

University of Nevada, Reno

**Nutrient Cycling Processes Along the Sierran Front
to the Cascades**

A thesis submitted in partial fulfillment of the
requirements for the degree of Master of Science in
Natural Resources and Environmental Science

by

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ABSTRACT

Previous research has identified a corresponding relationship between O horizon accumulation and high concentrations of N and P in overland/litter interflow leachate. This nutrient rich leachate can discharge directly into surrounding tributaries in the form of surface runoff or infiltrate into the soil matrix via preferential flow paths. The presence of seasonal preferential infiltration in forested Sierran soils is now well documented, but less known is whether or not the preferential infiltration of nutrient laden percolate results in the development of isolated nutrient “hot spots” in the underlying mineral soil. The purpose of this investigation was to assess the spatio-temporal dynamics of nutrient cycling in sub-alpine forest soils along the Sierran front northward to the Cascades. Large quantities of nutrients were found to reside in the O horizon, leaching at mostly unknown locations into the soil matrix; varying with total water flux and retention time. Nutrient rich “hot spots” were also found under natural conditions, but rarely occurred at the same sampling point for two consecutive years, fluctuating seasonally and annually. Only four of the 256 resin capsule grid points (1.5%), one of 96 first fall precipitation capsule grid points (0.01%) and one of the 128 resin lysimeter grid points (0.78%) exhibited similar trends over both years. Nutrient infiltration variability and sporadic distribution of “hot spots” may facilitate excessive nutrient loading into hydrologic systems and the opportunistic advancement of invasive plant species to out-compete natives. The proper understanding of nutrient cycling dynamics in forested ecosystems is essential for sustaining historical landscape attributes.

Key Words: nutrient cycling, sub-alpine forests, hydrologic, water quality

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GENERAL INTRODUCTION

The transport of nutrients from terrestrial to aquatic systems can contribute to the deterioration of water quality. Nutrient rich overland/litter interflow from the O horizon has been identified as a possible source (Loupe et al., 2007; Miller et al., 2005).

However, the spatio-temporal pattern of infiltration into aquatic and soil matrices is not fully understood. Research by Loupe et al. (2007) has established the presence of high concentrations of biologically available N and P within O horizon materials, and since rooting is mostly absent in O horizons (Johnson et al., 1997) nutrient rich overland/litter interflow leachate will presumably infiltrate into the underlying soil matrix creating biogeochemical “hot spots” or move across the soil surface infiltrating at variable down-gradient locations (Bundt et al., 2001; Burcar et al., 1994; Johnson et al., 2010; McClain et al., 2003; Miller et al., 2005). These “hot spots” can impact the surrounding environment by streaming excess nutrients into the surrounding hydrologic systems (Johnson et al., 2010 and 2011) and/or possibly create opportunities for invasive plant species to out compete native plant species for vital nutrients; however research on the latter is limited.

Recent research has recently documented the presence nutrient rich “hot spots” within the soil matrix in forested ecosystems of the Sierra Nevada (Johnson et al., 2010 and 2011). The overlying organic matter (O horizon) in these forested regions is believed to be an important nutrient contributor and the main driver creating these nutrient rich “hot spots” (Aerts et al., 1997; Gosz et al., 1976; Johnson et al., 2009; Loupe et al., 2007, Miller et al., 2005). However, findings by Johnson et al., (2011) suggest that

biogeochemical “hot spots” are not always a direct product of the overlying O horizon. The degree of compaction, hydrophobic zones, and intricate micro-site dynamics create a network of alternative flow paths. Nutrient transport mechanisms can be extremely diverse (Blume et al., 2009; Bundt et al., 2001; Loupe et al., 2007; Johnson et al., 2009; Miller et al., 2005). Assessing the spatio-temporal characteristics and acquiring a better understanding of nutrient dynamics is vital when determining the impact to a surrounding ecosystem. Investigating the diversity of how overland/litter interflow preferentially travels and creates “hot spots” is thus of importance. Researching the mechanics of nutrient cycling in alpine and sub-alpine forested systems can enhance our knowledge of nutrient transport processes and assist the development of appropriate adaptive management strategies. The purpose of this research was to characterize the natural nutrient transport mechanisms within Sierran and (to a limited extent) Cascade soils through investigating nutrient leachate from the O horizon under natural field and controlled laboratory settings.

Chapter 1 describes findings from a grid sampling scheme assessing the presence, spatial distribution, and nutrient content of “hot spots” at each geographic field location using resin capsules and lysimeters, organic litter and soil samples. Chapter 2 describes results from O horizon (O_i , O_e , and O_{e+i}), extraction to assess leachate nutrient concentration relative to residence time of the extracting solution and from a greenhouse rainfall leaching experiment performed on intact 0.37m^2 O horizon monoliths taken from the field to characterize points of preferential flow-through in the organic matrix.

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CHAPTER ONE:**Nutrient “Hot spots” in Forest Soils Along the****Sierran Front to the Cascades¹**

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ABSTRACT

Biogeochemical “hot spots” are of interest due to the potential influence on nutrient transport from terrestrial to aquatic systems. Previous research has identified “hot spots”, however the spatial scale and frequency of occurrence is uncertain. This study considered the seasonal and annual spatio-temporal distribution of nutrient “hot spots” along the Sierran front northward to the Cascades. Our objectives were to assess the presence or absence, chemical composition and geographic frequency distribution of “hot spots” in alpine forest ecosystems. Nutrient “hot spots” were found to exist under natural conditions. Elevated nutrient concentrations extracted with KCl, including ortho-P, Ca^{2+} , Mg^{2+} , $\text{NO}_3\text{-N}$ and $\text{NH}_4\text{-N}$ were identified at least once per sampling grid per year. However, these “hot spots” rarely occurred at the same sampling point for two consecutive years; only four of the 256 resin capsule grid points (1.5%), one of 96 first fall precipitation capsule grid points (0.01%) and one of the 128 resin lysimeter grid points (0.78%) exhibited similar trends over both years. Moderate and extreme outlier detection in the OM and directly underlying soil matrix was only depicted for four nutrients in the 126 sample cores, none of which were detected in the same sample core. The infiltration variability and sporadic distribution of “hot spots” may facilitate excessive nutrient loading into hydrologic systems and the opportunistic advancement of invasive plant species to out-compete natives. Understanding of the role of nutrient “hot spots” in forested ecosystems is essential for proper management strategies.

Key Words: nutrient cycling, sub-alpine forests, hydrology, water quality

INTRODUCTION

The potential transport of nutrients (mostly nitrogen (N) and phosphorus (P)) from terrestrial to aquatic systems is of concern to sub-alpine ecosystems because excess nutrients can alter biological functions and contribute to the deterioration of water quality (Schester et al., 2004). Excess N and P can reside within nutrient “hot spots” and may be a result of nutrient laden overland flow infiltrating into the underlying or surrounding soil matrix (Bundt et al., 2001; Burcar et al., 1994; Johnson et al., 2010; McClain et al., 2003; Miller et al., 2005). McClain et al., (2003) defined biogeochemical “hot spots” as areas showing high reaction rates (biological activity) relative to the surrounding matrix, where microbial and rooting activity is enhanced due to better nutrient supply.

Johnson et al., (1997) reported that plant roots are typically absent in the O horizon throughout the Sierras, and suggested that the buildup of O horizon mass due to fire exclusion combined with the lack of rooting systems and corresponding plant uptake may partly explain the presence of nutrient laden overland flow (Johnson et al., 2009) and development of “hot spots”. Supporting research has well documented that the large accumulation of organic matter (O horizon) in these forested regions is an important contributor of excess N and P loading in the overland/litter interflow (Aerts et al., 1997; Gosz et al., 1976; Johnson et al., 2009; Loupe et al., 2007, Miller et al., 2005). Johnson et al., (2009) further reported snowdrifts and forest canopy structure to cause nutrient cycling in these forested ecosystems to vary spatially, and later (Johnson et al., 2011) identified the periodic presence of nutrient rich “hot spots” within the soil matrix; albeit the spatio-temporal scale was uncertain. Their findings suggest that O horizon nutrient

rich interflow waters may not always leach from the point of origin, and in fact, may travel horizontally as well as vertically within the O horizon for some distance, possibly accumulating additional nutrients (mostly N and P) before leaching from the organic matrix at various points. Previous research from Miller et al., (2005) are in support of these findings in suggesting the movement of biologically available N and P from the O horizon along preferential flow paths within the O horizon and the underlying soil matrix. Collectively, these research results indicate that the microbial breakdown of organic residue can potentially create high fluxes of N and P into the soil matrix at undefined locations, potentially creating nutrient “hot spots”.

The forest floor (O horizon) thus appears to be an important source of soluble nutrients in overland/litter interflow (Aerts et al., 1997; Gosz et al., 1976; Johnson et al., 2009; Loupe et al., 2007, Miller et al., 2005). Although nutrient transport and conversion processes in the eastern Sierras are now much better documented (Blume et al., 2009; Bundt et al., 2001; Loupe et al., 2007; Johnson et al., 2009; Miller et al., 2005), forested ecosystems are dynamic and the drivers and controls of nutrient cycling processes are extremely diverse. Abiotic and biotic factors collectively contribute to the various nutrient pools (Coats et al., 1976; Miller et al., 2005). However, the precise dynamics such as decomposition rates, forest floor leachate, preferential infiltration, overland flow, and tributary discharge are less explicit. Deciphering the spatio-temporal distribution and the combination of drivers that contribute to the development of nutrient “hot spots” can enhance the understanding of micro-scale ecosystem dynamics and aid in the future development of proper land management strategies.

This investigation seeks to better characterize natural nutrient transport processes within alpine and sub-alpine forested watersheds. Identifying the presence or absence of nutrient “hot spots” and their spatio-temporal diversity is important when focusing on nutrient delivery via specific hydrologic flow paths (e.g., preferential infiltration and recharge or overland flow).

Our hypotheses were:

H₁) Preferential infiltration of nutrient rich overland/litter interflow will create biogeochemical “hot spots” within the soil matrix.

Corollary 1 - Both H₂O and KCl extractable, N and P “hot spots” will occur more frequently in the soil matrix when compared to that of other nutrients.

H₂) Nutrient rich water flow through the O horizon may not always preferentially infiltrate into the soil matrix directly below.

Understanding how “hot spots” develop can help to facilitate the spatio-temporal characterization of nutrient transport processes across the Sierran front and similar alpine forested ecosystems elsewhere.

METHODS AND MATERIALS

Study Site Locations

The study consisted of five field site locations: Castle Lake, CA, to the north at the foot of the Cascade mountains; Truckee, CA, Sagehen, CA, and Little Valley, NV, along the central Sierra Nevada; and King’s River, CA, the southern-most Sierra Nevada

location. The Sagehen, Little Valley and King's River sites also each contained two elevational ecotones (change in elevation and corresponding plant life) for a total of eight study site settings.

The Castle Lake (CL) site (elevation 1687 m; slope 5-50%) is located in northern California at the base of the Cascades (41°13'39"N, 122°23'01"W) in the Shasta-Trinity National Forest, Siskiyou County. The soils are mapped as a complex and include the Manny series, a loamy-skeletal, mixed, superactive, frigid, Humic Dystrochrept and the Endlich series, a loamy-skeletal, isotic, Typic Dystrocryept (Soil Survey, 2011). Overstory vegetation consists of red fir (*Abies magnifica* [A. Murray bis]), white fir (*Abies Concolor* [Grod. and Glend.]), ponderosa pine (*Pinus ponderosa* [Laws.]) and hazel alder (*Alnus serrulata* [(Ait.) Willd.]). Understory vegetation consists mostly of green leaf manzanita (*Arctostaphylos patula* [Greene]) and dwarf mountain manzanita (*Arctostaphylos neuadensis* [A. Gray]). Mean annual air temperature is 3.0 °C and mean annual precipitation 1400 mm, respectively with most precipitation occurring as snow in the winter months (Soil Survey, 2011).

The Truckee (TR) site (elevation 1767 m; slope 2-30%) is located approximately 10 km north of the town of Truckee, CA (39°05'32"N, 119°19'47"W), in the Tahoe National Forest, central Sierra Nevada. Soils developed from andesite, and are mapped as a complex which includes the Euer series, a loamy-skeletal, mixed, superactive, frigid Ultic Haploxeralf; the Martis series, a fine-loamy, mixed, superactive, frigid, Ultic Haploxeralf; the Kyburz series, a fine-loamy, mixed, active, frigid Ultic Haploxeralf; and the Trojan series, a fine-loamy, isotic, frigid, Ultic Agrikeroll (Soil Survey, 2011).

Overstory vegetation is a mixed conifer stand consisting of jeffrey (*Pinus Jeffreyii* [Grev. and Balf.]) and ponderosa pine with minor amounts white fir. Understory vegetation consists of great basin sagebrush (*Artemisia tridentate* [Nutt.]), mule's ear (*Wyethia amplexicaulis* [Nutt.]), and a various mixture of grasses. Mean annual air temperature is 5 °C, and mean annual precipitation is 940 mm, with most occurring as snow fall in the winter months (Soil Survey, 2011).

The Sagehen Upland (SU) site (elevation 1930 m; slope 3-30%) is approximately 16 km north of the town of Truckee, CA (39°26'26" N, 120°13'30" W) within the Sagehen Creek Experimental Watershed, Tahoe National Forest, along central Sierra Nevada. Soils developed from andesite and are mapped as a complex including the Fugawee series, a fine-loamy, isotic, frigid, andic Haploxeralf; and the Tahoma series, a fine-loamy, isotic, frigid Ultic Haploxeralf (Soil Survey, 2011). Overstory vegetation consists of jeffrey pine, and white fir. Understory vegetation consists of greenleaf manzanita, bitterbrush (*Purshia tridentate* [(Pursh) DC.]) and big basin sagebrush. The Sagehen Lowland (SL) site (elevation 1910 m) is down-slope and slightly west of SU (39°26'23" N, 120°13'30" W). Overstory species are the same as previously listed, however understory also consists of squaw carpet (*Ceanothus prostrates* [Benth.]) and mule's ear. Mean annual air temperature is 4.3 °C, and mean annual precipitation approximately 850 mm, respectively within the region (WRCC, 2011). When referring to both sites simultaneously the acronym SH will be used.

The Little Valley Jeffrey Pine (LVJP) field site (elevation 2016 m; slope 15-30%) is located approximately 32 km south-west of Reno, NV in the University of Nevada, Reno, Whittel Forest, Washoe County, eastern Sierra Nevada (39°14'44"N,

119°52'22"W). Soils developed from granite and are mapped as a complex including the Toiyabe series, a mixed, frigid, shallow Typic Xeropsamment; and the Corbett series, a mixed, frigid, Typic Xeropsamment (Soil Survey, 2011). Overstory vegetation is dominated by jeffrey pine and understory vegetation consists of greenleaf manzanita. The Little Valley Aspen (LVA) site (elevation 1981 m) is located approximately 3 km northwest of the LVJP site (39°15'37"N, 119°52'37"W) in the Whittel Forest. Soils developed from granite and dominated by the Marla series, a sandy, mixed, frigid Aquic Dystroxerept (Soil Survey, 2011). Overstory and understory are the same as previously listed, but also contain deciduous Aspen (*Populus tremuloides* [Michx.]). Mean annual air temperatures is 5.5 °C, and mean annual precipitation 890 mm, respectively within the region (Soil Survey, 2011). When referring to both sites simultaneously the acronym LV will be used.

The Kings River Experimental Watershed (KREW) Tower Site (KR1) (elevation 1981 m; slope 5-35%) is located approximately 80 km east of Fresno, CA (37°03'33"N 119°10'56"W) in the Sierra National Forest, southern Sierra Nevada. The granitic-derived soils are mapped as a complex including the Gerle series, a coarse-loamy, mixed, superactive, frigid Humic Dystroxerept; the Gagwin series, a mixed, frigid dystric seropsamment; and the Shaver series, a coarse-loamy, mixed, superactive, mesic Humic Dystroxerept (Soil Survey, 2011). Overstory vegetation is ponderosa pine, sugar pine (*Pinus lambertiana* [Dougl.]), white fir, and incense cedar (*Calocedrus decurrens* [(Torr.) Florin]) (Kings River Watershed, 2011; Soil Survey, 2011). Understory vegetation consists of mixed shrub species and grasses (Kings River Watershed 2011). The Kings River Experimental Watershed P301 site (KR2) (elevation 1910 m) is also located east of

Fresno, CA in the southern Sierra Nevada (37°03'47"N 119°12'04"W). Like the previous site, soils are dominated by the Gerle, Cagwin, and Shaver series (Soil Survey, 2011). Over and understory plant species are those previously identified, but occur at a greater density than for KR1. Mean annual air temperature is 9.5 °C, and mean annual precipitation is 1010 mm, respectively within the region (Soil Survey, 2011). When referring to both sites simultaneously the acronym KR will be used. General study site locations are depicted in Figure 1.

Experimental Design

Two 9 m² grids (one for resin capsule placement and one for resin lysimeter placement) each containing 16 sampling points (Figure 2) were established at each study site and setting. The same sampling grid was used for two consecutive years with exception of at the KR sites, where the first year two 16 m² grids (i.e. a capsule grid and a lysimeter grid) and the second year a 28 m² capsule grid and 16 m² lysimeter grid were installed. Although the area of the sampling grids at the KR sites varied for capsules from year to year, similar to the other study sites only 16 grid points were tested for this study. The UNIBEST PST-1 resin capsule grid consisted of four capsules per grid point each evenly placed within a smaller 100 cm² sub-grid to avoid overlap (excluding the KR site which were placed in a 400 cm² sub-grid) for a total of sixty-four capsules, and the second grid contained resin lysimeters with one lysimeter per grid point for a total of sixteen lysimeters. Capsules were installed at the mineral soil - O horizon interface. Lysimeters were installed beneath the O horizon, buried ~8 cm into the mineral soil, leaving the top exposed at the interface to intercept surface runoff. The study was conducted over two consecutive years (Summer 2009 through Spring 2011). Resin

capsules were installed during the summer of 2009; thirty-two capsules (2 per point) were removed after the first fall precipitation event on Oct. 15, 2009 at the TR, SL, and SU sites for a total of 32 grid point samples at each site. All other resin samplers were removed the following spring 2010. This protocol was repeated the second year summer 2010, with new samplers reinstalled into the same field/grid positions. The second year first fall precipitation event capsule removal occurred on Oct. 11, 2010, with final resin sampler removal in spring 2011.

All capsules removed were transported to the laboratory and washed with de-ionized water (DI) to remove any debris. The cleaned capsules were placed in a 125 ml flask with 20 ml of 2 M KCL, shaken for 20 minutes and then decanted. This process was repeated 3 times per capsule for a total extract collection of 60 ml. Resin lysimeters were removed in spring 2010 and 2011 and also washed with DI water to remove any debris. Resin beads were removed from the resin lysimeters, placed in a 125 ml flask with 100 ml of 1 M KCL solution, shaken for 60 minutes then decanted. A Spectro Arcos ICP (Inductively Coupled Plasma Spectrophotometer) was used to analyze for Ca^{2+} and Mg^{2+} and a Lachat QuickChem (8500 series-2 Flow Injection Analyzer) was used to analyze for ortho-P, $\text{NO}_3\text{-N}$, and $\text{NH}_4\text{-N}$ at Oklahoma State University Soil, Water and Forage Laboratory (SWAFL).

After all resin capsules and lysimeters were removed in spring of 2011, nine soil cores consisting of intact O horizon and underlying mineral soil were taken from the area between grid points (Figure 2) using an AMS soil core sampler (2 cm diameter by 6 cm depth). The O horizon and mineral soil depths were measured over the combined 6 cm depth, then separated, placed into individual zip-lock bags and transported back to the lab

for moisture content determination. O horizon samples were weighed then dried at 45°C for two days. Mineral soil samples were weighed then oven dried at 55°C for two days. Separate five grams of independently homogenized O horizon and mineral soil subsamples were extracted with 40 ml of DI using a Programmable Vacuum Extractor (SampleTek™). The extract was analyzed for Ca^{2+} , Mg^{2+} , K^+ , Na^+ , Cl^- , SO_4^{2-} , NO_3^- , NH_4^+ , and ortho-P using a Dionex ICS-3000 ion Chromatograph at UNRSL.

Statistical Analysis

DataDesk Version 6.0 software (Velleman, 1997) was used for the identification of moderate and extreme outliers; normalized datasets, box plots and bubble graphs were used to illustrate the presence/absence and distribution of nutrient “hot spots”. Box plot data was normalized (i.e. actual data was divided by largest value) then tested for moderate and extreme outliers (Velleman, 1997). Box plots illustrate the range from low (25th percentile) to high (75th percentile) with data points based relative to the median value. Extension bars, circles and asterisk extending off the box plots represent highest value, moderate and extreme outliers, respectively (Velleman, 1997). Bubble graphs were used to illustrate the specific grid location of moderate and extreme outlier values within the overall field plot. The size of the bubbles varies, where the larger the bubble the greater the nutrient concentration; however all nutrient data depicted in the bubble graphs represent numeric outliers ($\mu\text{mol}/\text{cm}^2$). Skewness was calculated to determine data distribution and the degree of outliers (i.e. moderate or extreme outliers). Skewness, (Joanes et al., 1998; Velleman, 1997) positive moderate and extreme outliers (Velleman, 1997) are determined from (adapted from Johnson et al., 2011):

Skewness (G_1):

$$G_1 = [(\sqrt{n} (n-1))/n-2]*(m_3/m_2^{3/2})$$

$$m_3 = \Sigma (v-a)^2/n \text{ (third moment of the data set)}$$

$$m_2 = \Sigma (v-a)^3/n \text{ (variance)}$$

n = sample size

v = actual measured value

a = average

Moderate Outlier:

$$x > Q3 + 1.5I$$

Extreme Outlier:

$$x > Q3 + 3I$$

x = the input value

Q3 = the 3rd quartile value (75th percentile)

I = inter-quartile range (25th to 75th percentile)

Within the following discussion the terms “correspond or co-location” will be used to describe any point or points within the grids where moderate and extreme outliers coincided, possibly indicating accumulating nutrient rich “hot spots”.

RESULTS

Nutrient Input

First Year Resin Capsule Data

Moderate and/or extreme positive outliers which suggest “hot spots”, were detected for all measured nutrients (ortho-P, NO₃-N, NH₄-N, Ca²⁺ and Mg²⁺) across all study sites. Typical data are illustrated in Figures 3, 5, and 7. At the CL site (Figure 3) ortho-P, NO₃-N, NH₄-N, and Ca²⁺ corresponded at a single grid point, whereas ortho-P, NO₃-N, NH₄-N, Ca²⁺ and Mg²⁺ all corresponded at a neighboring grid point. Ammonium and ortho-P also were co-located at a single grid point at CL. At the TR site outliers were detected, but at only one grid point where ortho-P, NO₃-N, NH₄-N, and Mg²⁺ were co-located. Ortho-P and NH₄-N, NO₃-N and Mg²⁺, and Ca²⁺ and Mg²⁺ were co-located at three different grid points for the SL site (Figure 5), but only a single Ca²⁺ and Mg²⁺ correspondence was detected at the SU site. Only independent nutrient outliers were detected at the LVA site whereas at the LVJP site (Figure 7) Ca²⁺ and Mg²⁺ were co-located at two different grid points. At King’s River, NO₃-N and NH₄-N outliers were detected at the KR1 site, but at the KR2 site NO₃-N and Mg²⁺ corresponded at a single grid point. Skewness values are presented in Table 1.

Second Year Resin Capsule Data

Moderate and/or extreme positive outliers were detected for all measured nutrients (ortho-P, NO₃-N, NH₄-N, Ca²⁺ and Mg²⁺). Typical data are illustrated in Figures 4, 6, and 8. The CL site (Figure 4) showed an ortho-P, NO₃-N, and NH₄-N nutrient spike that coincided at a single grid point. At the TR site corresponding high nutrient

concentrations were detected at two grid points: the first was $\text{NO}_3\text{-N}$, $\text{NH}_4\text{-N}$, Ca^{2+} and Mg^{2+} , and the second included all nutrients. At the SL site (Figure 6) ortho-P, $\text{NO}_3\text{-N}$ and $\text{NH}_4\text{-N}$ corresponded at a single grid point and $\text{NO}_3\text{-N}$ and $\text{NH}_4\text{-N}$ at a different grid point. Corresponding high nutrient concentrations were detected at the SU site at two grid points: the first was ortho-P, $\text{NO}_3\text{-N}$ and Mg^{2+} , and the second was $\text{NO}_3\text{-N}$, $\text{NH}_4\text{-N}$, Ca^{2+} and Mg^{2+} . A co-location of ortho-P and $\text{NO}_3\text{-N}$ was detected at the LVA site at four different grid points and at one of these points Ca^{2+} also coincided and at another grid point an ortho-P and $\text{NH}_4\text{-N}$ co-location was detected. Elevated concentrations of all nutrients corresponded to a single grid point at the LVJP site (Figure 8), while a $\text{NO}_3\text{-N}$ and $\text{NH}_4\text{-N}$ correspondence was detected at a different grid point. At the KR1 site a single $\text{NH}_4\text{-N}$ spike was detected and at the KR2 site a correspondence of ortho-P, $\text{NO}_3\text{-N}$, Ca^{2+} and Mg^{2+} was detected, while a co-location of Ca^{2+} and Mg^{2+} was found at a different grid point. Skewness values are presented in Table 2.

First and Second Year Resin Capsule Data Comparison

Nutrient rich “hot spots” were found to differ annually and rarely occurred at the same grid position over two consecutive years of data collection. Overall, 256 grid points per year were sampled using resin capsules and of these corresponding high nutrient concentrations were detected at only 4 of the 256 grid points for two consecutive years of study. Resin capsule measurements indicated that high nutrient concentrations occurred in the same grid position only about 1.5% of the time; an $\text{NH}_4\text{-N}$ outlier at the SL site, an $\text{NO}_3\text{-N}$ outlier at the LVJP site, respectively, and two $\text{NO}_3\text{-N}$ outliers were detected at the

CL site as occurring at the same grid positions for the two consecutive years (Figures 3-8).

First and Second Year First Fall Rainfall Resin Capsule Data

Multiple moderate and extreme outliers were identified each year at the TR, SL and SU sites, but very few nutrient spikes (1 of 96 total grid points) coincided at the same grid point for two consecutive years; only 1 of 32 grid points at TR detected a co-located Ca^{2+} and Mg^{2+} spike which although still present the second year, had decreased in intensity (Figure 9). No corresponding nutrient hot spots were detected at the SH sites (0 of 64). Skewness values are presented in Table 3.

First Year Resin Lysimeter Data

Moderate and/or extreme positive outliers were detected for all measured nutrients ($\text{NO}_3\text{-N}$, $\text{NH}_4\text{-N}$, Ca^{2+} and Mg^{2+}). Typical data are illustrated in Figure 10. At the CL site Ca^{2+} , Mg^{2+} , $\text{NO}_3\text{-N}$ and $\text{NH}_4\text{-N}$ were co-located at two grid points. While at the TR site a single $\text{NO}_3\text{-N}$ spike was detected and at the SL site a single Mg^{2+} spike was detected. Nutrients corresponded at two different grid locations at the SU site (Figure 10); $\text{NH}_4\text{-N}$ and Mg^{2+} , and $\text{NO}_3\text{-N}$ and Mg^{2+} , respectively. Various independent nutrient spikes were also detected. For the LVA site a independent $\text{NH}_4\text{-N}$ spike was detected and at the LVJP site a co-location of Mg^{2+} and $\text{NO}_3\text{-N}$ were found at a single grid point along with other independent spikes of each. At the KR1 site Ca^{2+} , Mg^{2+} and $\text{NH}_4\text{-N}$ corresponded at a single grid point, while Ca^{2+} , Mg^{2+} and $\text{NO}_3\text{-N}$ corresponded at another. The KR2 demonstrated a single $\text{NO}_3\text{-N}$ and $\text{NH}_4\text{-N}$ correspondence along with a single independent $\text{NH}_4\text{-N}$ spike. Skewness values are presented in Table 4.

Second Year Resin Lysimeter Data

Moderate and/or extreme positive outliers were identified for all measured nutrients ($\text{NO}_3\text{-N}$, $\text{NH}_4\text{-N}$, Ca^{2+} and Mg^{2+}). Typical data are illustrated in Figure 11. At the CL site $\text{NO}_3\text{-N}$ and $\text{NH}_4\text{-N}$ were co-located at a single grid point, whereas $\text{NH}_4\text{-N}$ and Ca^{2+} were co-located at another. For the TR site Ca^{2+} , Mg^{2+} , and $\text{NH}_4\text{-N}$ corresponded at a single grid point. At the SL site independent $\text{NH}_4\text{-N}$ spikes were detected and at the SU site (Figure 11) a correspondence of $\text{NO}_3\text{-N}$ and $\text{NH}_4\text{-N}$ was detected at a single grid point. The LVA site showed independent $\text{NO}_3\text{-N}$ and $\text{NH}_4\text{-N}$ nutrient spikes and at the LVJP an independent $\text{NO}_3\text{-N}$ spike. At the KR1 site only independent $\text{NO}_3\text{-N}$ and $\text{NH}_4\text{-N}$ spikes were detected and at the KR2 site a $\text{NO}_3\text{-N}$ and $\text{NH}_4\text{-N}$ co-location was detected. Across all sites Ca^{2+} and Mg^{2+} typically exhibited the highest detectable values. Skewness values are presented in Table 5.

First and Second Year Resin Lysimeter Comparison

Of the grid points at all the sites, corresponding outlier nutrient concentrations were detected at only 1 of 128 grid points (0.78%) for two consecutive years; a single $\text{NO}_3\text{-N}$ spike was detected at the SU site for the two consecutive years (Figure 10 and 11). Overall, nutrient fluxes were highly variable across all sites. Samples from the KR2 site were highest in $\text{NO}_3\text{-N}$ and $\text{NH}_4\text{-N}$ for two consecutive years, and the KR1 site had the highest Ca^{2+} and Mg^{2+} over the two consecutive years. The CL site had the second highest $\text{NO}_3\text{-N}$ and Mg^{2+} fluxes.

Water Extractions of OM and Underlying Mineral Soil

It was hypothesized that areas of preferential water flow containing high nutrient

concentrations traveling through the O horizon may not coincide with areas of preferential infiltration into the soil matrix. This was supported by our findings. Moderate and extreme outliers rarely corresponded between the O horizon and the underlying soil matrix cores. Of all the nutrient analyses performed over all the core samples across sites (126 total core samples) corresponding moderate and extreme nutrient outliers in both the OM and underlying soil matrix were seldom found (4 of 126 core samples); corresponding independent K^+ and Mg^{2+} spikes were detected at the CL site, a corresponding NO_3^- spike was detected at the LVA site, and a corresponding NH_4^+ spike was detected at the SU site (Figures 12-14). Skewness values are presented in Tables 6 and 7.

DISCUSSION

Hypothesis 1 - Preferential infiltration of nutrient rich overland/litter interflow will create biogeochemical “hot spots” within the soil matrix - was partially supported. Multiple independent nutrient spikes were detected along with sporadic nutrient co-locations across sites. Results thus indicate that points of high nutrient fluxes and accumulation exist within the soil matrix. Whether or not these “hot spots” are a direct result of preferential infiltration remains unclear. At the temporal scale results were inconsistent over the two year study period. Comprehensive or a complete nutrient correspondence at a single point for the two consecutive years was never detected at any location. These results indicate that spatio-temporal pattern of nutrient rich “hot spots” fluctuates at an unknown interval and that the where and when it might occur is largely unpredictable at this time. Johnson et al. (2011) also was able to identify the presence of “hot spots” within the soil matrix, but was unable to pin-point where and when

infiltration would occur. Corollary 1 - Both H₂O and KCl extractable, N and P “hot spots” will occur more frequently within the soil matrix compared to that of other detectable nutrients - was not supported. Points of high nutrient accumulations within the soil matrix were extremely variable; while N and P spikes were detected independently and jointly, rarely did these spikes occur more frequently than any of the other nutrients studied. Nitrogen and P have been under extensive study and are of particular interest due to the impacts in these sub-alpine ecosystems (Schester et al., 2004). Since excess amounts of biologically available N and P have been found to stem from the O horizon (Loupe et al., 2007 and Miller et al., 2005), findings should indicate that N and P “hot spots” occur more frequently, but results were inconclusive.

Hypothesis 2- Nutrient rich water flow through the O horizon may not always preferentially infiltrate into the soil matrix directly below - was supported. Water extractable nutrients were extremely variable and in very few instances were moderate and extreme outlier nutrient spikes detected as corresponding between the O horizon and the directly underlying soil matrix. Johnson's et al., (2011) research also suggested that nutrient rich leachate may not always infiltrate into the soil matrix from the O horizon directly above; lateral movement of leachate may occur creating leaching at various unknown points. These results were also consistent among the various extraction methods (i.e. H₂O vs. KCl). While the resin samples represented seasonal trends and the OM and soil core extracts were merely a snapshot, data from both illustrated the high variability of moderate and extreme outliers. These results could be explained in part by environmental factors; e.g., no two years received the same amount of precipitation or experienced the same type of annual climate variation. Although the region may remain

generally similar overall, yearly dynamics and the landscape mosaic can be extremely diverse. As precipitation infiltrates into and through the organic matrix the rate and direction of flow appear highly dependent on amount of water entering, the residual moisture content, and the micro-site dynamics such as water repellency and/or presence of persistent preferential flow paths.

CONCLUSIONS

The phenomena of nutrient “hot spots” suggest that nutrient mobility fluctuates seasonally. Since nutrient fluxes into the soil matrix are variable and rooting is mostly absent in the O horizon (Johnson et al., 1997), plant species may have to adapt for survival. The possibility exists that a majority of these “hot spots” have a potential to infiltrate directly from the terrestrial to aquatic matrices impacting hydrologic systems, or remain available for opportunistic annual species. Multiple factors contribute to nutrient cycling in these forested systems; the intricate dynamics of temperature, initial moisture content of surrounding matrix, amount of nutrients present, type of contributing parent materials supplying nutrients, ionic exchange capacity, bulk density, soil texture, uptake by microbial communities and plant species, climate and aeration all play a role in nutrient fluxes and forest nutrient cycling processes (Brady et al., 2010). Further research is needed that expands our knowledge base into the spatio-temporal infiltration patterns of nutrients. Accessing the frequency, distribution and relative occurrence of nutrient “hot spots” can aid in the development of better management strategies and help preserve these sub-alpine and alpine systems.

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Table 1- First year resin capsule skewness values for Castle Lake (CL), Truckee (TR), Sagehen (SL and SU), Little Valley (LVA and LVJP), and Kings River (KR1 and KR2) sites. Bold values indicate a highly skewed distribution (Bulmer, 1979).

Table 2 - Second year resin capsule skewness values for Castle Lake (CL), Truckee (TR), Sagehen (SL and SU), Little Valley (LVA and LVJP), and Kings River (KR1 and KR2) sites. Bold values indicate a highly skewed distribution (Bulmer, 1979).

Table 3 - First and second year first fall rainfall resin capsule skewness values for the Truckee (TR) and Sagehen (SL and SU) sites. Bold values indicate a highly skewed distribution (Bulmer, 1979).

Table 4 – First year resin lysimeter skewness values for Castle Lake (CL), Truckee (TR), Sagehen (SL and SU), Little Valley (LVA and LVJP), and Kings River (KR1 and KR2) sites. Bold values indicate a highly skewed distribution (Bulmer, 1979).

Table 5 - Second year resin lysimeter skewness values for Castle Lake (CL), Truckee (TR), Sagehen (SL and SU), Little Valley (LVA and LVJP), and Kings River (KR1 and KR2) sites. Bold values indicate a highly skewed distribution (Bulmer, 1979).

Table 6 - Organic matter (OM) H₂O extraction skewness values for Castle Lake (CL), Truckee (TR), Sagehen (SL and SU), Little Valley (LVA and LVJP), and Kings River (KR1 and KR2) sites. Bold values indicate a highly skewed distribution (Bulmer, 1979).

Table 7- Mineral soil H₂O extraction skewness values for Castle Lake (CL), Truckee (TR), Sagehen (SL and SU), Little Valley (LVA and LVJP), and Kings River (KR1 and KR2) sites. Bold values indicate a highly skewed distribution (Bulmer, 1979).

First Year Resin Capsule Skewness Values					
Site ↓	NO3-N	NH4-N	Ortho-P	Ca ²⁺	Mg ²⁺
CL	3.78	2.52	2.52	1.48	1.40
TR	2.18	4.55	1.82	1.03	0.89
SL	1.70	3.29	1.37	1.33	1.37
SU	1.74	1.29	0.65	0.90	1.55
LVA	2.25	1.50	0.00	1.28	2.98
LVJP	3.71	0.80	0.00	1.18	1.35
KR1	2.42	1.70	0.98	0.51	0.68
KR2	2.23	0.49	0.43	0.15	1.10

Table 1- -First year resin capsule skewness values for Castle Lake (CL), Truckee (TR), Sagehen (SL and SU), Little Valley (LVA and LVJP), and Kings River (KR1 and KR2) sites. Bold values indicate a highly skewed distribution (Bulmer, 1979).

Second Year Resin Capsule Skewness Values					
Site ↓	NO3-N	NH4-N	Ortho-P	Ca ²⁺	Mg ²⁺
CL	3.33	3.67	2.43	1.22	1.44
TR	4.49	1.98	3.20	2.39	2.47
SL	1.83	2.89	1.51	0.87	1.00
SU	2.71	3.68	2.30	1.58	1.68
LVA	2.76	4.57	1.84	1.14	0.89
LVJP	1.66	2.43	2.08	1.77	1.21
KR1	0.26	1.56	1.04	0.00	0.01
KR2	1.88	1.01	1.93	2.42	1.86

Table 2- Second year resin capsule skewness values for Castle Lake (CL), Truckee (TR), Sagehen (SL and SU), Little Valley (LVA and LVJP), and Kings River (KR1 and KR2) sites. Bold values indicate a highly skewed distribution (Bulmer, 1979).

Site ↓	First Fall Rainfall Removal 2009 Skewness Values			First Fall Rainfall Removal 2010 Skewness Values		
	TR	SL	SU	TR	SL	SU
NO3-N	1.02	2.67	2.19	3.61	1.83	2.45
NH4-N	3.80	4.23	1.94	5.38	5.64	3.81
ortho-P	1.51	2.67	1.53	4.21	3.15	2.57
Ca ²⁺	1.87	1.58	1.49	2.84	3.10	2.34
Mg ²⁺	1.45	2.04	1.49	2.85	3.23	2.02

Table 3- First and second year first fall rainfall resin capsule skewness values for the Truckee (TR) and Sagehen (SL and SU) sites. Bold values indicate a highly skewed distribution (Bulmer, 1979).

First Year Resin Lysimeter Skewness Values				
Site ↓	NO3-N	NH4-N	Ca	Mg
CL	2.98	3.63	2.36	3.07
LVA	1.05	2.00	0.81	0.93
LVJP	1.75	0.00	0.48	1.66
SL	-0.03	0.65	0.35	0.84
SU	3.22	3.24	1.38	1.61
TR	1.45	0.06	0.48	0.33
KR1	1.49	1.39	3.42	1.91
KR2	1.42	2.27	0.38	0.47

Table 4 – First year (long-term) resin lysimeter skewness values for Castle Lake (CL), Truckee (TR), Sagehen (SL and SU), Little Valley (LVA and LVJP), and Kings River (KR1 and KR2) sites. Bold values indicate a highly skewed distribution (Bulmer, 1979).

Second Year Resin Lysimeter Skewness Values				
Site ↓	NO3-N	NH4-N	Ca	Mg
CL	1.57	3.67	1.20	0.84
LVA	2.12	2.69	0.55	0.70
LVJP	-3.09	0.00	-0.65	-0.60
SL	0.54	3.94	0.62	0.49
SU	3.22	4.00	0.13	0.34
TR	0.62	3.87	2.36	2.81
KR1	1.23	3.92	0.79	0.77
KR2	2.98	3.72	0.59	0.72

Table 5 - Second year (long-term) resin lysimeter skewness values for Castle Lake (CL), Truckee (TR), Sagehen (SL and SU), Little Valley (LVA and LVJP), and Kings River (KR1 and KR2) sites. Bold values indicate a highly skewed distribution (Bulmer, 1979).

OM H ₂ O Extraction Skewness Values										
Sites	NO ₂ ⁻	NO ₃ ⁻	NH ₄ ⁺	SO ₄ ²⁻	PO ₄ ³⁻	Cl ⁻	Na ⁺	K ⁺	Mg ²⁺	Ca ²⁺
CL	0.75	0.65	0.34	1.30	2.01	1.06	0.89	0.50	1.58	0.94
LVA	4.02	1.61	0.06	0.91	0.99	0.16	0.04	-0.29	1.45	1.31
LVJP	0.00	3.01	2.68	1.37	1.35	3.62	2.87	1.95	2.81	2.63
SL	3.76	3.30	1.87	1.54	-0.06	0.51	1.63	2.81	1.84	1.67
SU	0.00	3.83	2.73	0.66	0.82	1.32	-0.55	-0.95	1.46	0.90
TR	4.45	2.42	1.85	1.35	0.97	-0.07	-0.22	-0.10	0.09	0.37
KR1	3.00	1.55	0.92	1.38	0.53	0.53	-0.91	0.98	1.37	1.69
KR2	3.00	0.33	0.10	-0.01	-0.24	-0.41	-0.22	0.17	0.10	-0.24

Table 6- Organic matter (OM) H₂O extraction skewness values for Castle Lake (CL), Truckee (TR), Sagehen (SL and SU), Little Valley (LVA and LVJP), and Kings River (KR1 and KR2) sites. Bold values indicate a highly skewed distribution (Bulmer, 1979).

Soil H ₂ O Extraction Skewness Values										
	NO ₂ ⁻	NO ₃ ⁻	NH ₄ ⁺	SO ₄ ²⁻	PO ₄ ³⁻	Cl ⁻	Na ⁺	K ⁺	Mg ²⁺	Ca ²⁺
CL	4.22	3.57	0.79	0.55	2.06	2.37	1.03	1.79	0.84	0.60
LVA	0.00	0.27	0.74	0.87	0.78	1.41	-0.01	0.21	0.41	-0.07
LVJP	0.00	-0.53	1.57	0.88	2.10	4.04	3.86	4.35	4.39	3.98
SL	0.00	2.26	2.39	3.01	2.43	0.52	1.21	0.07	1.95	1.46
SU	0.00	2.91	1.95	0.24	2.45	1.91	0.63	-0.31	1.13	-0.69
TR	4.36	2.92	1.24	0.20	0.00	0.92	0.23	-0.17	1.66	1.05
KR1	0.00	2.96	2.79	0.28	1.92	0.11	2.00	-1.01	-0.48	-0.97
KR2	0.00	0.45	2.09	0.63	2.41	0.58	-0.48	-1.46	-0.07	0.40

Table 7- Mineral soil H₂O extraction skewness values for Castle Lake (CL), Truckee (TR), Sagehen (SL and SU), Little Valley (LVA and LVJP), and Kings River (KR1 and KR2) sites. Bold values indicate a highly skewed distribution (Bulmer, 1979).

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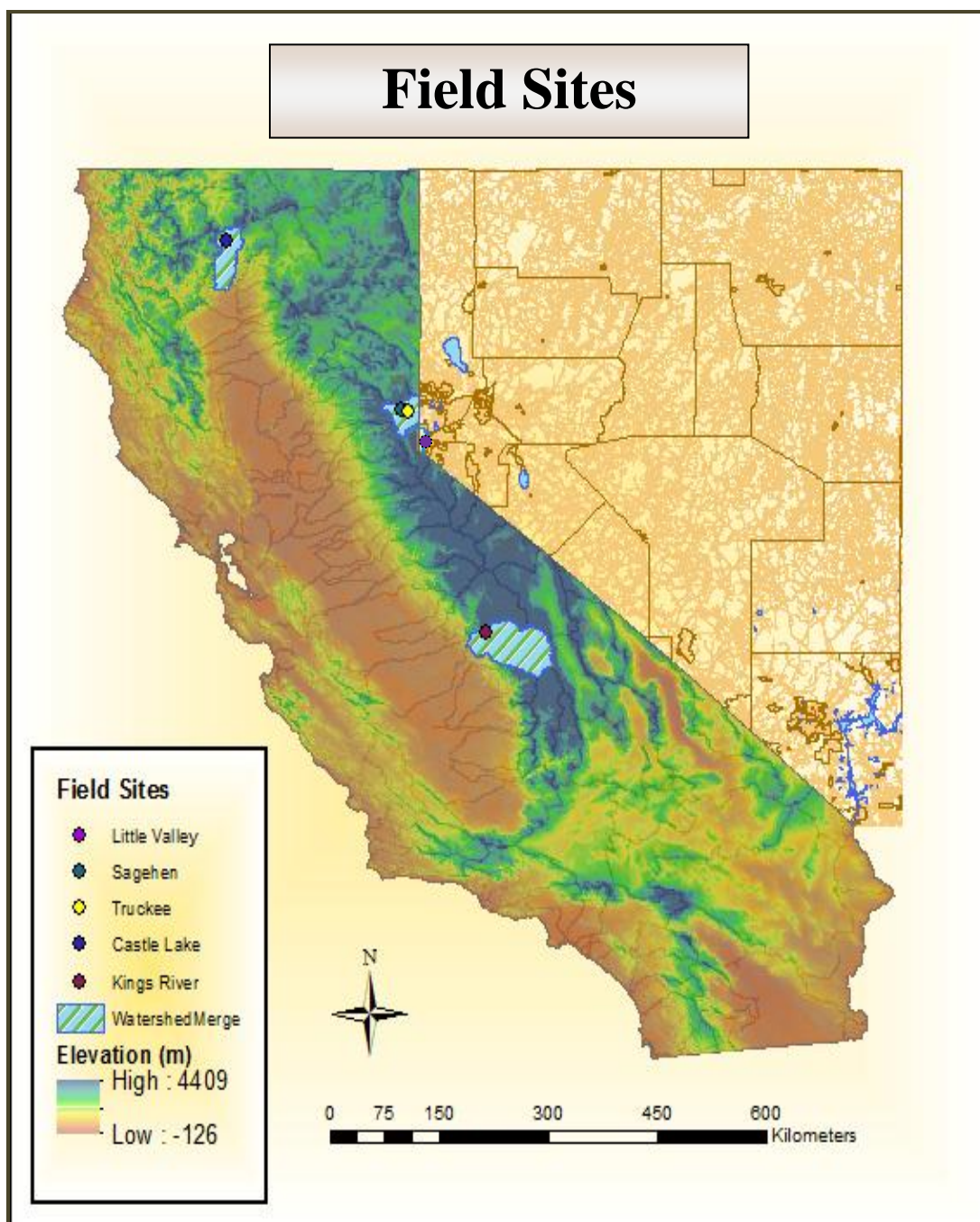


Fig. 1 - Site map depicting relative distance between the five field sites where samplers were installed: Little Valley NV, Sagehen CA, Truckee CA, Castle Lake CA, and Kings River CA.

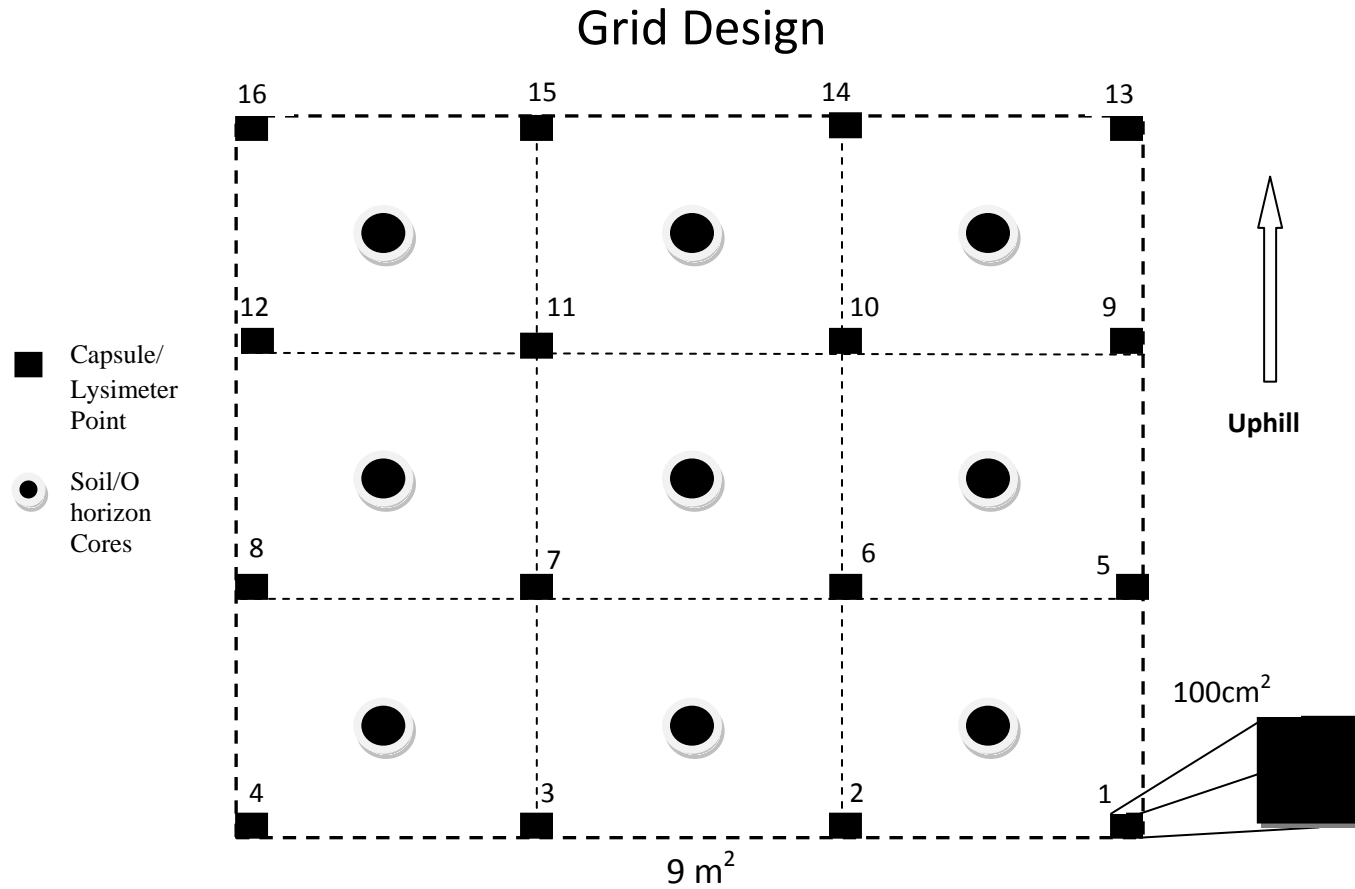


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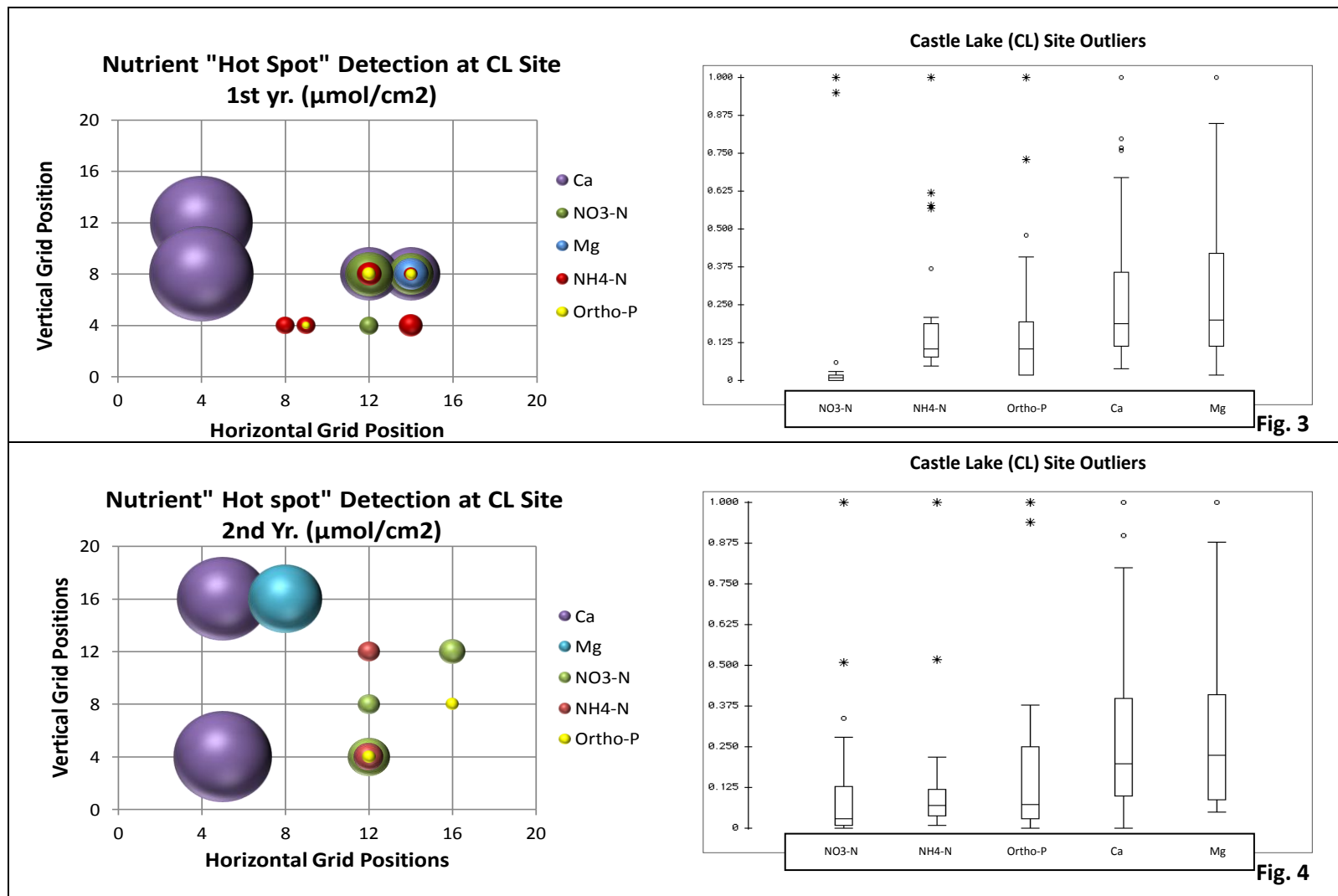


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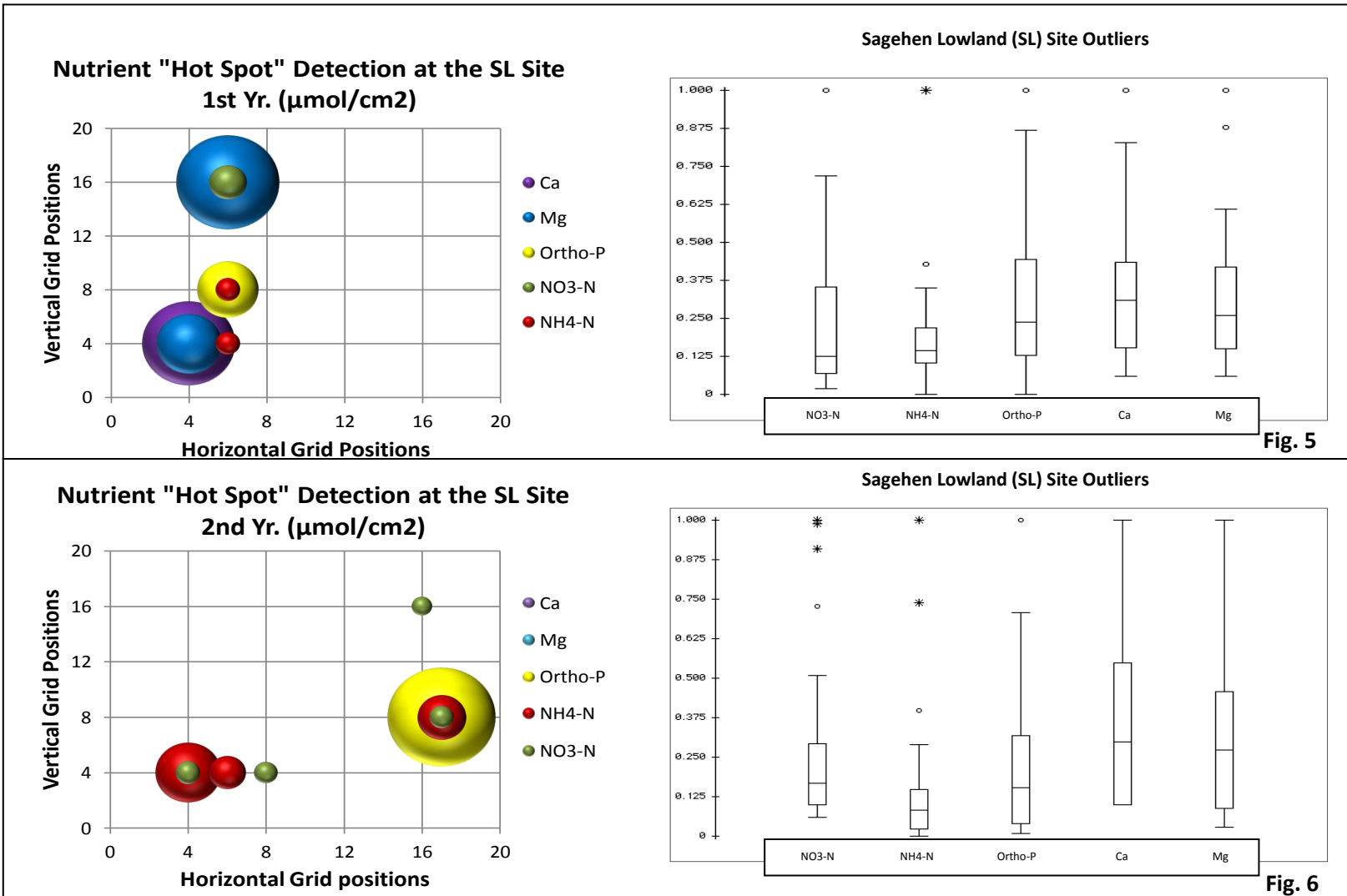


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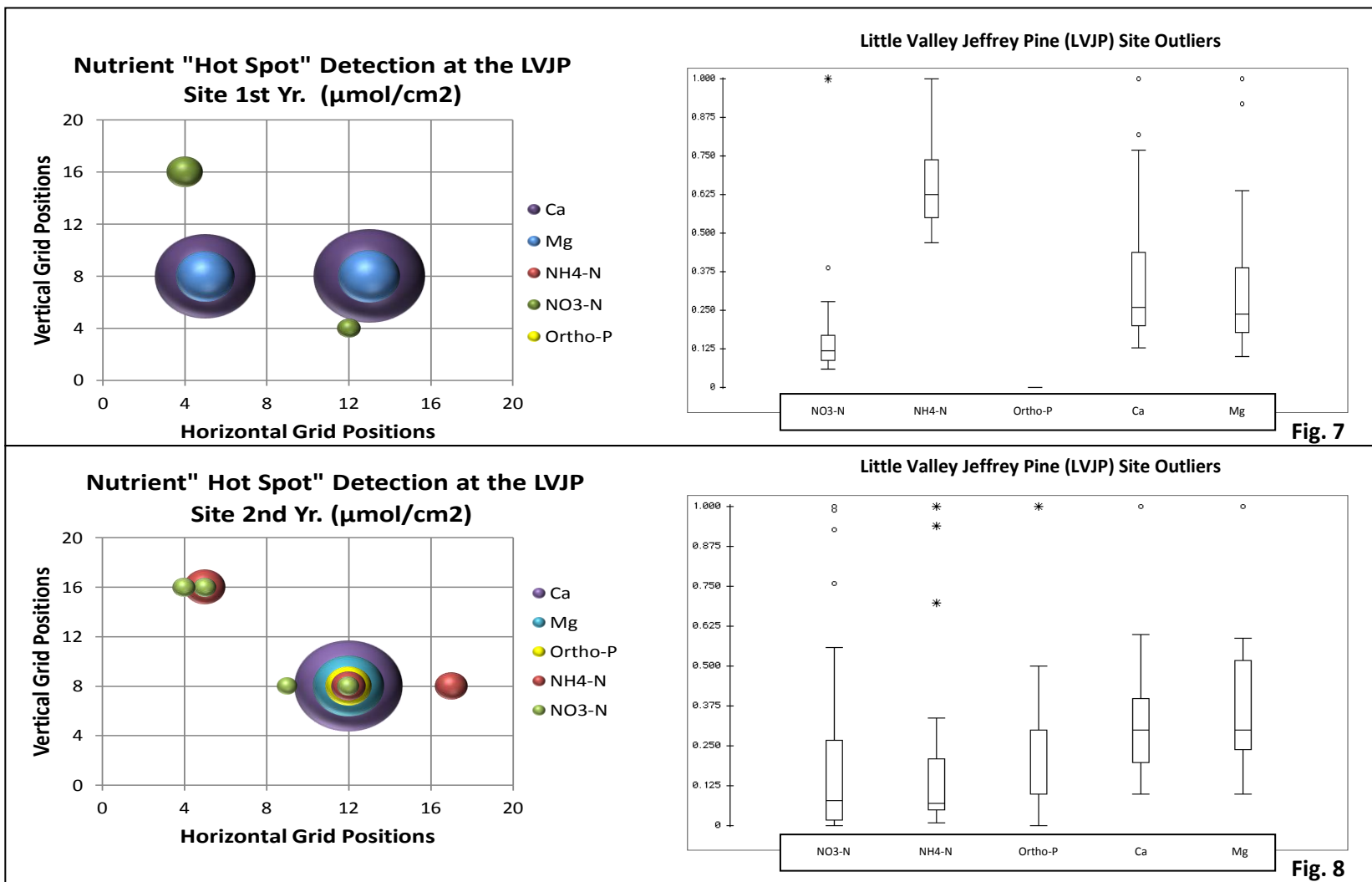


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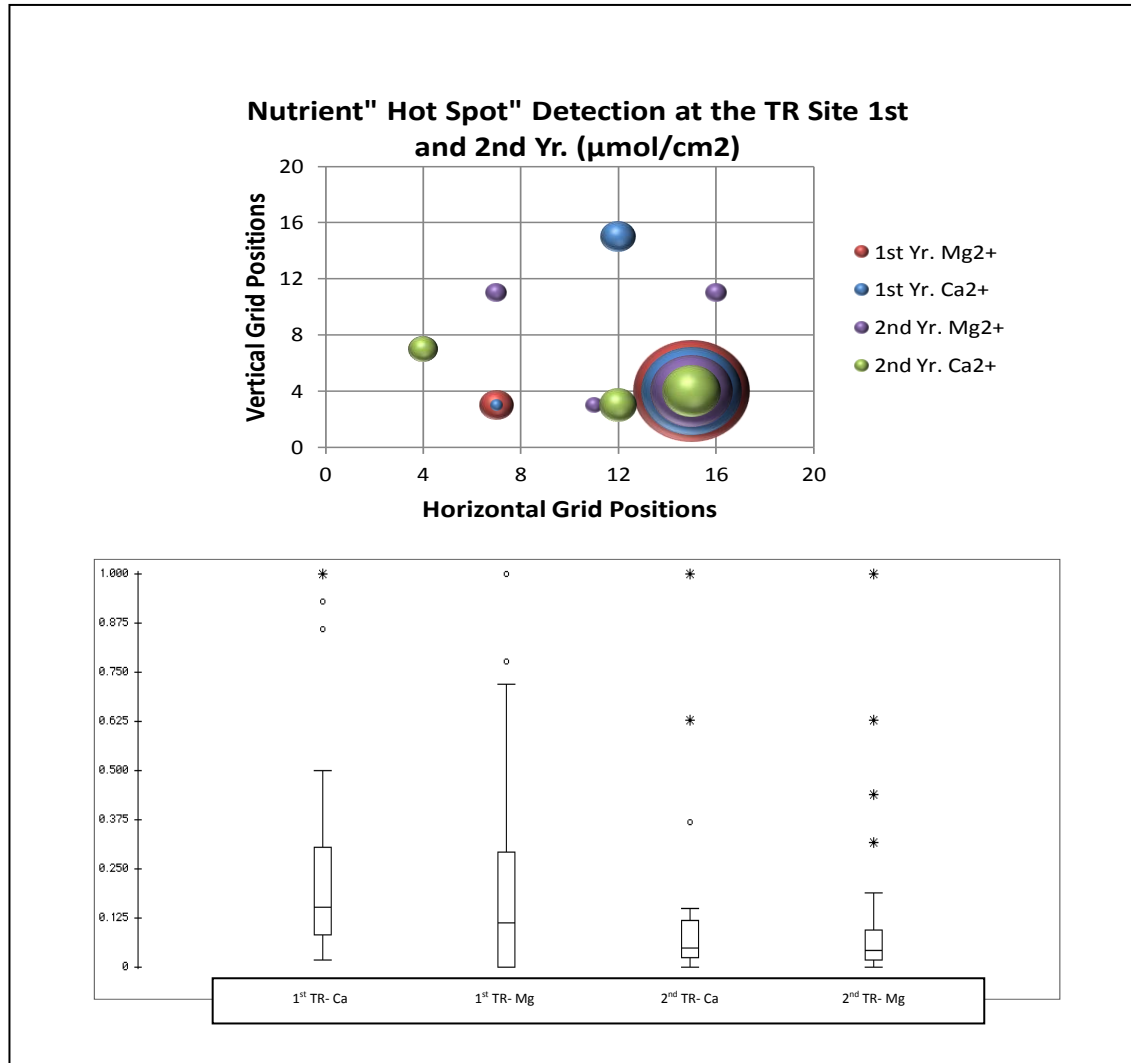


Fig. 9 – First –Second year first fall rainfall resin capsule nutrient “hot spot” detection at the Truckee (TR) site. The box plot determines Ca^{2+} and Mg^{2+} moderate and extreme outliers, while the bubble graph depicts overlapping orientation within capsule grid.

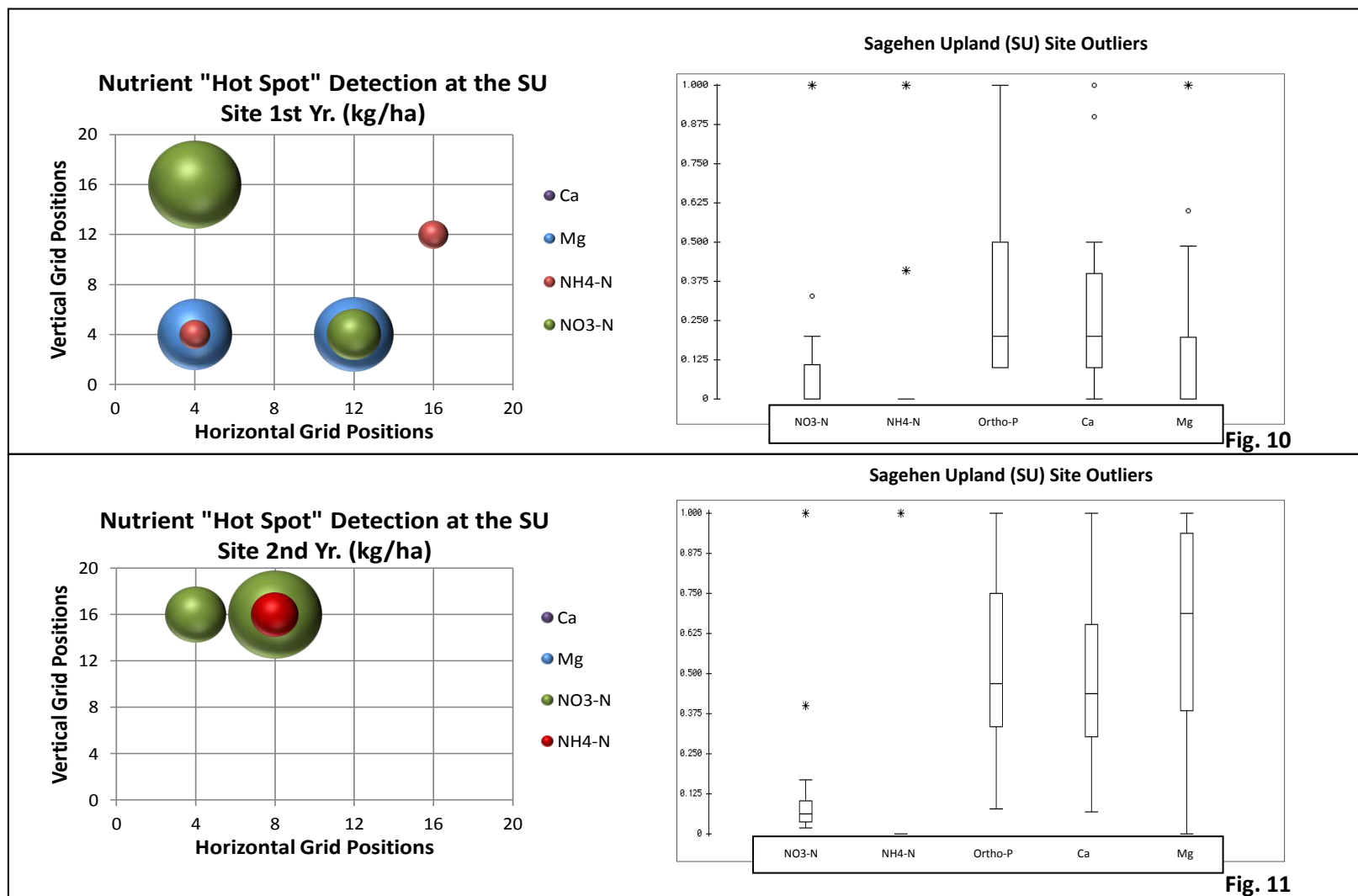


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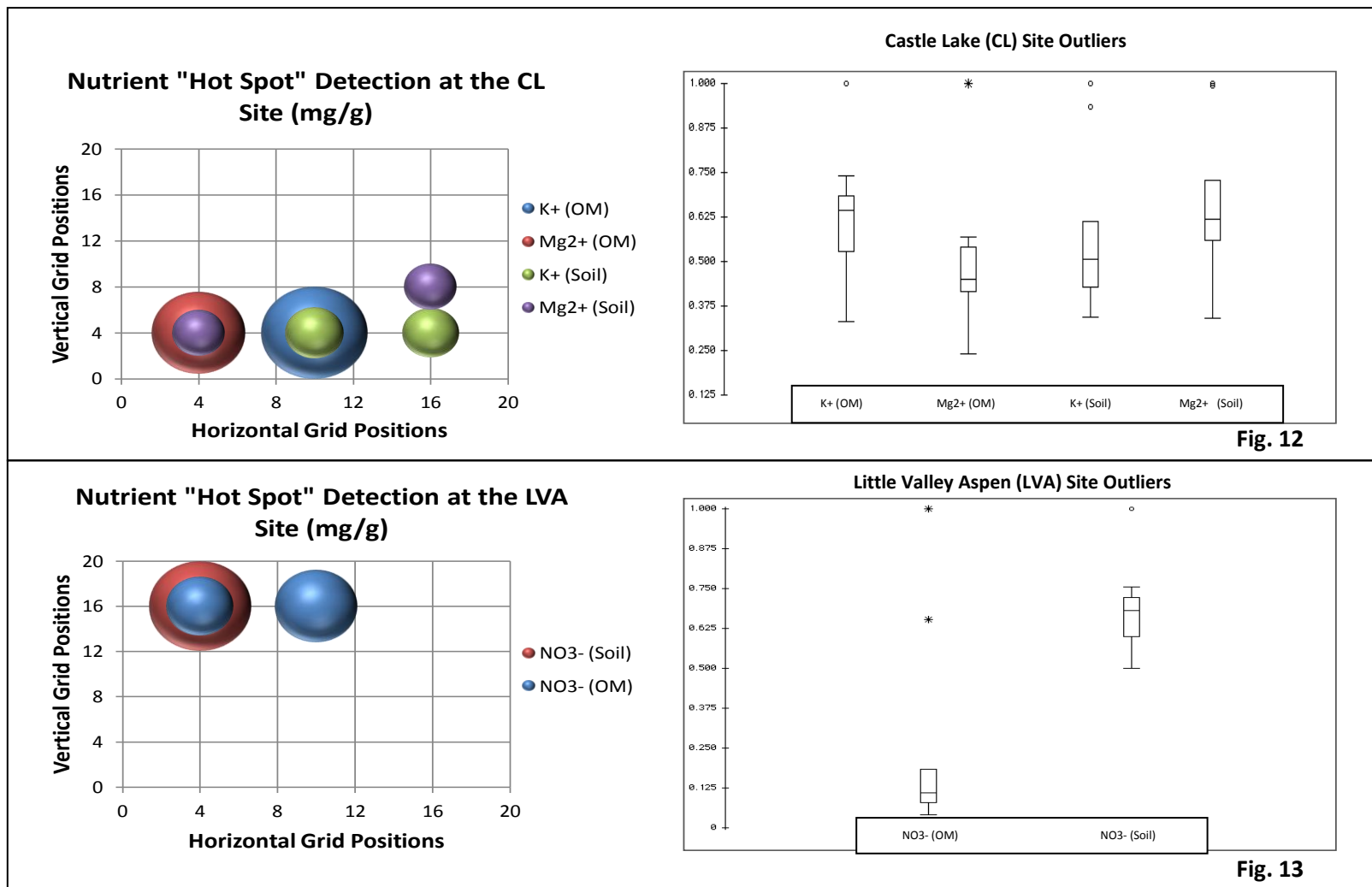


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Fig. 13 – Organic matter (OM) and soil core sample nutrient “hot spot” correlation at the Little Valley Aspen (LVA) site. The box plot determines NO₃-N moderate and extreme outliers, while the bubble graph depicts overlapping orientation within capsule grid.

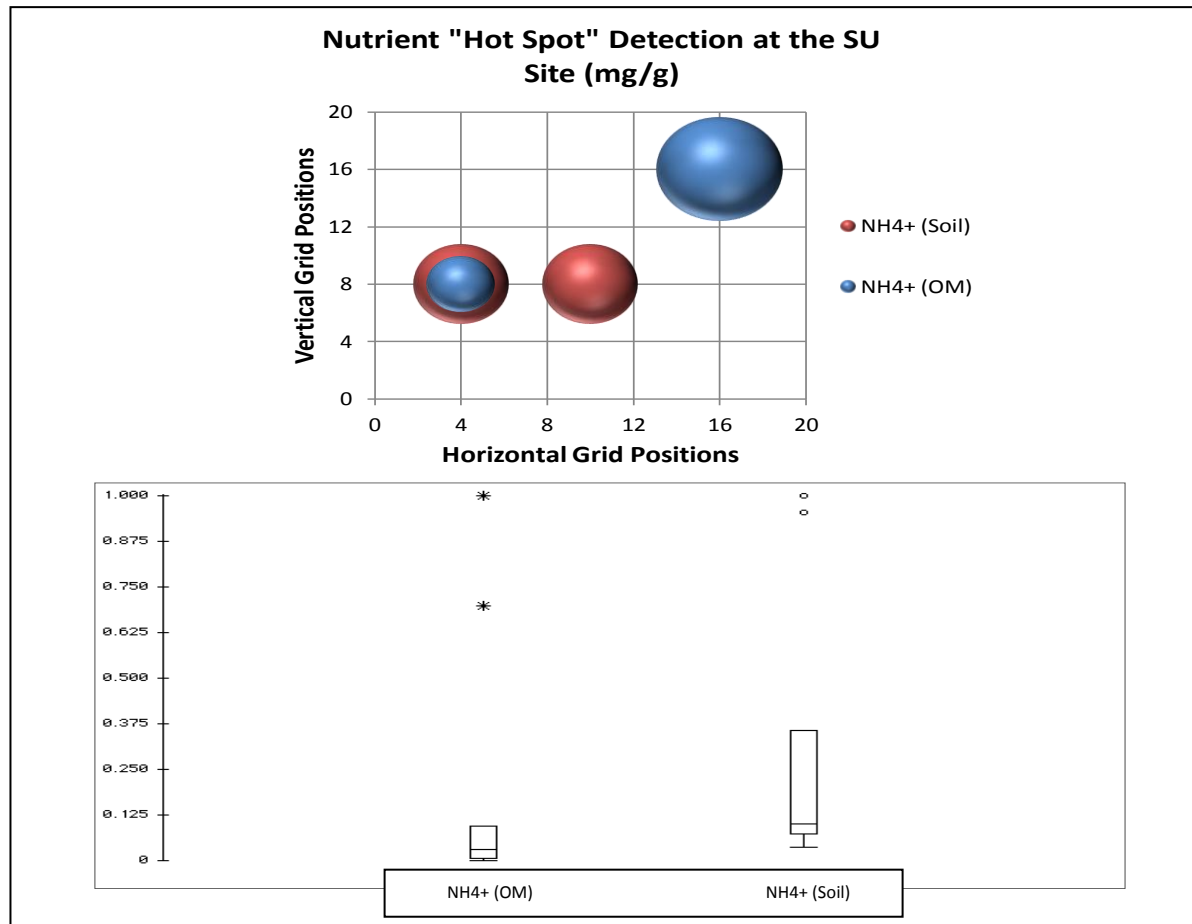


Fig. 14 – Organic matter (OM) and soil core sample nutrient “hot spot” correlation at the Sagehen Upland (SU) site. The box plot determines NH_4^+ moderate and extreme outliers, while the bubble graph depicts overlapping orientation within capsule grid.

CHAPTER TWO:**Effect of Water Flux and Extraction Interval On O Horizon Nutrient Extraction¹**

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¹**A contribution of the Department of Natural Resources & Environmental Science.**

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I would like to personally thank Brooke Eustis and the many undergraduates of the Castle Lake Research Station for all their valuable help sampling throughout the harsh winter months and Erin Carroll-Moore, Casandra Woodward, Rachel Funk, Kevin Meany and my family (Brian, Makenna and Riley) for all their patience, hard work and dedication.

ABSTRACT

O horizon leachate from alpine systems can contribute soluble inorganic nutrients (primarily N and P) to mineral soil and aquatic systems. The residing nutrient pools and leaching processes through the O horizon are therefore important and knowledge of the relationship between laboratory extraction time and residence time on extractable nutrient content is essential. O horizon monoliths (0.37 m^2) were taken from five geographic locations: Castle Lake, CA, Truckee, CA, Sagehen, CA, Little Valley, NV and King's River, CA. One monolith from each site was separated by O horizon layer (O_e , O_i , and O_{e+i}), homogenized, placed into cylinders and extracted with DI water in the laboratory over four time periods (10 min, 30 min, 60 min and 120 min). O horizon nutrient extraction relative to extraction time was assessed. A greenhouse experiment was also performed on intact monoliths to identify points of preferential flow through the organic matrix during artificial rainfall precipitation and the relative leachate nutrient concentration for independent collection intervals of 1-3 min, 3-7 min, and 7-12 min. Laboratory extraction results showed an increasing trend in sulfate, nitrate, chloride and ortho-P extraction from all O horizon materials with increase in extraction time up to 60 min. Over time the O_e , O_i , and O_{e+i} materials each contributed different amounts of SO_4^{2-} , NO_3^- , Cl^- and ortho-P. No interaction was detected between extraction time and O horizon material. Greenhouse experiment results showed leachate from the KR O horizon to be greater in overall SO_4^{2-} , NO_3^- , NH_4^+ , Cl^- and ortho-P concentrations when compared to that from the TR, SH, and LV sites, while an increase in collection interval

resulted in significantly lower leachate SO_4^{2-} , NO_3^- , Cl^- and ortho-P concentrations across all sites. No interaction was detected between site and extraction interval.

Key Words: water quality, nutrient transport, sub-alpine forests, Sierra Nevada

INTRODUCTION

Nutrient cycling in forested systems is extremely diverse and the mechanisms that drive nutrient flux have been altered over the past several decades (Johnson et al., 1997 and 2009). Historically, mature forested ecosystems have functioned as a balanced feedback loop with efficient nutrient inputs/outputs (Johnson et al., 1997 and 2009). Now, the total nutrient pool is greater due to the excess organic matter contributions, which has also increased the pool of biologically available nutrients (Johnson et al., 1997 and 2009; Loupe et al., 2007; Miller et al., 2005). Nutrient pools in the O horizon may supply an excess of micro- and macronutrients to terrestrial and aquatic systems (Bundt et al., 2001; Johnson et al., 2010). While contributing to soil fertility and plant available nutrients (Bundt et al., 2001; Johnson et al., 2010; Schimel and Bennet, 2004); biological activity, decomposition and mineralization rates can be altered (Bundt et al., 2001; Johnson et al., 2010; McClain et al., 2003; Miller et al., 2005; Parkin et al., 1987; Ran et al., 2009; Schimel and Bennet, 2004).

Miller et al., (2005) established that overland/litter interflow contained high amounts of biologically available N and P and Loupe et al., (2007) reported the high concentrations of inorganic N and P leachate to be derived from the accumulating O horizon, but the point of entry into the soil matrix is unknown. Bundt et al., (2001) recognized that zones of preferential infiltration where biologically available nutrients reside are desirable for microbial communities. Schimel and Bennet (2004) reported that fine plant roots ($\leq 2\text{mm}$) can invade areas where large nutrient pools reside and “out-compete” beneficial soil microbes, and Atlas et al., (1998) concluded that many of

today's environmental issues stem from the role microbial communities play.

We now believe that high concentrations of biologically available N and P will be different from the O horizon materials due to microbial decomposition and mineralization, and increase with greater precipitation, eventually leaching into the soil matrix due to the lack of root uptake in the O horizon (Miller et al. 2005) possibly creating nutrient rich zones. However, the spatial distribution of nutrients, exact flow-through pathways and a quantification of OM and soil storage capacities are mildly understood.

To accurately interpret nutrient dynamics in the field, knowledge of the relationship between laboratory extraction time and residence time on extractable nutrient content is essential. Hence, investigating nutrient concentrations within O horizon leachate over various time intervals and determining the spatio-temporal pattern of leaching events should aid in the understanding of nutrient dynamics and the development of an accurate nutrient budget. The purpose of this investigation was to study the effect of extraction/retention time on O horizon leachate nutrient concentrations through variable laboratory extraction and greenhouse leaching experiments. Our hypotheses were:

Lab Extraction Hypotheses

H₁- Nutrient concentrations in O horizon extracts will increase with increasing extraction time.

H₂- Nutrient concentrations in O horizon extracts will differ between O_e, O_i and combined O_{e+i} materials.

Greenhouse Hypothesis

H₁- O horizon leachate nutrient concentrations from intact O horizon monoliths will vary with water flux and retention time.

Corollary 1 – The less contact time between the applied water and O horizon material and less total water flux through O horizon materials will result in lower leachate nutrient concentrations.

Understanding the various degrees of nutrient leachate as related to precipitation events in forested systems across the Sierran front to the Cascades is essential. A need for the potential nutrient contributions from the O horizon in relation to that amount of precipitation can help lead research in the proper direction and aid in the development of an accurate nutrient budget which is currently lacking in these sub-alpine forested ecosystems.

MATERIALS AND METHODS

Study Site Locations

Three intact 0.37 m² O horizon monoliths were collected at each of five field locations (King's River, CA, Little Valley, NV, Sagehen, CA, Truckee, CA, and Castle Lake, CA) in late summer 2009 and 2010 (Fig.1).

The Kings River (KR) Experimental Watershed site (elevation 1981m; 5-35%) is

located approximately 80 km east of Fresno, CA. (37°03'33"N 119°10'56"W) in the Sierra National Forest, western Sierra Nevada. The granitic-derived soils are mapped as a complex including the Gerle series, a coarse-loamy, mixed, superactive, frigid Humic Dystrocherept; the Gagwin series, a mixed, frigid dystric Xeropsamment; and the Shaver series, a coarse-loamy, mixed, superactive, mesic Humic Dystrocherept (Soil Survey, 2011). Overstory vegetation is ponderosa pine (*Pinus ponderosa* [Laws.]), sugar pine (*Pinus lambertiana* [Dougl.]), white fir (*Abies Concolor* [Grod. and Glend.]), and incense cedar (*Calocedrus decurrens* [(Torr.) Florin]) (Kings River Watershed, 2011; Soil Survey, 2011). Understory vegetation consists of mixed shrub species and grasses (Kings River Watershed 2011). Mean annual temperature is 9.5 °C, and mean annual precipitation is 1010 mm, respectively (Soil Survey, 2011).

The Little Valley (LV) site (elevation 2030m; slope 15-30%) is located approximately 32 km south-west of Reno, NV in the Whittel National Forest, Washoe County, eastern Sierra Nevada (39°14'44"N, 119°52'22"W). Soils developed from granite and are mapped as a complex including the Toiyabe series, a mixed, frigid, shallow Typic Xeropsamment; and the Corbett series, a mixed, frigid, Typic Xeropsamment (Soil Survey, 2011). Overstory vegetation is dominated by jeffrey pine (*Pinus Jeffreyii* [Grev. and Balf.]) and understory vegetation consists of greenleaf manzanita (*Arctostaphylos patula* [Greene]). Mean annual temperature is 5.5 °C, and mean annual precipitation is 890 mm, respectively (Soil Survey, 2011).

The Sagehen (SH) site (elevation 1810m; 3-30%) is approximately 16 km north of the town of Truckee, CA. (39°26'26" N, 120°13'30" W), in the University of California Berkeley Sagehen Creek Experimental Watershed, Tahoe National Forest, central Sierra

Nevada. Soils developed from andesite and are mapped as a complex including the Fugawee series, a fine-loamy, isotic, frigid, andic Haploxeralf; and the Tahoma series, a fine-loamy, isotic, frigid Ultic Haploxeralf (Soil Survey, 2011). Overstory vegetation consists of jeffrey pine, and white fir. Understory vegetation consists of greenleaf manzanita, bitterbrush (*Purshia tridentate* [(Pursh) DC.]) and great basin sagebrush (*Artemesia tridentate* [Nutt.]). Mean annual temperature is 4.3 °C, and mean annual precipitation is approximately 850 mm, respectively (WRCC, 2011).

The Truckee (TR) site (elevation 1767 m; slope 2-30%) is located approximately 10 km north of the town of Truckee (39°05'32"N, 119°19'47"W) CA, in the Tahoe National Forest, central Sierra Nevada. Soils developed from andesite, and are mapped as a complex which includes the Euer series, a loamy-skeletal, mixed, superactive, frigid Ultic Haploxeralf; the Martis series, a fine-loamy, mixed, superactive, frigid, Ultic Haploxeralf; the Kyburz series, a fine-loamy, mixed, active, frigid Ultic Haploxeralf; and the Trojan series, a fine-loamy, isotic, frigid, Ultic Agrikeroll (Soil Survey, 2011). Overstory vegetation is a mixed conifer stand consisting of jeffrey pine, ponderosa pine with minor amounts white fir. Understory vegetation consists of great basin sagebrush, mule's ear (*Wyethia amplexicaulis* [Nutt.]), and a various mixture of grasses (Soil Survey, 2011). Mean annual temperature is 5 °C, and mean annual precipitation is 940 mm, respectively with most occurring as snow fall in the winter months (Soil Survey, 2011).

The Castle Lake (CL) site (elevation 1687 m; slope 5-50%) is located in northern California at the base of the Cascades (41°13'39"N, 122°23'01"W) in the Shasta-Trinity National Forest, Siskiyou County. The soils are mapped as a complex and include the

Manny series, a loamy-skeletal, mixed, superactive, frigid, Humic Dystroxerept and the Endlich series, a loamy-skeletal, isotic, Typic Dystrocryept (Soil Survey, 2011). Overstory vegetation consists of red fir (*Abies magnifica* [A. Murray bis]), white fir, ponderosa pine and hazel alder (*Alnus serrulata* [(Ait.) Willd.]). Understory vegetation consists of greenleaf manzanita and dwarf mountain manzanita (*Arctostaphylos neuadensis* [A. Gray]). Mean annual temperature is 3.0 °C and mean annual precipitation is 1400 mm, respectively, with most precipitation occurring as snow in the winter months (Soil Survey, 2011).

Experimental Design

Monoliths consisted of intact O_e (partially decomposed OM, but still recognizable) and O_i (fresh fallen litter, recognizable) horizons; the O_a (highly decomposed litter, non-recognizable) was negligible in most cases and therefore not sampled. A 0.37 m² piece of plywood was placed on top of the undisturbed O horizon matt in the field and the underlying organic layers cut-out around the template using a hand trowel. The plywood was then removed from the surface and slid underneath the O horizon layers along the organic/mineral soil interface creating an “intact” O horizon monolith. The monolith was then removed from the field, lightly encased in a plastic tarp and taken back to lab for analysis.

One monolith collected in summer 2010 from each geographic location was separated into three O horizon layer treatments (O_e, O_i, and O_{e+i}) and independently homogenized. Three replicate 5.75g samples of O_e, O_i, and O_{e+i} material were extracted with 20 mL of DI water over various time intervals (10 min, 30 min, 60 min, 120 min)

using a SAMPLETEK™- 24VE Programmable Vacuum Extractor. The litter extract (leachate) was analyzed for SO_4^{2-} , NO_3^- , NH_4^+ , Ca^{2+} , Mg^{2+} , K^+ , Na^+ , Cl^- , and ortho-P using a Dionex ICS-3000 ion Chromatograph at the University of Nevada Reno Soils Laboratory (UNRSL).

Remaining monoliths were left to dry naturally in the greenhouse inside the lightly wrapped tarps to avoid cross-contamination. Air dried monoliths (except those at CL which did not remain intact during transit) were placed onto a clear piece of 0.64 mm thick plexiglass with 0.64 mm diameter holes equally spaced ~3cm apart on a 0.58 m² grid and the sheet sloped to a 2% gradient to avoid pooling of water. Water was applied through a FullJet[®] Spray Nozzle (1.36 L/min. @ 0.07 N/mm²) as artificial rainfall. The application rate was dictated by the type of spray nozzle; we selected a square spray nozzle with the lowest application rate to obtain an even distribution of water over the 0.37 m² monolith area. The application flux was 3.7 mm/min. Following onset of the artificial rainfall, leachate breakthrough was collected during three time intervals (1-3 min, 3-7 min and 7-12 min.), respectively, using 125 ml sample bottles per flow-through event. If no flow-through was apparent within the first sampling interval, we took our sample during the second, and so on. Leachate samples were collected as leachate breakthrough thus occurred within a given sampling interval. For example, rainfall application was initiated at $t = 0$. When leachate breakthrough occurred at $t = 1$ to 3 min a sample for that time interval was taken. When leachate breakthrough occurred at $t = 3-7$ min a sample for that time interval was taken, and so on. Sampling was ended once the 125 ml sample bottle was full, if percolation ceased, or when the sampling interval expired. Once the second or third time interval started, collections were taken only from

new points of leachate breakthrough emerging within that time interval. This allowed comparison of initial breakthrough nutrient concentrations relative to residence time (1-3 min, 3-7 min, or 7-12 min, respectively) of the penetrating solution. Samples were not taken from the same point of flow-through or from the disturbed edges of the monolith. Flow-through leachate was analyzed for SO_4^{2-} , NO_3^- , NH_4^+ , Ca^{2+} , Mg^{2+} , K^+ , Na^+ , Cl^- , and ortho-P using a Dionex ICS-3000 ion Chromatograph at the (UNRSL).

Statistical Analysis

For the laboratory extraction and greenhouse experiments, Single and Two Factors ANOVA was used to assess variation within and between groups. Categorical variables for the laboratory extraction experiment were extraction time and O horizon material and for the greenhouse experiment were site and extraction interval. Scheffe Post - Hoc Tests assessed the variation within each categorical variable. All statistical analysis was run using DataDesk Version 6.0 (Vellmen, 1997).

RESULTS

Laboratory Extraction Experiment

Extraction time and O horizon material (O_i , O_e , and O_{e+i}) resulted in significantly different ($p \leq 0.019$) sulfate, nitrate, chloride and ortho-P nutrient extraction (Table 1). In general, nutrient extraction increased with increasing extraction time up to about 60 min, following which little further increase was observed in most cases. Sulfate extraction was initially low for the 10 and 30 min extraction times, but typically increased for longer extractions (Figure 2). Sulfate extraction from the O_i vs. O_e and the O_i vs. O_{e+i} ($\text{O}_i < \text{O}_e$ and O_{e+i}) was statistically different ($p \leq 0.026$), but not for O_e vs. O_{e+i} (Figure 2). Nitrate

extraction was also lower for the 10 and 30 min extraction times, increased for the 60 min extraction period, with only a slight further increase between the 60 to 120 min extraction times; suggesting that maximum extraction was close to attainment after a 60 min residence time (Figure 3). O_i vs. O_e , O_i vs. O_{e+i} , and O_e vs. O_{e+i} materials were all statistically different ($p \leq 0.038$) in nitrate extract concentration per extraction interval (Figure 3). Chloride extraction also increased with extraction time, but showed little evidence of a plateau characteristic (Figure 4). Chloride extract concentrations from the O_i vs. O_e and the O_i vs. O_{e+i} were statistically different ($p \leq 0.001$) (i.e. $O_i < O_{e+i} \leq O_e$) (Figure 4). Ortho-P extraction similarly increased with extraction time and showed some evidence of a plateau effect between the 60 min and 120 min extraction time (Figure 5). Ortho-P extract concentrations from the O_i vs. O_{e+i} were statistically different ($p \leq 0.023$) (i.e. $O_i < O_{e+i} \leq$ or $\geq O_e$) (Figure 5). Since the independent O_i and O_e extract nutrient concentrations were similar to or less than the combined O_{e+i} material and most nutrient concentrations in the extract appeared to approach a plateau between the 60 and 120 min extraction periods, it is reasonable to consider that a minimum of 60 min extraction of the combined O_{e+i} horizon is sufficient to assess the average nutrient discharge potential. Scheffe post-hoc tests results for the categorical variables extraction time and O horizon material are depicted in Tables 2 and 3.

Greenhouse Experiment

Greenhouse findings showed a significant effect ($p \leq 0.013$) of study site location and collection interval in overall nutrient discharge for SO_4^{2-} , NO_3^- , NH_4^+ , Cl^- and ortho-P; albeit no interaction of the categorical variables was detected (Table 4). There was no

significant difference in measured nutrient discharge between the 1-3 min vs. 3-7 min collection intervals, however the comparative nutrient discharge between 1-3 min vs. 7-12 min and 3-7 min vs. 7-12 min collection intervals was significantly different ($p \leq 0.027$) for most nutrients (Table 5). Leachate nutrient discharge from the KR site was statistically greater ($p \leq 0.005$) than all other sites (i.e. TR, SH, and LV) for most measured nutrients excluding NH_4^+ and Cl^- , while no differences in nutrient discharge were detected between the TR vs. SH, TR vs. LV, or SH vs. LV sites, except Cl^- for the SH vs. LV sites (Table 6). Graphical depictions indicate that most nutrient discharge concentrations decreased with increased collection interval across all sites, with exception of Cl^- at the SH and LV sites (Figures 6-10).

DISCUSSION

Laboratory Extraction Hypothesis 1- Nutrient concentration in the O horizon extract will increase with increasing extraction time was supported ($p \leq 0.019$) for NO_3^- , SO_4^{2-} , Cl^- and ortho-P across all O horizon materials. Hypothesis 2- Nutrient concentration in O horizon extracts will differ between O_e , O_i and combined O_{e+i} material was partially supported. Extract nutrient concentrations between the O_i vs. O_e were significantly greater ($p \leq 0.026$) from the O_e for NO_3^- , SO_4^{2-} , and Cl^- . Extract nutrient concentrations between the O_i vs. O_{e+i} were significantly greater ($p \leq 0.023$) from the O_{e+i} for NO_3^- , SO_4^{2-} , Cl^- and ortho-P, while results between the O_e vs. O_{e+i} were only significantly greater ($p \leq 0.038$) from the O_{e+i} for NO_3^- .

Laboratory extraction biomass materials were dissected with consistency to ensure accuracy and the packing of the extraction cylinders was repetitious. Since the

biomass and extract volume were held constant throughout the experiment, extract nutrient concentrations (mg L^{-1}) are equivalent to extract nutrient amounts (mg kg^{-1}). Results suggest that excess nutrient loading is driven by the higher decomposed materials (i.e. the O_e and O_{e+i} materials). However, it is not understood exactly why the O_i plus the O_e material doesn't always equal that of the combined O_{e+i} material. Loupe et al., 2007 established that N and P amounts were greatest from the O_e and O_{e+i} materials, but didn't disclose if the O_i plus the O_e equaled the O_{e+i} . Possible nutrient extract differences could be attributed to the slight variance in plant material, soil incorporation into O horizon, pH or degree and rate of decomposition relative to the various materials. As leachate travels through the O horizon in the field less surface area would be exposed, limiting cation and anion dissolution and/or exchange processes. As Johnson et al., (1997), Loupe et al., (2007), and Miller et al., (2005) have reported, large amounts of nutrients do reside in the O horizon and contribute to watershed nutrient pools. Since rooting is absent in the O horizon (Johnson et al., 1997), when precipitation events occur nutrients are typically flushed into the interflow leachate (Miller et al., 2005), generally streaming along a preferential flow path. Through the homogenization of the O horizon materials a disturbance was created, possibly exposing more surface area and nutrients.

Greenhouse Hypothesis 1- O horizon leachate nutrient concentrations from intact O horizon monoliths will vary with water flux and retention time was supported. Nitrate, SO_4^{2-} , NH_4^+ , Cl^- and ortho-P varied across sites with water flux and retention time. The KR site generally showed higher NO_3^- , SO_4^{2-} , NH_4^+ , Cl^- and ortho-P concentrations when compared to that of the TR, SH and LV sites. Corollary 1 – The less contact time

between the applied water and O horizon material and less total water flux through the O horizon will result in lower leachate nutrient concentrations was not supported. Data showed nutrient concentrations from the 1-3 min leachate collection interval to be greater for SO_4^{2-} , NO_3^- , Cl^- and ortho-P, with respectively lower measured discharge concentrations as residence time (collection interval) and total water flux through the O horizon increased.

The greenhouse experiment was designed to collect leachate discharge at specified time intervals. However, no two monoliths (replicates or not) discharged leachate with the same spatio-temporal pattern. Once precipitation was initiated, the accumulating moisture soon migrated to a flow-path and infiltrated into the biomass. As the amount applied and duration of the event increased, the percolate often traveled laterally within the biomass until complete flow-through occurred. Multiple points of flow-through percolation appeared as duration of the precipitation event increased. Although each new emergence of discharge leachate was sampled in accordance with the pre-designed sampling interval, the discharge intensity (amount and rate) of the later points were never as great as that from the first point of discharge. As a point of reference for flow-through characteristics, extra (non-experimental) monoliths were treated with ~200 mm of simulated rainfall for one hour in an attempt to achieve biomass saturation. However, once dissected many dry patches remained within the monoliths; supporting the theory of hydrophobic zones diverting leachate into adjacent preferential flow paths (Burcar et al., 1994; Loupe et al., 2007; and Miller et al., 2005).

Loupe et al., (2007) performed a similar experiment but rather than obtain leachate relative to specific points of biomass infiltration and percolate discharge instead sampled leachate from the entire 1.5 m² O horizon over a much longer time period. Results from Loupe et al., (2007) assessed the nutrient leachate loading via respective O horizon materials (O_e, O_i and O_{e+i}) and established that although discharge concentrations of inorganic N were high, discharge inorganic P concentrations were highest from the initial leaching cycle. Our greenhouse results indicate that SO₄²⁻, ortho-P and to a lesser extent NH₄⁺ discharged during early stage flow through.

CONCLUSIONS

Laboratory extraction experiments indicate that the combined O_{e+i} material extracted over a 60 min extraction period is a valid representation of average potential nutrient discharge. Greenhouse leaching experiments indicate that there is an initial discharge of most nutrients during the 1-3 min collection interval that diminishes with extended collection time; albeit these results are somewhat disparate when considering each nutrient independently. These nutrients have a potential to leach directly into the soil matrix creating excess nutrient loading and availability for various plant species or can directly leach into and contaminate hydrologic systems. Multiple factors contribute to nutrient leaching processes; degree of compaction within the O horizon, residing nutrients, temperature, decomposition rates, and initial moisture content (Brady et al., 2010). We have now established that nutrient leachate does follow flow paths within the O horizon. Assessing potential maximum nutrient discharge as suggested through our research can aid in the development of an accurate nutrient budget and a greater

understanding of nutrient cycling in general. However, it is suggested that further research investigating the random spatio-temporal patterns of preferential flow and the retention mechanisms relative to nutrient transport systems be conducted to better understand nutrient loading.

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	Horizon	Time	Horizon*Time
Sulfate	≤ 0.001	≤ 0.001	0.510
Nitrate	≤ 0.001	≤ 0.001	0.592
Ortho-P	0.019	≤ 0.001	0.966
Sodium	0.095	0.381	0.947
Ammonium	0.500	0.360	0.210
Potassium	0.966	0.835	0.997
Magnesium	0.355	0.248	0.862
Calcium	0.799	0.905	0.989
Chloride	≤ 0.001	≤ 0.001	0.950

Table 1- Laboratory extraction *p*-values within and between groups using ANOVA: One Factor and Two Factor Analysis for all measured nutrients. Highlighted areas depict significant *p*-values per categorical variable(s).

Scheffe Post -Hoc Tests				
Horizon	Sulfate	Nitrate	Ortho-P	Chloride
O_i vs. O_e	0.026	≤ 0.001	0.165	≤ 0.001
O_i vs. O_{e+i}	≤ 0.001	≤ 0.001	0.023	≤ 0.001
O_e vs. O_{e+i}	0.132	0.038	0.689	0.677

Table 2- Laboratory extraction *p*-values within group variation, Scheffe post-hoc test for sulfate, nitrate, ortho-P, and chloride. Highlighted areas depict significant *p*-values for O horizon materials.

Scheffe Post -Hoc Tests				
Extraction Time (min.)	Sulfate	Nitrate	Ortho-P	Chloride
10 vs. 30	0.300	0.438	0.026	0.061
10 vs. 60	≤ 0.001	≤ 0.001	≤ 0.001	≤ 0.001
30 vs. 60	≤ 0.001	0.043	0.123	0.184
10 vs. 120	≤ 0.001	0.006	≤ 0.001	≤ 0.001
30 vs. 120	≤ 0.001	0.300	≤ 0.001	≤ 0.001
60 vs. 120	0.889	0.820	0.214	0.078

Table 3- Laboratory extraction *p*-values within group variation, Scheffe post-hoc test for sulfate, nitrate, ortho-P, and Chloride. Highlighted areas depict significant *p*-values for time extractions.

	Site	Extraction Interval	Site *Extraction Interval
Sulfate	≤ 0.001	≤ 0.001	0.867
Nitrate	≤ 0.001	0.023	0.103
Ortho-P	≤ 0.001	≤ 0.001	0.799
Sodium	--	--	--
Ammonium	0.001	0.271	0.496
Potassium	--	--	--
Magnesium	--	--	--
Calcium	--	--	--
Chloride	≤ 0.001	0.013	0.700

Table 4- Greenhouse nutrient discharge *p*-values within and between groups using ANOVA: One Factor and Two Factor Analysis for all measured nutrients. Highlighted areas depict significant *p*-values per categorical variable(s).

Scheffe Post -Hoc Tests				
Extraction Interval	Sulfate	Nitrate	Ortho-P	Chloride
(1-3 min) vs. (3-7 min)	0.251	0.084	0.950	0.825
(1-3 min) vs. (7 -12 min)	≤ 0.001	0.375	≤ 0.001	0.072
(3-7 min) vs. (7 -12 min)	0.070	0.027	0.002	0.017

Table 5- Greenhouse nutrient discharge *p*-values for extraction interval groups Scheffe post-hoc test for sulfate, nitrate, ortho-P, and chloride. Highlighted areas depict significant *p*-values for O horizon materials.

Scheffe Post -Hoc Tests					
Site	Sulfate	Nitrate	Ortho-P	Ammonium	Chloride
TR vs. SH	0.715	0.203	0.730	0.145	0.162
TR vs. LV	0.893	0.228	0.938	0.217	0.635
SH vs. LV	0.963	0.985	0.108	0.968	≤ 0.001
TR vs. KR	0.005	0.018	0.006	1.000	0.373
SH vs. KR	≤ 0.001	≤ 0.001	≤ 0.001	0.007	≤ 0.001
LV vs. KR	≤ 0.001	≤ 0.001	≤ 0.001	≤ 0.001	0.913

Table 6- Greenhouse nutrient discharge *p*-values within site groups Scheffe post-hoc test for sulfate, nitrate, ortho-P, and chloride. Highlighted areas depict significant *p*-values for time extractions.

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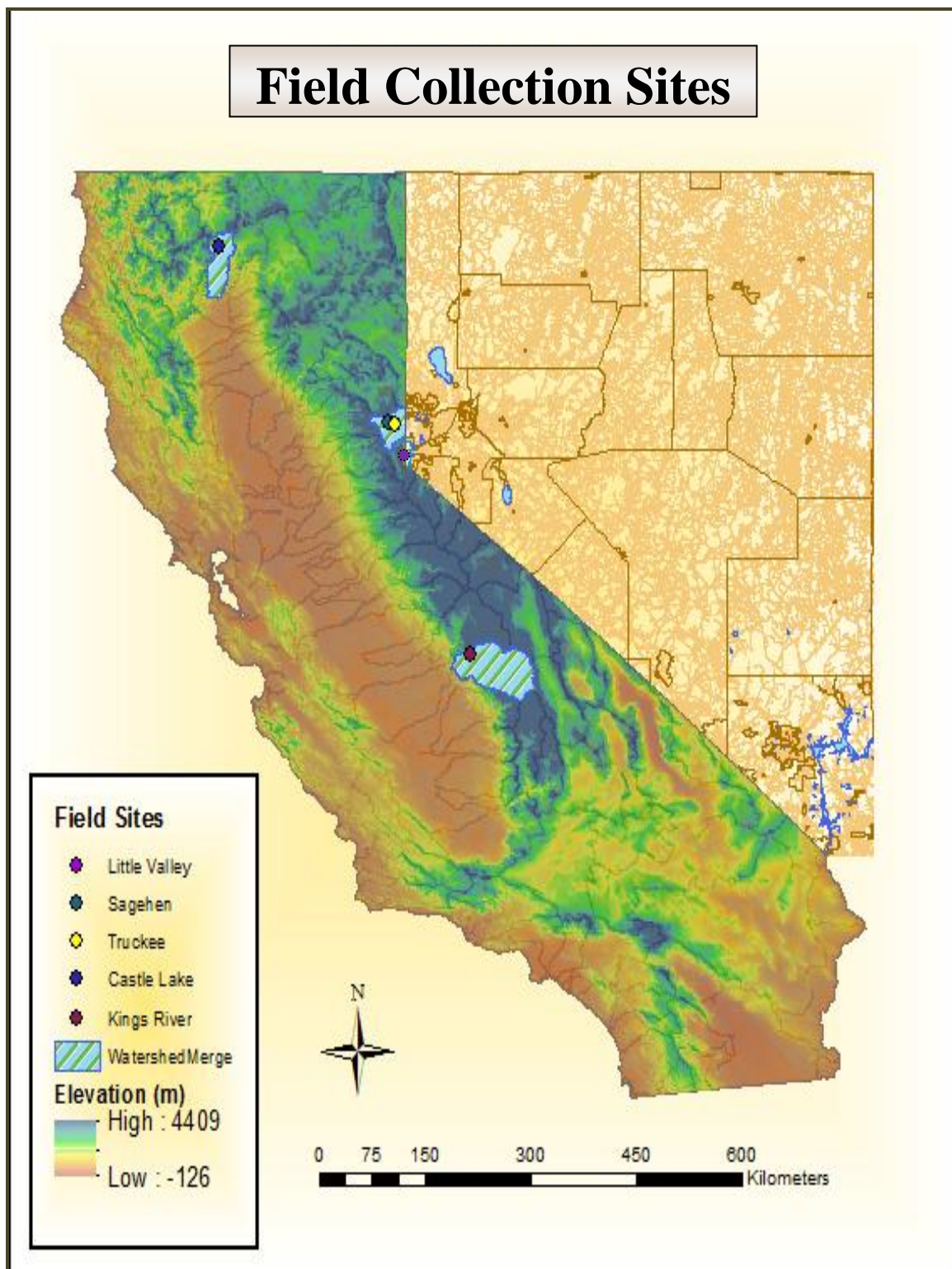


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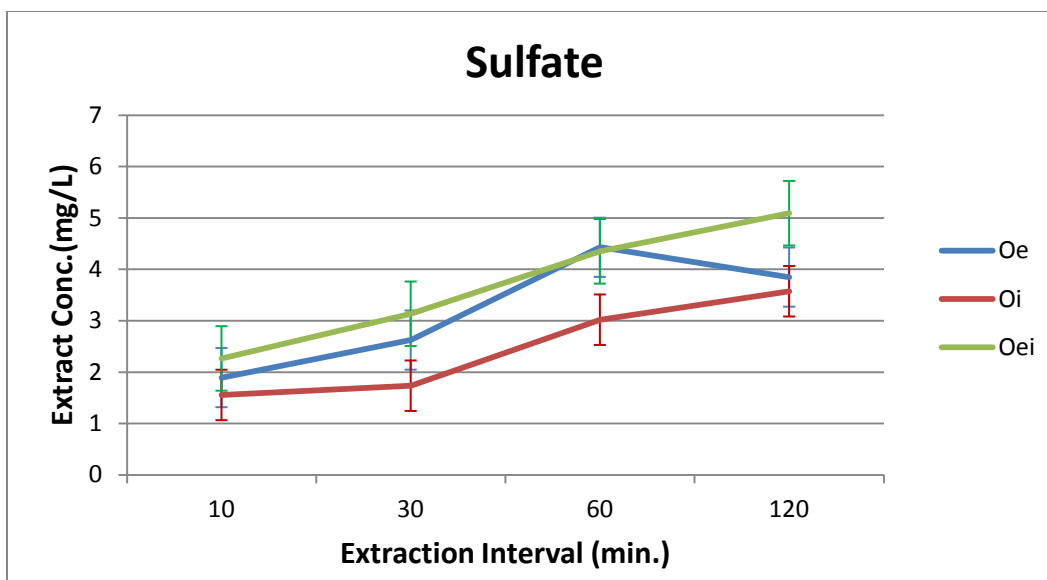


Fig. 2 – Laboratory extract sulfate concentrations (mg/L) as affected by O horizon material and time.

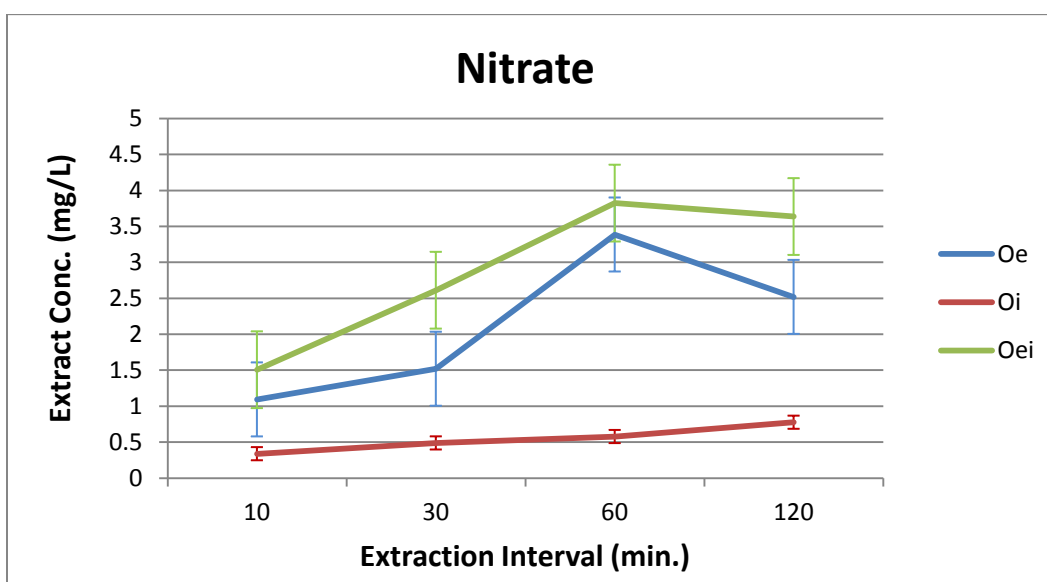


Fig. 3 – Laboratory extract nitrate concentrations (mg/L) as affected by O horizon material and time.

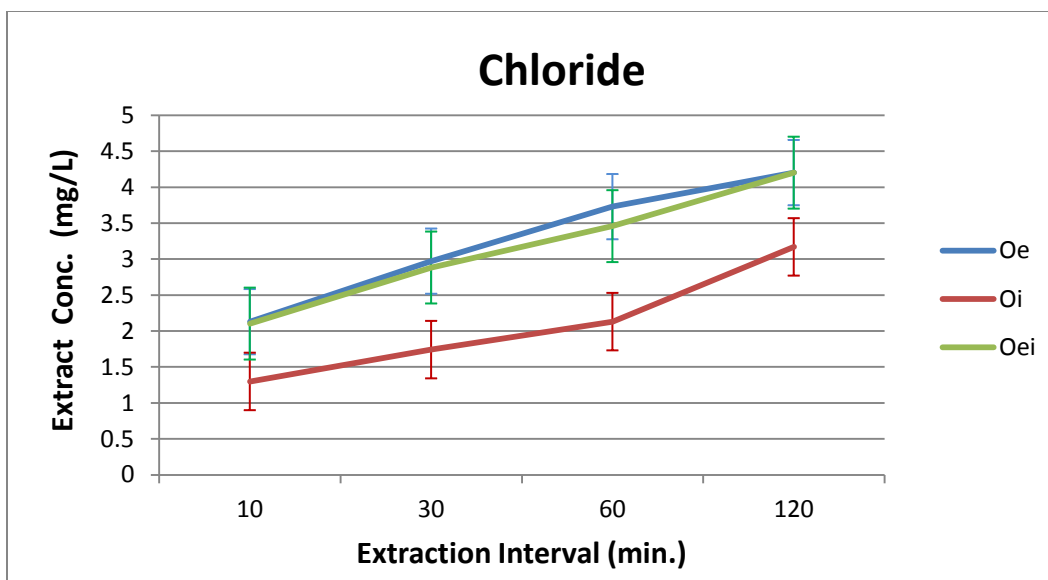


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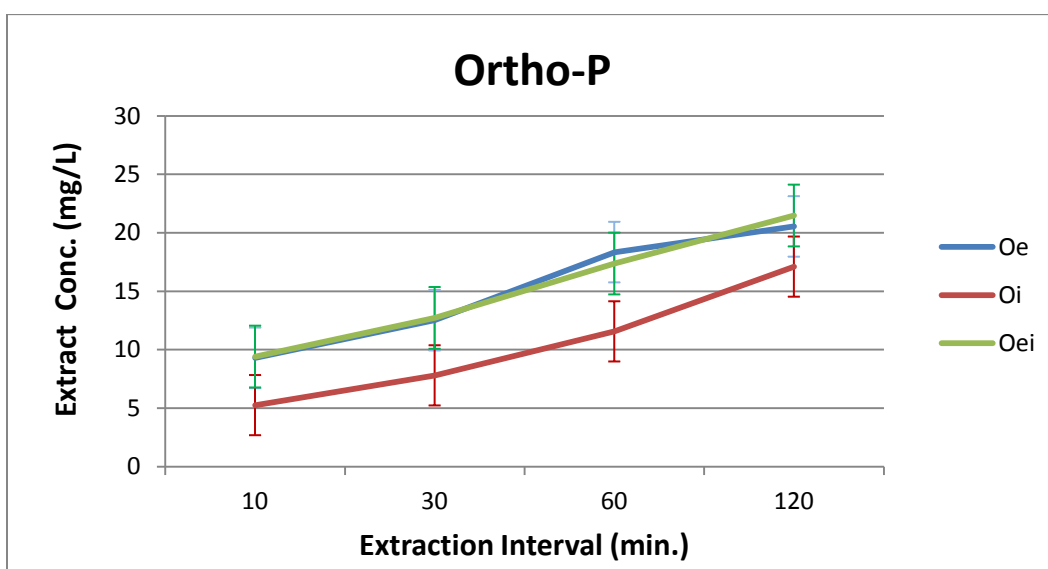


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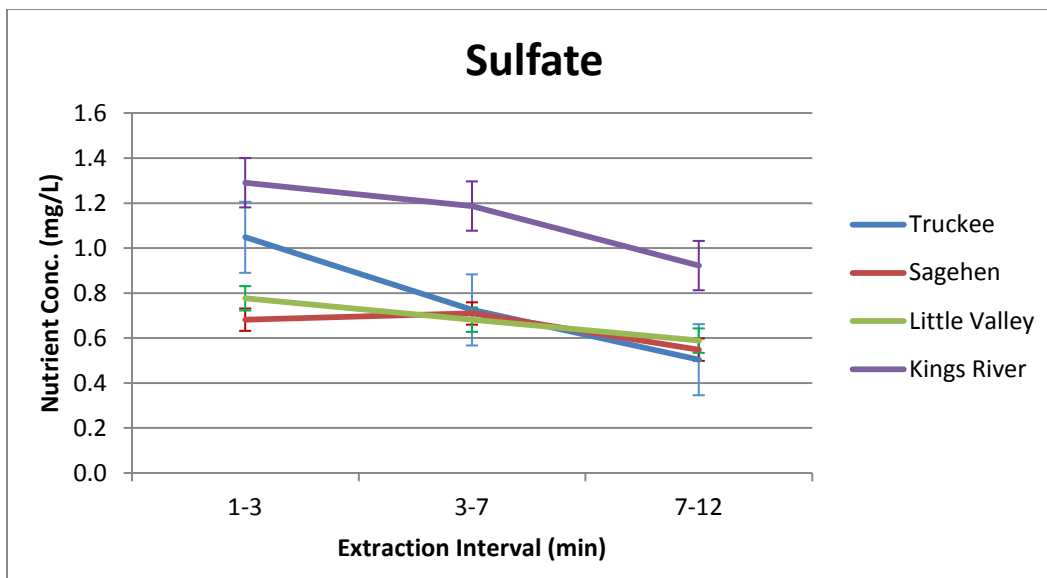


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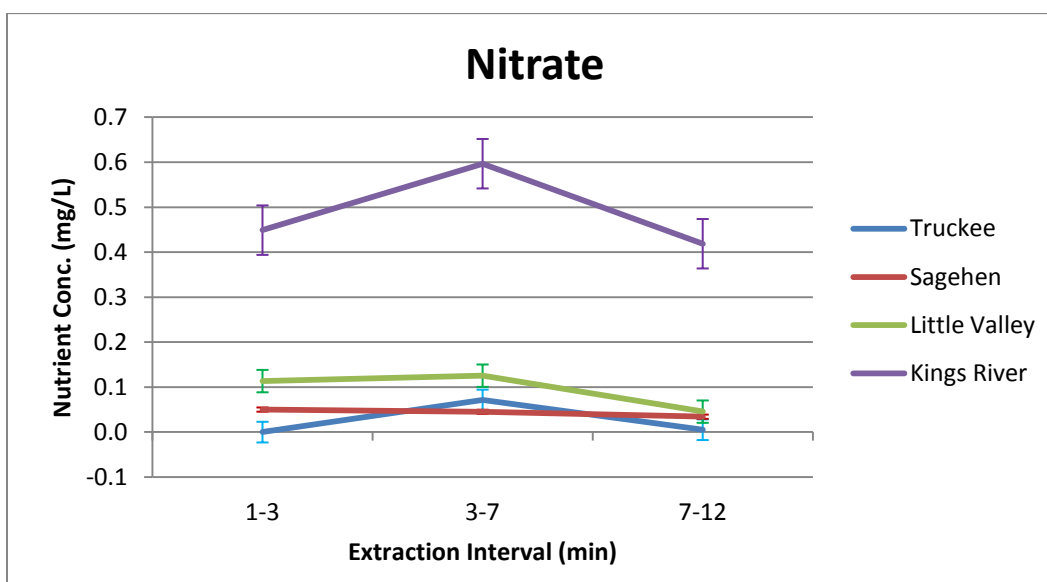


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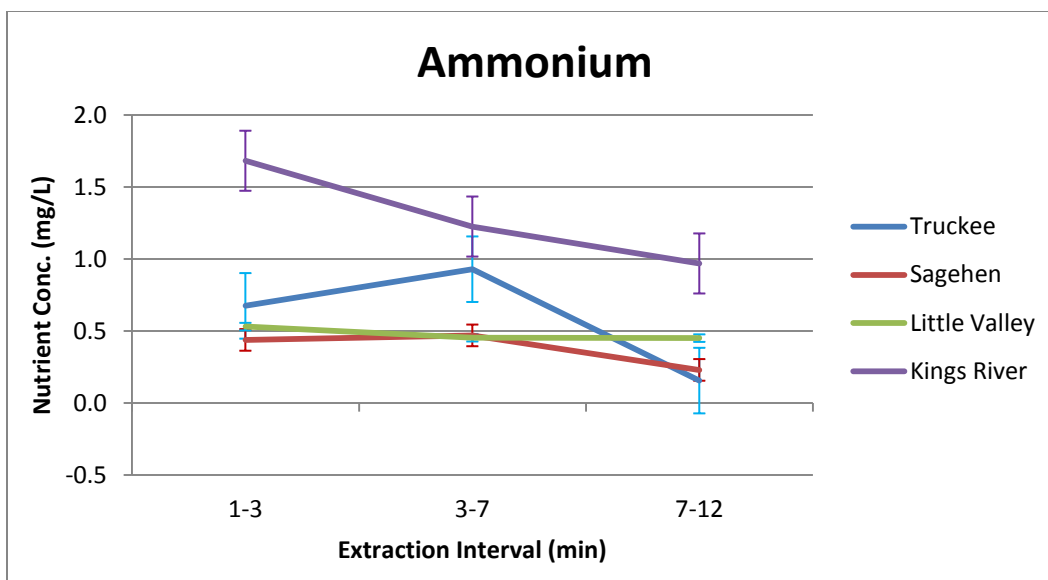


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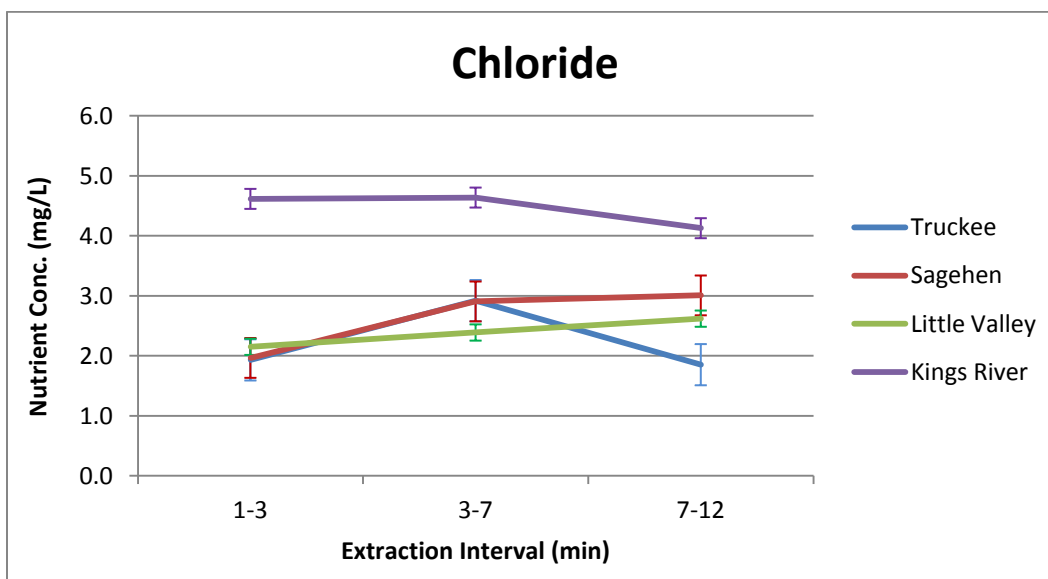


Fig. 9 – Greenhouse chloride discharge concentrations as affected by breakthrough extraction interval for the Truckee (TR), Sagehen (SH), Little Valley (LV) and King’s River (KR) study sites.

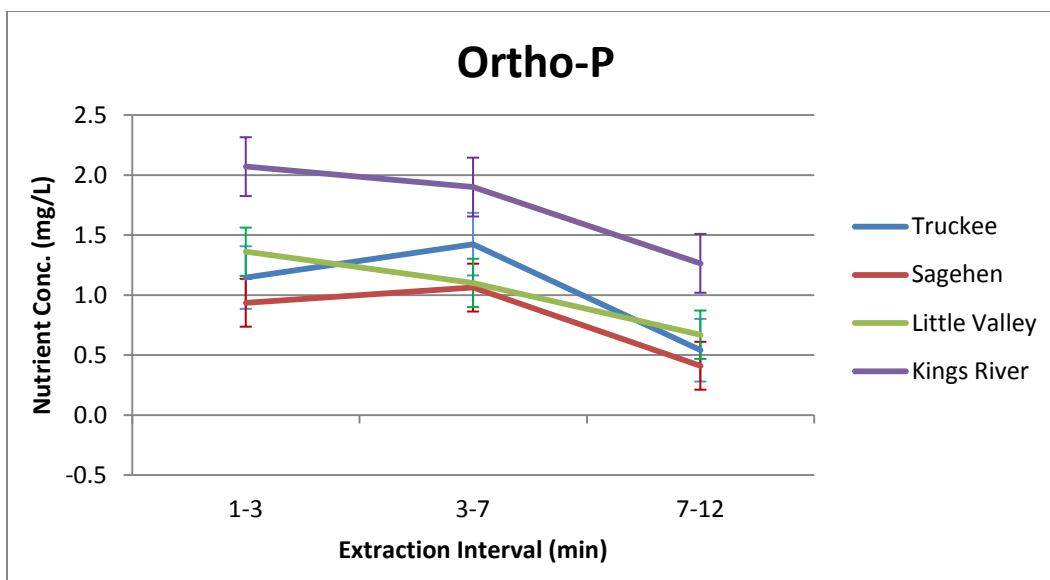


Fig. 10 – Greenhouse ortho-P discharge concentrations as affected by breakthrough extraction interval for the Truckee (TR), Sagehen (SH), Little Valley (LV) and King’s River (KR) study sites.

CHAPTER THREE:

General Conclusions

Large amounts of biologically available nutrients reside in O horizon materials and contribute to watershed nutrient pools (Johnson et al., 1997; Johnson et al., 2009; Loupe et al., 2007; and Miller et al., 2005). As precipitation events occur nutrients can become dissolved or suspended into interflow leachate and travel via preferential flow paths (Burcar et al., 1994; Loupe et al., 2007; and Miller et al., 2005). Nutrient rich interflow infiltrates at unknown locations into the soil matrix at a diverse spatio-temporal scale. Johnson et al., (2011) identified the presence of nutrient rich “hot spots” within the soil matrix that were potentially generated from preferential flow paths through the O horizon into the mineral soil, however, the nutrient rich leachate may not always infiltrate into the underlying soil matrix; i.e., leachate may travel laterally through the O horizon and infiltrate at an alternate point.

Across all sites nutrient rich overland/litter interflow preferentially infiltrated into the soil matrix at variable locations. These areas of preferential water flow through the O horizon didn't always infiltrate into the immediate underlying soil matrix. Although biogeochemical “hot spots” were created within the soil matrix, the exact cause and mechanism remains uncertain. For the two year study period a similar nutrient correspondence at a single grid was rarely detected. The spatio-temporal infiltration pattern of nutrient rich “hot spots” was highly variable seasonally, annually and largely unknown.

The laboratory extraction experiments established that extraction time and O horizon material were significantly different ($p \leq 0.019$) in sulfate, nitrate, chloride and ortho-P nutrient extraction. The independent O_i and O_e extract nutrient concentrations were similar to or less than the combined O_{e+i} material and most nutrient concentrations between the 60 and 120 min extraction periods reached a plateau; suggesting that a minimum of 60 min extraction of the combined O_{e+i} horizon is adequate to assess the average nutrient discharge potential.

The greenhouse experiment depicted the dynamic and heterogeneous nature of the O horizon. Each monolith was found to contain a variable degree of decomposition and compaction and no two monoliths discharged interflow leachate at the same spatio-temporal scale or rate. However, greenhouse findings did show a significant effect ($p \leq 0.013$) of study site location and collection interval in overall nutrient discharge for SO_4^{2-} , NO_3^- , NH_4^+ , Cl^- and ortho-P; albeit no interaction of the categorical variables was detected. The initial discharge of most nutrients occurred during the 1-3 min collection interval that decreased with an increase in collection time.

The number of preferential flow paths contributing to nutrient transport systems may never be fully understood or predictable. Assessments estimated trends and generalized spatial scale infiltration patterns, but “pin-pointing” nutrient infiltration and discharge continues to be a challenging process. Our studies further characterize the spatial nutrient transport processes and provide information on the extreme seasonal variability of nutrient cycling dynamics along the Sierran front to the Cascades. We have roughly established that nutrient “hot spots”, where all nutrients are co-located will occur

about once every 9 m². Whether or not these nutrient “hot spots” actually serve as a nutrient supply to the surrounding plant community or freely stream directly into adjacent hydrologic systems without plant uptake is unclear, but the potential of either process exists. Temperature, initial moisture content of OM and the soil matrix, amount of nutrients present, type of decomposing material, decomposition rates, ionic exchange capacity, bulk density, soil texture, uptake by microbial communities and plant species, climate, and aeration all play a major role in nutrient fluxes and cycling processes (Brady et al., 2010). Understanding these drivers further can aid in better characterization of the natural nutrient transport processes and the relative importance of “hot spots” in Sierran and Cascade soils.

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