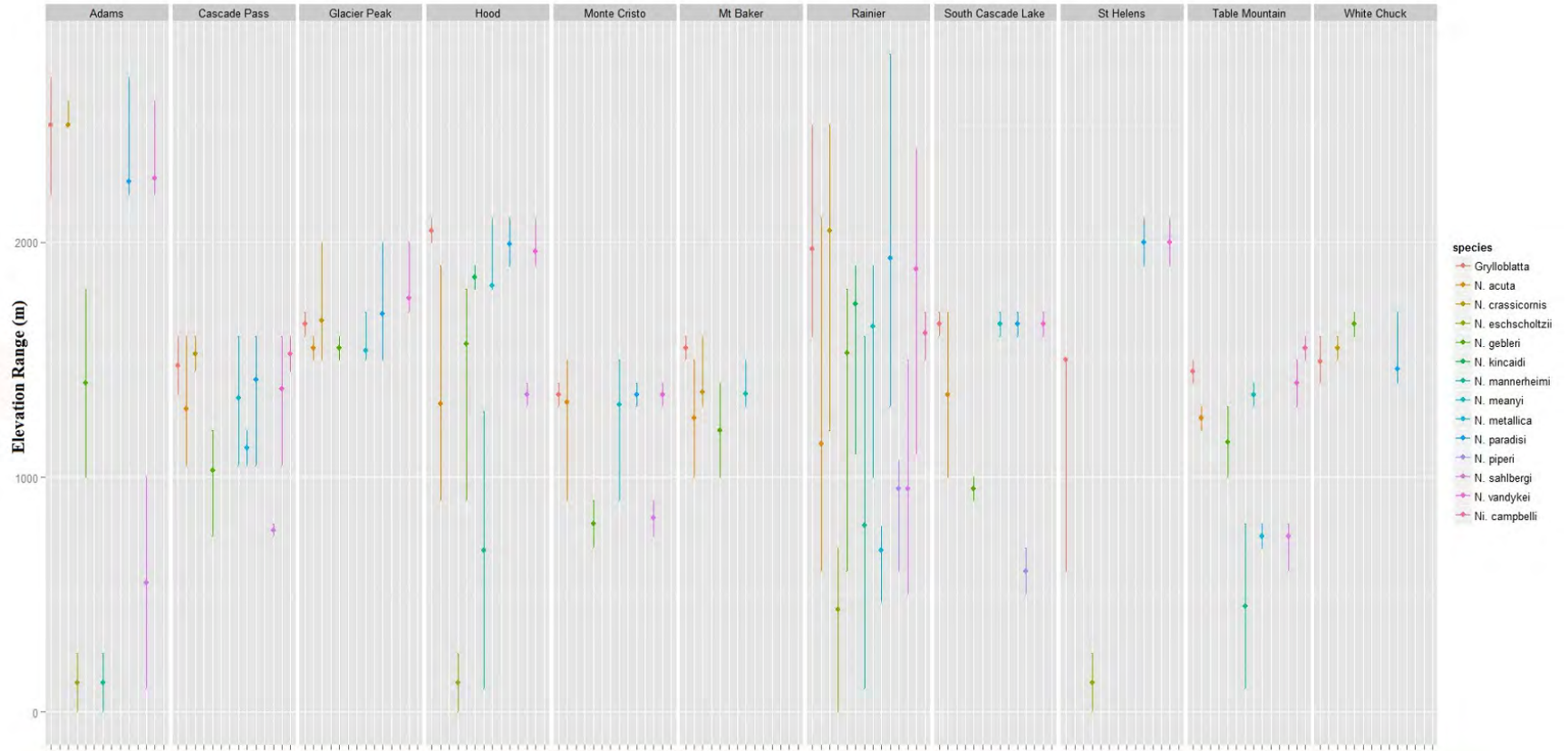


Figure 2. Altitudinal distribution of *Nebria* and *Grylloblatta* species by site. Mean-weighted value indicated by circle.

Table 2. Terrain roughness at each site (in 10km² and 1km² radius).

Study Sites	Terrain roughness 10km ²	Terrain roughness 1km ²
Table Mountain	0.506	0.479
Monte Cristo Peak	0.497	0.328
White Chuck Mountain	0.5	0.49
Newhalem Creek	0.468	0.385
Blue Lake	0.479	0.458
Rainy Lake	0.472	0.426
Cascade Pass	0.503	0.533
South Cascade Lake	0.472	0.537
White Chuck Mountain	0.487	0.53
Glacier Peak	0.484	0.395
Monte Cristo Peak	0.485	0.492
Surprise Mountain	0.467	0.213
Mt. Rainier	0.495	0.513
Mt. St. Helens	0.506	0.471
Mt. Adams	0.496	0.471
Mt. Hood	N/A	N/A

Table 3. Correlation (*r*) of presence data and elevational range with topographic roughness.

	Presence of species		Elevation range of species	
	Roughness 10km ²	Roughness 1km ²	Roughness 10km ²	Roughness 1km ²
<i>Nebria paradisi</i>	-0.04	0.69	0.02	-0.10
<i>N. crassicornis</i>	-0.14	-0.08	-0.27	0.07
<i>N. vandykei</i>	0.28	0.73	0.01	0.06
<i>N. meanyi</i>	0.53	0.44	0.00	0.27
<i>N. kincaidi</i>	0.50	0.50	-1.00	-1.00
<i>N. gebleri</i>	NA	NA	0.47	0.18
<i>N. acuta</i>	0.53	0.44	0.02	0.53
<i>N. piperi</i>	-0.44	0.42	1.00	-1.00
<i>N. sahlbergii</i>	0.14	0.08	-0.47	-0.47
<i>N. metallica</i>	0.15	-0.10	-1.00	0.33
<i>N. mannerheimii</i>	0.27	0.01	-0.01	0.74
<i>N. eschscholtzii</i>	0.50	0.50	-0.68	0.17
<i>Ni. campbelli</i>	0.57	0.22	-0.94	0.60
<i>Grylloblatta sp.</i>	0.53	0.44	0.21	-0.05

Associations of elevational range and roughness (**Table 3**) show conflicting results between regional and local terrain roughness. In several species, such as *N. piperi*, *N. metallica*, and *Ni. campbelli*, strong correlations ($r > \pm 0.5$) are reversed across these scales. These results

are difficult to interpret and may be due to limited data for these species, and/or their overall narrow range size. Positive correlations of abundance with local terrain roughness are found for the riparian species *N. mannerheimi* and *N. acuta*. Topographic relief appears to have a much stronger effect on diversity than range size for species.

Genetic Diversity and Connectivity:

Preliminary analyses of genetic diversity were collected for four species of montane insects at a single mitochondrial gene (nuclear genetic data are being processed). These data suggest that considerable variation exists across the Cascades Range (**Table 3**). Comparing genetic diversity in the North Cascades to mountains in the Central Cascades (Mt. Hood, Mt. Adams, Mt. St. Helens, Surprise Mountain, and Mt. Rainier) shows a high degree of pairwise sequence divergence and pairwise *F_{ST}*. These values are consistent with limited connectivity at this large geographical scale. Within the North Cascades, *Grylloblatta* and *N. vandykei* show considerable pairwise sequence divergence, while *N. meanyi* has minor differences. I was unable to calculate diversity values of *N. paradisi* within the North Cascades at the time of this report, as several sites are still being processed for mitochondrial data.

One particularly noteworthy result is the substantial diversity evident in *Grylloblatta* specimens, both within the North Cascades and in comparison to the Central Cascades. A neighbor-joining phylogenetic tree (see **Figure 3**) suggests that several genetic clades are present, most likely representing distinct (and undescribed) species.

Table 3. Genetic divergence of populations in the North Cascades, relative to the Central Cascades. All pairwise *F_{ST}* are statistically significant.

Species	Pairwise Sequence Divergence: North to Central Cascades	Pairwise Sequence Diversity within North Cascades	Pairwise <i>F_{ST}</i>
<i>Grylloblatta</i>	76.88	10.0	0.544
<i>Nebria vandykei</i>	4.79	2.27	0.684
<i>Nebria paradisi</i>	3.13	N/A	0.748
<i>Nebria meanyi</i>	0.29	0.42	0.023

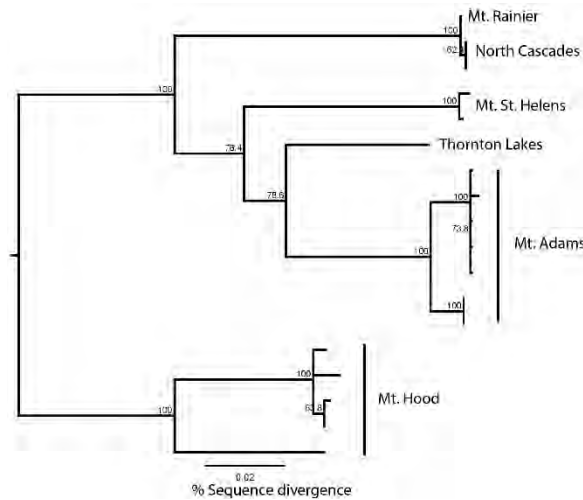


Figure 3. Mitochondrial phylogenetic tree of *Grylloblatta*, showing deep sequence divergence across the Cascades Range and a unique lineage at Thornton Lakes.

IV. Discussion and Management Implications

Significant Findings

Cold-specialized insects in the genus *Nebria* and *Grylloblatta* comprise a number of endemic species restricted to mountain habitats in the Pacific Northwest (Kavanaugh 1988, Schoville and Graening 2013). This study significantly extended our knowledge of these groups in the North Cascades ecosystem and provided, for the first-time, estimates of distribution and abundance at sites across the Cascades Range. Topographic relief appears to be correlated with the presence of several species, suggesting that sites with limited relief may be more prone to species extirpation in a changing climate. This appears to be particularly important for determining the presence of riparian species at large spatial scales, and high elevation species at local scales.

Several important discoveries include a large expansion of the known range of the rare beetle *Nippononebria campbelli* and the ice-crawler genus *Grylloblatta*. Both species are widespread at sites throughout the North Cascades. Additionally, the *Grylloblatta* population at Thornton Lakes is genetically unique and highly divergent, and may represent an undescribed species. Finally, estimates of genetic diversity provide support for the distinctiveness of *Nebria* and *Grylloblatta* populations in the North Cascades, as well as an indication that populations within the North Cascades may be genetically divergent.

Objectives of Study and Future Work

The first objective of this study was to determine the diversity and abundance of *Nebria* and *Grylloblatta* species in the North Cascades ecoregion. Surveys were conducted at 11 sites within the North Cascades, as well as an additional 5 sites in the central Cascades Range. Presence/absence data was collected for all of these sites, particularly at high elevation. Due to difficulties with weather, only a subset of 11 sites were successfully surveyed for abundance data. These sample sites showed considerably variability in the presence, range size, and abundance of these insects across the Cascades. In the North Cascades region, communities consist of fewer species that have smaller, compressed altitudinal distributions. One particular note is that some riparian species were absent from sites within the North Cascades, which might be due to lack of appropriate habitat conditions (e.g. river size, cobble beach habitat). Topographic relief might partly account for these variation in diversity patterns, as significant correlations were observed at both regional and local scales for several species. Several high elevation species are absent from sites at the periphery of the North Cascades ecoregion.

The second objective was to estimate genetic connectivity among populations in this region for several species. Preliminary genetic data representing one mitochondrial gene was collected for three *Nebria* species and for *Grylloblatta*. Genetic divergence was evident for all species when comparisons were made to the Central Cascades, suggesting limited connectivity at very large spatial scales. Within the North Cascades, two *Nebria* species and *Grylloblatta* show genetic differences across sites, suggesting connectivity might also be low at a local scale. One particularly noteworthy result is the high genetic divergence of the *Grylloblatta* population at Thornton Lakes, which may represent a unique, undescribed species.

A third objective was to support student projects and public science education. Students working on this project included: Rachel Slatyer, an Australian PhD student (Univ. of Melbourne), who completed two chapters in her dissertation on beetle distributions and

physiology in the Cascades; Zachary Boor, an undergraduate at UW-Madison, who completed a senior project on alpine beetle mitochondrial genetics; Tierney Bougie, an undergraduate at UW-Madison, who completed a senior project on *Grylloblatta* mitochondrial genetics. More recently, Jack Ralph and Kira Schlicht, both undergraduates at UW-Madison, have worked on additional gene sequencing of the alpine beetles. All students have been involved in laboratory research, data analysis, and scientific writing. Public outreach efforts, including a presentation at North Cascades National Park (BioBlitz symposium on “Cold Environments and Cold Adapted Biota”) in July 2014, helped disseminate results from this project.

Ongoing work includes completion of genetic analysis for *Nebria vandykei*, *N. paradisi* and *Grylloblatta*. I am currently developing next generation sequencing data to provide high resolution measurements of connectivity across populations in the Cascades. I anticipate publishing this work in the coming year. One future project will also assess the status of *Grylloblatta* taxa within the North Cascades, to potentially describe a new species from Thornton Lakes. I am also anticipating two publications resulting from the work of Rachel Slatyer, one currently under review that examines thermal and water stress limits in *Nebria* species, and another that focuses on distributional range limits of the beetles across the Cascades. Additional effort in the future should be directed at increasing our understanding of the ecological requirements of each species, and providing additional sampling episodes and locations to improve inference about abundance and diversity changes. One goal I have is to develop predictive models of species distributions, based on known records and physiological data. This would allow researchers to identify sites that are most likely to undergo change and monitor those sites for changes in abundance and diversity of these insects.

Management Implications

One of the benefits of this research was to make a direct contribution to monitoring programs in North Cascades National Park and Baker-Snoqualmie National Forest. Diversity and abundance estimates can be used as an index of habitat suitability and changes in environmental conditions at these sites. These insects are excellent proxies for changes in snow conditions across the North Cascades, as they are dependent on snowfield habitats or cold-drainage riparian habitats. A second benefit of this research is that peer-reviewed scientific publication will be published, highlighting alpine insect biodiversity in the Skagit River Watershed. All data will be made available on public databases (e.g. National Center for Biotechnology Information GenBank database) and on my research website, enabling other investigators and park managers to pursue research on these insects. Finally, the data presented could be used by managers in two ways. First, diversity measures and genetic connectivity measures provide some insight into regions of the North Cascades that may be isolated and susceptible to change. Sites at the periphery of the range lack diversity, and the Thornton Lakes population of *Grylloblatta* suggests there may be a biogeographic divide in the North Cascades ecoregion. Insect populations at these sites should be managed separately, based on these results. Second, genetic data provide better understanding of how these insects recolonized the North Cascades and are interconnected across its range. Genetic data allow for prioritization of sites that have high genetic diversity (perhaps those sites represent the initial recolonization following the last glacial maximum). Additional nuclear genetic data should provide a more robust assessment of genetic diversity and connectivity in these insects.

V. Literature Cited

- Carroll, C., J. R. Dunk, and A. Moilanen. 2010. Optimizing resiliency of reserve networks to climate change: multispecies conservation planning in the Pacific Northwest, USA. *Global Change Biology* **16**:891-904.
- Excoffier, L., G. Laval, and S. Schneider. 2005. Arlequin (version 3.0): An integrated software package for population genetics data analysis *Evolutionary Bioinformatics Online* **1**:47-50.
- Johnston, K. M., K. A. Freund, and O. J. Schmitz. 2012. Projected range shifting by montane mammals under climate change: implications for Cascadia's National Parks. *Ecosphere* **3**:art97.
- Kavanaugh, D. H. 1978. The Nearctic species of *Nebria* Latreille (Coleoptera: Carabidae: Nebriini): classification, phylogeny, zoogeography, and natural history. University of Alberta, Edmonton, Alberta, Canada.
- Kavanaugh, D. H. 1988. The insect fauna of the Pacific Northwest Coast: present patterns and affinities and their origins. Pp. 125-149. Page 168 in J. A. Downes and D. H. Kavanaugh, editors. Symposium: origins of the North American insect fauna. *Memoirs of the Canadian Entomological Society*.
- Kavanaugh, D. H., and S. D. Schoville. 2009. A new and endemic species of *Nebria* Latreille (Insecta: Coleoptera: Carabidae: Nebriini), threatened by climate change in the Trinity Alps of Northern California. *Proceedings of the California Academy of Sciences* **60**:73-84.
- Körner, C., and E. M. Spehn, editors. 2002. *Mountain biodiversity: a global assessment*. Parthenon Publication Group, Boca Raton, Florida.
- La Sorte, F. A., and W. Jetz. 2010. Projected range contractions of montane biodiversity under global warming. *Proceedings of the Royal Society B: Biological Sciences* **277**:3401-3410.
- Lenoir, J., J. C. Gégout, P. A. Marquet, P. de Ruffray, and H. Brisse. 2008. A significant upward shift in plant species optimum elevation during the 20th century. *Science* **320**:1768-1771.
- Manel, S., and R. Holderegger. 2013. Ten years of landscape genetics. *Trends in Ecology & Evolution* **28**:614-621.
- Mann, D. H., J. S. Edwards, and R. I. Gara. 1980. Diel activity patterns in snowfield foraging invertebrates on Mount Rainier, Washington. *Arctic and Alpine Research* **12**:359-368.
- Minder, J. R. 2010. The sensitivity of mountain snowpack accumulation to climate warming. *Journal of Climate* **23**:2634-2650.
- Moritz, C., J. L. Patton, C. J. Conroy, J. L. Parra, G. C. White, and S. R. Beissinger. 2008. Impact of a century of climate change on small-mammal communities in Yosemite National Park, USA. *Science* **322**:261-264.
- Nolin, A. W., and C. Daly. 2006. Mapping "at risk" snow in the Pacific Northwest. *Journal of Hydrometeorology* **7**:1164-1171.
- Raymond, C. L., D. L. Peterson, and R. M. Rochefort. 2013. The North Cascadia adaptation partnership: A science-management collaboration for responding to climate change. *Sustainability* **5**:136-159.
- Ricketts, T. H., E. Dinerstein, D. M. Olson, C. J. Loucks, W. Eichbaum, D. Della Salla, K. Kavanagh, P. Hedao, P. Hurley, K. Carney, R. Abell, and S. Walters, editors. 1999. *Terrestrial Ecoregions of North America: A Conservation Assessment*. Island Press, Washington, D.C.

- Schoville, S. D., and G. O. Graening. 2013. Updated checklist of the ice-crawlers (Insecta: Grylloblattodea: Grylloblattidae) of North America, with notes on their natural history, biogeography and conservation. *Zootaxa* **3737**:351-378.
- Schoville, S. D., and G. K. Roderick. 2010. Evolutionary diversification of cryophilic *Grylloblatta* species (Grylloblattodea: Grylloblattidae) in alpine habitats of California. *BMC Evolutionary Biology* **10**:163.
- Schoville, S. D., G. K. Roderick, and D. H. Kavanaugh. 2012. Testing the “Pleistocene species pump” in alpine habitats: lineage diversification of flightless ground beetles (Coleoptera: Carabidae: *Nebria*) in relation to altitudinal zonation. *Biological Journal of Linnean Society* **107**:95-111.
- Schoville, S. D., R. A. Slatyer, J. C. Bergdahl, and G. A. Valdez. 2015. Conserved and narrow temperature limits in alpine insects: Thermal tolerance and supercooling points of the ice-crawlers, *Grylloblatta* (Insecta: Grylloblattodea: Grylloblattidae). *Journal of Insect Physiology* **78**:55-61.
- Spehn, E., and C. Körner. 2005. A global assessment of mountain biodiversity and its function. Pages 393-400 in U. M. Huber, H. K. M. Bugmann, and M. A. Reasoner, editors. *Advances in Global Change Research*. Springer Netherlands.
- Spies, T., T. Giesen, F. Swanson, J. Franklin, D. Lach, and K. Johnson. 2010. Climate change adaptation strategies for federal forests of the Pacific Northwest, USA: ecological, policy, and socio-economic perspectives. *Landscape Ecology* **25**:1185-1199.

VI. Partnerships

Collaborations were developed with federal agencies at North Cascades National Park and Baker-Snoqualmie National Forest, to provide them with information and data on insect communities. Written reports have been shared with these agencies, integrating my survey and connectivity data in reference to previous research in the Cascades Range (e.g. Carroll et al. 2010, Spies et al. 2010). Species photographic keys and tabulated distributional data have been developed to facilitate future monitoring studies of these insect taxa.

Additional funding was provided to support Rachel Slatyer’s travel and participation in this project, in the form of a National Geographic Young Explorer’s Grant (#9502-14) and a travel grant from the University of Melbourne. Funds for genetics work were also provided by the University of Wisconsin.

VII. Publications and Presentations

Peer-reviewed Publications:

Schoville, S.D., R.S. Slatyer, J.C. Bergdahl, G.A. Valdez. 2015. Conserved and narrow temperature limits in alpine insects: thermotolerance and supercooling points of the ice-crawlers, *Grylloblatta* (Insecta: Grylloblattodea: Grylloblattidae). *Journal of Insect Physiology* **78**: 55-61.

Publications in Review or in Preparation:

In Review, 2015: Slatyer, R.S., and S.D. Schoville. “Physiological limits are not associated with elevation in a radiation of montane beetles.” *PLoS One*

In Preparation, 2015: Slatyer, R.S., and S.D. Schoville. “Ecological correlates of geographic range size: a case study in North American ground beetles (genus *Nebria*).”

In Preparation, 2016: Bougie, T., R. Dudko, M. Medeiros, and S.D. Schoville. “Evolutionary responses to climate variation in the ice-crawlers (*Grylloblatta* spp.) of western North America.”

Presentations:

Schoville, S.D. July 2014, North Cascades National Park BioBlitz. “The biodiversity, natural history and conservation of snow-field insects in the North Cascades.”

Boor, Z. and S.D. Schoville. March 2015, Undergraduate Research Symposium, University of Wisconsin-Madison. “Genetic connectivity of beetles in the Pacific Northwest.”

2500-2700	5	2694.945	0	0	0	0	0.4	0	0	0	0	0.2	0	0	0	
EncounterRate			0	0	0	0	0.0001	48	0	0	0	7.42E-05	0	0	0	
StandardError_ER			0	0	0	0	0.0003	32	0	0	0	0.000166	0	0	0	
PeakAbundance			0	0	0	0	0.004	0	0	0	0	0.002	0	0	0	
low edge		1	500	600	600	1000	1300	1100	100	600	1100	1200	470	1500	1600	
high edge		700	1500	2100	1800	1900	2800	2400	1600	1075	1900	2500	790	1700	2500	
mean		350.5	1000	1350	1200	1450	2050	1750	850	837.5	1500	1850	630	1600	2050	
A-W mean		437.33	950	1143.	1528.	1642.	1930.9	1885.7	792.8571	950	1736	2050	688	1613	1971.4	
				182	571	857	09	14							29	
Mt. Adams																
2600-2700	2	1022.242	0	0	0	0	1.5	0	0	0	0	0	0	0	0	2
EncounterRate			0	0	0	0	0.0014	68	0	0	0	0	0	0	0	0.0019
StandardDev_ER			0	0	0	0	0.0020	75	0	0	0	0	0	0	0	0.0013
PeakAbundance			0	0	0	0	0.006	0	0	0	0	0	0	0	0	0.006
2500-2600	4	1686.462	0	0	0	0	0.5	0.25	0	0	0	0.25	0	0	0	0.5
EncounterRate			0	0	0	0	0.0002	0.0001	96	48	0	0.000148	0	0	0	0.0002
StandardDev_ER			0	0	0	0	0.0003	0.0002	42	96	0	0.000296	0	0	0	0.0003
PeakAbundance			0	0	0	0	0.002	0.002	0	0	0	0.002	0	0	0	0.002
2400-2500	2	641.439	0	0	0	0	0	0.5	0	0	0	0	0	0	0	0
EncounterRate			0	0	0	0	0	0.0007	8	0	0	0	0	0	0	0
StandardError_ER			0	0	0	0	0	0.0011	02	0	0	0	0	0	0	0
PeakAbundance			0	0	0	0	0	0.002	0	0	0	0	0	0	0	0
2200-2300	3	1274.337	0	0	0	0	10.333	3	0	0	0	0	0	0	0	0.6666
EncounterRate			0	0	0	0	0.0081	0.0023	09	54	0	0	0	0	0	0.0005
StandardError_ER			0	0	0	0	0.0086	0.0015	8	69	0	0	0	0	0	0.0004
PeakAbundance			0	0	0	0	0.044	0.01	0	0	0	0	0	0	0	0.002
low edge		0	100	NA	1000	NA	2200	2200	0	NA	NA	2500	NA	NA	2200	
high edge		250	1000	NA	1800	NA	2700	2600	250	NA	NA	2600	NA	NA	2700	

low edge	0	1300	900	900	1800	1900	1900	100	NA	1800	NA	NA	NA	2000
high edge	250	1400	1900	1800	2100	2100	2100	1280	NA	1900	NA	NA	NA	2100
mean	125	1350	1400	1350	1950	2000	2000	690	NA	1850	NA	NA	NA	2050
A-W mean	125	1350	345	667	706	09	1960	690	NA	1850	NA	NA	NA	2050

Cascade Pass

750-800	1	502.458	1	0	1	0	0	0	0	0	0	0	0	0	0
EncounterRate			0.0019		0.001										
StandardDev_ER			9	0	992	0	0	0	0	0	0	0	0	0	0
PeakAbundance			0	0	0	0	0	0	0	0	0	0	0	0	0

1050-1200	2	1005.752	0	2	6.5	1.5	0.5	1.5	0	0	0	0	0.5	0	0
EncounterRate			0.001	0.006	0.001	0.0004	0.0014						0.0004		
StandardError_ER			0	989	463	491	97	91	0	0	0	0	97	0	0
PeakAbundance			0	0.002	0.007	0.000	0.0007	0.0021	0	0	0	0	0.0007	0	0

1350-1450	2	1015.48	0	0	0	0	3.5	3.5	0	0	0	0	0	0	0.5
EncounterRate			0	0	0	0	0.0034	0.0034							0.0004
StandardError_ER			0	0	0	0	47	47	0	0	0	0	0	0	92
PeakAbundance			0	0	0	0	0.0034	0.0034	0	0	0	0	0	0	0.0006

1450-1600	7	3770.539	0	2.333	0	1.285	13.142	5.2857	0	0	0	1.571429	0	0.85714	0.2857
EncounterRate			0	333	0	714	86	14	0	0	0	0	0	3	14
StandardError_ER			0	0.000	0	0.000	0.0034	0.0014	0	0	0	0.000417	0	0.00022	7.58E-05
PeakAbundance			0	0.000	0	0.000	0.0016	0.0013	0	0	0	0.000481	0	0.00049	0.0002

low edge	NA	750	1050	750	1050	1050	1050	NA	NA	NA	1450	1050	1450	1350
high edge	NA	800	1600	1200	1600	1600	1600	NA	NA	NA	1600	1200	1600	1600
mean	NA	775	1325	975	1325	1325	1325	NA	NA	NA	1525	1125	1525	1475
A-W mean	NA	775	1290	923	714	63	1375	NA	NA	NA	1525	1125	1525	1475

Glacier Peak

1500-1600	3	1496.806	0	1.666	1	9	5.6666	67	0	0	0	2.333333	0	0	0
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EncounterRate				0.001	0.000	0.006	0.0037									
				0	113	668	013	86	0	0	0	0	0.001559	0	0	0
StandardDev_ER				0	0.001	0.000	0.002	0.0036								
				0	929	668	672	8	0	0	0	0	0.001391	0	0	0
PeakAbundance				0	0.01	0.004	0.026	0.024					0.008	0	0	0
1600-1700	4	1784.549		0	0	0	2	15.25	0	0	0	0	3.25	0	0	0.25
EncounterRate				0	0	0	0.001	0.0085								0.0001
				0	0	0	121	46	0	0	0	0	0.001821	0	0	4
StandardError_ER				0	0	0	0.002	0.0159								0.0002
				0	0	0	242	77	0	0	0	0	0.001852	0	0	8
PeakAbundance				0	0	0	0.016	0.116					0	0	0	0.002
1700-1800	3	1202.234		0	0	0	0	26					2.3333	0	0	0
EncounterRate				0	0	0	0	0.0216	0.0019				1.333333	0	0	0
				0	0	0	0	27	41				0.001109	0	0	0
StandardError_ER				0	0	0	0	0.0130	0.0017				0.00096	0	0	0
				0	0	0	0	73	32				0.00096	0	0	0
PeakAbundance				0	0	0	0	0.086	0.008				0.004	0	0	0
1800-1900	2	1007.657		0	0	0	0	4	1.5				1	0	0	0
EncounterRate				0	0	0	0	0.0039	0.0014				0.000992	0	0	0
				0	0	0	0	69	89				0.000992	0	0	0
StandardError_ER				0	0	0	0	0.0014	0.0021				0	0	0	0
				0	0	0	0	03	05				0	0	0	0
PeakAbundance				0	0	0	0	0.01	0.006				0.002	0	0	0
1900-2000	2	1058.119		0	0	0	0	34	0.5				1	0	0	0
EncounterRate				0	0	0	0	0.0321	0.0004				0.000945	0	0	0
				0	0	0	0	33	73				0.000945	0	0	0
StandardError_ER				0	0	0	0	0	0.0006				0.001337	0	0	0
				0	0	0	0	0	68				0.001337	0	0	0
PeakAbundance				0	0	0	0	0.068	0.002				0.004	0	0	0
low edge		NA	NA	1500	1500	1500	1500	1700	NA	NA	NA	1500	NA	NA	NA	1600
high edge		NA	NA	1600	1600	1700	2000	2000	NA	NA	NA	2000	NA	NA	NA	1700
mean		NA	NA	1550	1550	1600	1750	1850	NA	NA	NA	1750	NA	NA	NA	1650
A-W mean		NA	NA	1550	1550	1538.095	1694.079	1762.5	NA	NA	NA	1666.667	NA	NA	NA	1650

Monte Cristo

1300-1400	7	3239.412		0	0.571	0	4.142	3.4285	0.5714								0.8571
EncounterRate				0	429	0	857	71	29				0	0	0	0	43
				0	0.000	0	0.001	0.0010	0.0001				0	0	0	0	0.0002
StandardDev_ER				0	176	0	279	58	76				0	0	0	0	65
				0	0.000	0	0.002	0.0024	0.0004				0	0	0	0	0.0005
				0	467	0	236	17	67				0	0	0	0	76

PeakAbundance			0	0.008	0	0.04	0.042	0.008	0	0	0	0	0	0	0.01
1400-1500	1	490.7209	0	1	0	2	0	0	0	0	0	0	0	0	0
EncounterRate			0	0.002	0	0.004	0	0	0	0	0	0	0	0	0
StandardError_ER			0	0.038	0	0.076	0	0	0	0	0	0	0	0	0
PeakAbundance			0	0	0	0	0	0	0	0	0	0	0	0	0
low edge		NA	750	900	700	900	1300	1300	NA	NA	NA	NA	NA	NA	1300
high edge		NA	900	1500	900	1500	1400	1400	NA	NA	NA	NA	NA	NA	1400
mean		NA	825	1200	800	1200	1350	1350	NA	NA	NA	NA	NA	NA	1350
A-W mean		NA	825	1320.	302	1309.	247	1350	1350	NA	NA	NA	NA	NA	1350
White Chuck Mountain															
1400-1500	2	1014.466	0	0	0	0	16	0	0	0	0	0	0	0	0.5
EncounterRate			0	0	0	0	0.0157	0	0	0	0	0	0	0	0.0004
StandardDev_ER			0	0	0	0	0.0223	0	0	0	0	0	0	0	0.0006
PeakAbundance			0	0	0	0	0.064	0	0	0	0	0	0	0	0.002
1500-1600	9	5342.789	0	0	0	0	11.333	0	0	0	0	4	0	0	1.2222
EncounterRate			0	0	0	0	0.0021	0	0	0	0	0.000749	0	0	0.0002
StandardError_ER			0	0	0	0	0.0021	0	0	0	0	0.001314	0	0	0.0006
PeakAbundance			0	0	0	0	0.078	0	0	0	0	0.044	0	0	0.022
1600-1700	1	506.5359	0	0	0	0	3	0	0	0	0	0	0	0	0
EncounterRate			0	0	0	0	0.0059	0	0	0	0	0	0	0	0
StandardError_ER			0	0	0	0	0	0	0	0	0	0	0	0	0
PeakAbundance			0	0	0	0	0.006	0	0	0	0	0	0	0	0
low edge		NA	NA	NA	1600	NA	1400	NA	NA	NA	NA	1500	NA	NA	1400
high edge		NA	NA	NA	1700	NA	1700	NA	NA	NA	NA	1600	NA	NA	1600
mean		NA	NA	NA	1650	NA	1550	NA	NA	NA	NA	1550	NA	NA	1500
A-W mean		NA	NA	NA	1650	NA	1460.8	11	NA	NA	NA	1550	NA	NA	1491.6
South Cascade Lake															
1600-1700	2	1009.161	0	0	0	5	110	19	0	0	0	0	0	0	2

PeakAbundance				0	0.002	0.034	0	0	0	0	0	0	0	0	0	0
	1300-1400	3	1228.015				0	0	0.6666							
				0	0	0	2	0	67	0	0	0	0	0	0	0
EncounterRate							0.001	0	0.0005							
				0	0	0	629	0	43	0	0	0	0	0	0	0
StandardError_ER							0.002	0	0.0004							
				0	0	0	155	0	7	0	0	0	0	0	0	0
PeakAbundance				0	0	0	0.01	0	0.002	0	0	0	0	0	0	0
	1400-1500	1	529.2364				0	0	0	0	0	0	0	0	0	0
EncounterRate				0	0	0	0	0	0	0	0	0	0	0	0	0
StandardError_ER				0	0	0	0	0	0	0	0	0	0	0	0	0
PeakAbundance				0	0	0	0	0	0	0	0	0	0	0	0	0
low edge		NA		600	1200	1000	1300	NA	1300	100	NA	NA	NA	700	1500	1400
high edge		NA		800	1300	1300	1400	NA	1500	800	NA	NA	NA	800	1600	1500
mean		NA		700	1250	1150	1350	NA	1400	450	NA	NA	NA	750	1550	1450
A-W mean		NA		750	1250	1150	1350	NA	1400	450	NA	NA	NA	750	1550	1450
Mt. St. Helens																
	1900-2050	6	2851.885					3.8333	1.8333							
				0	0	0	0	33	33	0	0	0	0	0	0	0
EncounterRate								0.0013	0.0006							
				0	0	0	0	44	43	0	0	0	0	0	0	0
StandardError_ER								0.0006	0.0006							
				0	0	0	0	04	04	0	0	0	0	0	0	0
PeakAbundance				0	0	0	0	0.014	0.008	0	0	0	0	0	0	0
low edge				0	NA	NA	NA	NA	1900	1900	NA	NA	NA	NA	NA	600
high edge				250	NA	NA	NA	NA	2100	2100	NA	NA	NA	NA	NA	1500
mean				125	NA	NA	NA	NA	2000	2000	NA	NA	NA	NA	NA	1050
A-W mean				125	NA	NA	NA	NA	2000	2000	NA	NA	NA	NA	NA	1500