University Of Nevada, Reno

Nutrient Hot Spots in a Sierra Nevada Soil: Physical Assessments and Contributing Factors

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ABSTRACT

An understanding of soil chemistry is important for biogeochemical cycling not only belowground but above ground as well. Soil nutrients play a key role in the function of an ecosystem. Nutrient hot spots in the mineral soil are believed to be vital components of a soil system influencing biological uptake and biogeochemical cycling. Three studies were done each looking into different aspects of soil nutrient hot spots at two sites in the Kings River Experimental Watershed (KREW). The first study consisted of using three different resin based sampling methods (UniBest® resin capsules, PRS™ probes, and resin lysimeters) to investigate the presence and temporal effects of soil nutrient hot spots. All three sampling methods showed nutrient hot spots in the soil. Individual nutrient hot spots were more prominent than a sample point that had nutrient hot spots for all the nutrients. Inorganic nitrogen was the most common hot spot found. The size of the hot spots varied from ~2 cm (the size of a single capsule) to 40 cm^2. UniBest® resin capsules and PRS™ probes appeared to be more influenced by interflow after a single precipitation event rather than being left in the soil for the entire season. Calcium on the probes appeared to be displacing potassium and ammonium on the membrane when the probes were left in the soil for the entire season. The resin lysimeters showed that hot spots can be ephemeral (hot moments).

The other two studies were focused on potential influences on the formation of hot spots. One study looked at correlations between microbial biomass and water extractable nutrient hot spots in the mineral soil. The results were inconclusive. At one site the data showed that water extractable nutrient hot spots were co-located with microbial biomass, however at the other site it did not. This suggests that microbial biomass is not always associated with nutrient hot spots. The study also showed that nitrate was the most frequent hot spot found and the hot spots were commonly located in locations of lower concentrations for other nutrients. The last study investigated the influences of O-horizon interflow on soil nutrient concentrations and hot spot formation. The study found that at one site interflow can increase decomposition rates and therefore possibly increase nutrient availability into the soil. A 17% increase in soil moisture content did not increase the formation of hot spots in the soil or average nutrient concentrations for resin capsules or water extractable nutrients; however, truncating interflow with PRS™ probes caused an increase in the number of individual hot spots, but did not cause the formation of hot spots for multiple nutrients in one location.

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INTRODUCTION

Soils are an important aspect to the biodiversity of a landscape. They play critical roles in the health and sustainability of an ecosystem, yet due to the complex heterogeneity of a soil system a comprehensive understanding of the soil matrix is still poorly understood (Gardi et al 2009). In the past, large scale soil sampling and bulking were the common practices for quantifying and analyzing a soil system; however this can mask crucial components of a soil and lead to false conclusions on the composition and behavior of a soil. A greater understanding of the soil's role on the health of an ecosystem and its interactions can help give a better perspective to biogeochemical cycling, give insight to more effective management practices, and provide a greater understanding of evolving landscapes.

Heterogeneity and variability of nutrients has been shown to exist on a small, meter sized, scale (Johnson et al. 2009, Johnson et al. 2010, Johnson et al. 2011). The variability of nutrients in a soil system on a meter sized scale is important to the function of a soil in an ecosystem (Schimel and Bennet 2004, Johnson et al. 2011). Soil plays a key role in the availability of nutrients for aboveground vegetation. The heterogeneity of a soil often results in inorganic nutrients in concentrated locations relative to the surrounding matrix. These locations of concentrated inorganic nutrients are deemed as hot spots and are believed to play a pertinent role in the biogeochemical cycling of nutrients and in helping plants out-compete microbes (Schimel and Bennet 2004). Understanding nutrient hot spots on a local scale is relatively new field of research and a large misrepresentation of soil nutrient concentrations can result if they are not taken into consideration.

The goal of this research was to gain a further understanding of nutrient hot spots in the soil on a local scale. Hot spots had been defined by positive skew (Kurunc et al. 2011) and statistical outliers (Johnson et al. 2009; Johnson et al. 2010; and Johnson et al. 2011). Inorganic nutrient hot spots on a local scale have been identified by several different sampling methods; the principle causes for their formation, size, and longevity are hypothesized, but widely unknown. Hot spots have been found using resin based sampling methods and from water extractable nutrients (Johnson et al. 2009; Johnson et al. 2010; and Johnson et al. 2011).

Chapter one looks at the size of hot spots, the effectiveness of resin based sampling methods for determination, and longevity of hot spots. To determine the size and resin effectiveness, two different types of resin samples (UniBest® resin capsules and PRS™ probes) were placed in a 4x4 meter grid at alternating grid pints in sets of four. The four samples at each grid point were placed approximately 20 cm apart forming a square. After the first precipitation event the two of the four samples at each grid point were removed. The square of samples helped to determine the size of hot spots and the removal of the first two samples helped to establish the effectiveness of resin based sampling methods. For temporal variations 16 resin lysimeters were placed in a grid for two years after one year the set of lysimeters was removed and another new set put in the same location.

Chapter two looks at the influence of microbial activity on nutrient hot spot formation in the soil. Microbes play a key role in the biogeochemical cycling of nutrients in the soil. Bundt et al. (2001) found enhanced microbial activity in locations of preferential flow paths with a more favorable nutrient and substrate supply. Factors affecting microbial activity in the soil include soil chemistry and preferential flow paths (Williamson et al. 2005; Hackl et al. 2005; Zhang 2005). Therefore, microbial activity could be a useful indicator for nutrient hot spots in the soil. To assess the presence and influence of microbial activity on nutrient hot spots, soil cores were taken and the mineral soil was analyzed for water extractable nutrients and microbial biomass.

Chapter three focuses on nutrient-laden preferential flow paths as an influencing factor on hot spot formation in the mineral soil. In the King's River Experimental Watershed (KREW) where this research takes place, the summers are dry and there is no rooting in the O-horizon (Stark 1973). The dry summers can cause the soil to become hydrophobic and lead to nutrient-rich interflow moving in the O-horizon just above the mineral soil (Miller at al. 2005). This nutrient-laden interflow finds a preferential flow path into the mineral soil or can migrate to a body of water. Once in the mineral soil the nutrients can bind with the soil particles creating a hot spot. Bundt et al. (2001) found carbon contents that were 10-70% higher, as well as elevated levels of organic nitrogen, CEC, and base saturation at preferential flow locations. To determine the influence of preferential flow paths on hot spot formation barriers were placed in the O-horizon to truncate interflow and enhance nutrient concentrations in the mineral soil.

THESIS OVERVIEW

The primary objectives of this research were to gain a greater understanding of nutrient hot spots in a Western Sierra Nevada soil. The first chapter focuses on the size and longevity of hot spots formation as well as the effectiveness of using resin-based sampled methods for measuring soil nutrient flux. The second chapter looks into the relationship between microbial communities and hot spots in the mineral soil. The third and final chapter assesses the influences of nutrient-laden interflow on the decomposition rates of the O-horizon and hot spot formation. All of this research gains greater insight into the heterogeneity of the soil matrix.

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Chapter One

Nutrient hot spots in a Sierra Nevada forest soil: I. Spatial and temporal patterns in resin based measurements

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ABSTRACT

Meter scale grids were established in two locations in the King's River Experimental Watershed (KREW) on the west side of the Sierra Nevada Mountains to investigate the presence and status of soil nutrient hot spots. One grid was instrumented with UniBest® resin capsules and Western Ag Innovations PRS™ probes in sets of four and a second grid was instrumented with resin lysimeters. After the first precipitation event in the fall, two each of resin sample types, capsules and probes, were removed (event samples). The remaining sets were left in place for the entire winter season and removed in the summer (season samples). Hot spots (identified by positive significant outliers) were found in both probe and capsule data. The size of the hot spots varied from ~2 cm (the size of a single capsule) to 40 cm^2 (the area encompassed by four replicate resin collectors at a single grid point). Potassium concentrations were higher in the event probe data than season data whereas the reverse was for calcium, suggesting that calcium may have displaced potassium on the probe over the season (t-test $P < 0.01$). Data from the resin lysimeters (collected over two seasons from the same locations to assess the temporal variability), showed that hotspot locations shifted spatially from year to year, suggesting that there were ephemeral "hot moments" as well. Among the nutrients measured, inorganic nitrogen exhibited the most abundant hot spot found in all sample types.

Key Words: Soils, Nutrients, Hot Spots, Sierra Nevada Mountains

INTRODUCTION

Today's typical forest structure of the Sierra Nevada is characterized by a greater amount of shade tolerant tree species, increased understory, and greater tree density compared to pre-European settlement conditions (Kilgore et al. 1979; Caprio et a. 1995; Taylor 2004). The increase in forest density and decreasing fire regime has led to a buildup of organic matter and debris (logs, etc) on the forest floor (which is evident when comparing historic photographs with those of todays forest structure). There have also been shifts in the biodiversity of the forest structure since pre-European settlement (Taylor 2004). These shifts in biodiversity and buildup of organic matter can lead to changes in the soil composition.

Soil is an important aspect of biodiversity that is often overlooked and neglected (Gardi et al 2009). In the past, large scale soil sampling and bulking were used to analyze and quantify soil characteristics; however, this method may mask important aspects of a soil's complex and diverse system. Nutrients in soil play an essential role in maintaining the biodiversity of a landscape and the heterogeneity of nutrients on a small scale is becoming more recognized as an important aspect of a soil system (Schimel and Bennet 2004, Johnson et al. 2011). Zones or patches of high nutrient concentrations relative to the surrounding soil matrix are designated as hot spots by McClain et al. (2003) and Schimel and Bennet (2004). Hot spots of inorganic nutrients in a soil matrix are believed to play a pertinent role in the biogeochemical cycling of nutrients, plant nutrition, and water quality (McClain et al. 2003; Schimel and Bennet 2004; Johnson et al. 2011). The presence of hot spots on a local scale in the soil has been observed in the form of positive skews (Kurunc et al. 2011) and statistical outliers for both resin-based sampling methods and soil nutrient concentrations (Johnson et al. 2009; Johnson et al. 2010; and Johnson et al. 2011).

McClain et al. (2003) express that there is deficient knowledge of the mechanisms that produce hot spots. To better understand nutrient hot spots on a local scale, a study was performed in the King's River Experimental Watershed (KREW) on the west side of the Sierra Nevada Mountains in California, USA. The objective of this research was to assess the formation, longevity, and size of hot spots on a local scale using various resin-based measurements. To meet this objective three types of resin samplers (resin capsules, PRS™ probes, and resin lysimeters) were placed in the soil as a passive measurement method for nutrient flux; areas depicting high nutrient flux may be indicative of hot spots within the soil matrix. This was implemented on a meter-sized scale for one year for the resin capsules and PRS™ probes and for two years with the resin lysimeters. In Chapter 2, soil core samples were extracted from these grids and analyzed for water extractable nutrient hot spots and microbial biomass.

METHODS AND MATERIALS

Study Site Description

The King's River Experimental Watershed (KREW) (located on the western side of the Sierra Nevada Mountains) approximately 105 km northeast of Fresno, California in Fresno County, was established in 2000 to create a better understanding of the function of headwaters in ecosystems and the effects of forest management practices that are used to increase the health of a forest (Figure 1). The Southern Sierra Critical Zone Observatory

(CZO) is co-located at KREW and is used as an environmental laboratory to study the physical, chemical, and biological processes of the earth's surface. KREW is characterized by warm dry summers and cold winters, where most of the precipitation is snow. The mean annual temperature is 8°C. The mean annual precipitation is ~137 cm and annual snowfall ranges from 100-300 cm for the area (Hunsaker 2012). Site vegetation is a mixed conifer forest composed of sugar pine (*P. lambertiana Douglas*), ponderosa pine (*Pinus ponderosa Lawson and C. Lawson*), incense-cedar (*Calocedrus decurrens (Torr.) Florin*) and white fir (*Abies concolor (Gord. & Glend.) Lindl. ex Hildebr*). The understory consists of unidentified brush species, green leaf manzanita (*Arctostaphylos patula Greene*), and squawcarpet (*Ceanothus prostratus Benth*). The soil is from the Shaver series; a coarse-loamy, mixed mesic Pachic Xerumbrept derived from granite (Johnson et al 2011).

Two field sites were chosen for study. Site one (Tower site) is at an elevation of 1980 meters, Latitude: 37° 3' 33.626" N Longitude: 119° 10' 56.184" W. Site two (P301) is at a lower elevation, 1910 meters, Latitude: 37° 3' 46.649" N Longitude: 119° 12' 3.844" W. Both sites have similar soil and vegetation, but site two has nearly 100% canopy closure.

Experimental Design

A 16m^2 grid was established at each field site consisting of 32 sampling points. At 16 sampling points, four Western Ag Innovations PRS^{tm} Probes (two cation and two anion) and at the alternating 16 sampling points where four resin capsules were installed. Both the four sets of probes and capsules were placed 20 cm apart which formed a square at each of the sampling points (Figure 2). At each sampling point, the samplers were placed approximately 20 cm apart and the capsule sampling points were off-set from the probe sampling points. UniBest® resin capsules were used to capture nutrients from the interstitial flow within the O-horizon. These capsules are two centimeters in diameter and have 10 g of positive and negatively charged beads. The ion exchange resin capsule primarily collects the labile forms of inorganic nutrients (Skogley 1996). Western Ag Innovations PRS™ probes were also used to capture nutrient flux from the O-horizon. We used 17.5 cm^2 cation and anion probes both composed of an ion exchange membrane. The probes are designed to adsorb ions through electrostatic attraction and are believed to simulate root adsorption making them useful for understanding nutrient supply rates within the soil matrix. The probes were installed 10 cm into the O-horizon and the capsules were inserted below the O-horizon just above the mineral soil in late summer. Two of the probes (one cation and one anion) and two of the resin capsules were removed after the first large precipitation event (totaling 26 cm over 48 hours) in October of 2009 and the last set of samplers were removed in June of 2010.

A second grid was established for resin-based lysimeters as described by Susfalk and Johnson (2002) at each site. This grid was 4x4 m in size and consisted of 16 sampling points. At each sampling point, a resin lysimeter was inserted into the mineral soil with the top of the lysimeter at the O-horizon and mineral soil interface. After one year, the old lysimeters were removed and a new one was placed in the same location in an effort to assess the temporal variation in nutrient flux.

Analytical Methods:

The resin capsules were washed free of all debris with deionized water. Care was taken to prevent sample contamination. They were then extracted with 20 mL of 2 M KCl three times, each time being shaken on a platform shaker for 20 minute intervals. The 60 mL extract was then shipped to Oklahoma State University Soil Water and Foliage Analysis Laboratory (SWFAL) for analysis. Ammonium, nitrate, and orthophosphate were analyzed on a Lachat 8000 flow injection analyzer (Hatch co. Loveland, C.O. USA). Calcium, magnesium, and sodium were analyzed using a Jarrell Ash inductively coupled plasma spectrophotometer (Thermo Jarrell Ash Corp., Franklin MA). Sodium was only analyzed for the capsules removed after the first precipitation event.

The PRS™ probes were washed free of all debris using deionized water. They were then shipped to Western Ag Innovations Saskatoon Canada where they were soaked for one hour in 17.5 mL of 0.5 M HCl. The extract was then analyzed for ammonium and nitrate colorimetrically using a Technicon Autoanalyzer II (Seal Analytical, Mequon, Wisconsin). Phosphorus, magnesium, calcium, and potassium were all analyzed on a Perkin Elmer Optima 3000-DV ICP using an inductive coupled plasma emission spectroscopy.

The resin lysimeters were taken from the soil, the sand discarded and then washed with deionized water to remove any debris. They were then set to dry on a clean counter for a minimum of 24hrs. The dried resin was then carefully removed and 100mL of 1 M KCl extractant was added to each resin sample. These samples were covered in Parafilm® and shaken on a platform shaker for one hour. The filtered extract was sent to Oklahoma State University SWFL for analysis. Ammonium, nitrate, and orthophosphate were analyzed on a Lachat 8000 flow injection analyzer (Hatch co. Loveland, C.O.

USA). Calcium, magnesium, and sodium were analyzed using a Jarrell Ash inductively coupled plasma spectrophotometer (Thermo Jarrell Ash Corp., Franklin MA).

Data Analysis

The data were analyzed for extreme and moderate outliers using the program DataDesk (Velleman 1997). Student t-tests were also performed as single tailed and two-sample unequal variance (heteroscedastic) to test for the differences between event and season samples with the resin capsules and probes. Log transform of the data did not alter the results and therefore not used in the t-test analysis. Linear regression determining the coefficients of determination (r^2) was performed comparing individual nutrient concentrations collected on the capsules and probes from the event and season data. DataDesk defines positive and extreme outliers as:

Extreme outliers:

$X > Q_3 + 3 \times IQR$

Moderate outliers

$X > Q_3 + 1.5 \times IQR$

x = the value

Q_3 = the third quartile value (75th percentile), and

IQR = interquartile range (range from 25th to 75th percentile)

Skewness Values were determined as:

$Skew=M_3/M_2^{3/2}$

where

$M_2=\sum(yi-\bar{y})^2/n$

$M_3 = \sum (yi - \bar{y})^3 / n$

$\bar{y}$ = sample mean

M_2 = variance

M_3 = third moment of the data

Skewness was calculated in excel and is defined as the characterization of the asymmetry of a distribution around its mean (Brown 1997). A skewness value is considered significant if it is equal to or greater than twice the standard error (Brown 1997). For smaller data sets it is more reasonable to use the standard error of the skewness *(ses)* developed by Routledge, 1997 (Brown 2012). We calculated *ses* using the following equation:

$$SES = \sqrt{\frac{6\mathrm{N}(\mathrm{N}-1)}{(\mathrm{N}-2)(\mathrm{N}+1)(\mathrm{N}+3)}}$$

RESULTS

In the remainder of this chapter data from resin capsules and PRS™ probes removed after the first precipitation event will be called event samples and those left in the soil for the entire snow season (September- June) will be referred to as season samples.

Resin Capsules

Table 1 shows the means with standard errors, P-values for t-tests, and skews for resin capsule data and Figures 3-5 show values by grid location and outliers. The capsule nutrient concentrations were highest for calcium, exceeding 40 $\mu mol \cdot cm^{-2}$, and lowest for orthophosphate, rarely exceeding 1 $\mu mol \cdot cm^{-2}$. A majority of nitrate-N values in the event samples were also below 1 $\mu mol \cdot cm^{-2}$; however the outliers for nitrate were orders of magnitude higher than orthophosphate outliers (Figures 3 and 5). The ammonium-N data never exceeded 1.5 $\mu mol \cdot cm^{-2}$ for the P301 site (Figure 3). The ammonium-N for the Tower site showed much higher outlier concentrations than orthophosphate for both sites and the ammonium-N for the P301 site (Figures 3 and 5). Magnesium reached above 5 $\mu mol \cdot cm^{-2}$ twice, both times being season nutrient data, once at the Tower site and once at the P301 site (Figure 4). Calcium reached above 40 $\mu mol \cdot cm^{-2}$ four times in the season data, once at the P301 site and three times at the Tower site (Figure 4).

With the exceptions of Tower nitrate-N and ammonium-N, the means of the season data were higher than the event means (Table 1). Season calcium and magnesium were significantly higher ($P<0.05$) than event values at both sites while ammonium-N was higher at the P301 site. Data from the event-based resin capsules exhibited a significant positive skew for all nutrient concentrations at both field sites, which was not true for the season data. Nitrate-N was the only nutrient exhibiting a significant positive skew at both sites for event, and season data.

The event capsule nutrient concentrations for the Tower site demonstrated significant correlations ($P<0.01$) with one another (Table 2). Event capsule nutrient concentrations at P301 were significantly correlated as well ($P<0.01$), with the exception of ammonium not correlating with any nutrients (Table 2). With the exception of calcium and magnesium at both sites, and magnesium and nitrate-N at the P301 site, the season capsule data did not exhibit clear correlations ($r^2>0.5$).

Two resin event capsule samples from point 13 at the Tower site exhibited hot spots (either moderate or extreme) for all nutrients (Figures 3-5). Point 12 at P301 was an apparent hot spot (either extreme or moderate) for all nutrients except ammonium-N (Figures 3-5). Data from point 15 at P301 indicated a hot spot for nitrate-N, orthophosphate, calcium and magnesium. The only nutrient that did not exhibit any extreme outlier concentration was calcium; however data did show two event-based moderate outliers at each site (Figure 4).

There was only one season sample location at each site (grid point 16 for both P301 and Tower) that exhibited hot spots for more than one nutrient. For P301 the nutrients were nitrate-N and magnesium and for the Tower site they were nitrate-N and ammonium-N. Nitrate-N was also the nutrient that demonstrated the most extreme outliers, with four of them being event based extreme outliers (Figure 3). There were more outliers (extreme and moderate) for the event capsule data than for the season capsule data (22 and 8 respectively) (Figures 3-5).

Plant Root Simulator™ (PRS) Probes

The nutrient concentrations were significantly different (t-test $P \leq 0.05$) for event and season data at both sites except for Tower nitrate-N and ammonium-N (Table 3). With three exceptions (potassium at both sites and ammonium at P301), average nutrient concentrations for probe data were greater for the season data. Potassium at both sites was significantly higher (t-tests $P < 0.01$) for event data compared to the season data as was ammonium from the P301 site.

The P301 season probes were the only data to display a significant positive skew for all nutrients analyzed (Table 3). The data from the event probes for the Tower site had a significant positive skew for ammonium-N, nitrate-N, calcium, and magnesium, whereas data from the P301 site had a significant positive skew for nitrate-N ammonium-N and phosphate-P. The only nutrients where a significant positive data skew was identified for both sites and sample type (event or season) were ammonium-N and nitrate-N.

Data from the Tower site showed strong correlations among nutrient concentrations for the event data (Table 4). P301 showed fewer correlations between the event data. The season r^2 values were all <0.5 and the only significant correlations were between magnesium and nitrate at P301 and phosphate with magnesium and calcium and potassium with calcium at the Tower site ($p \leq 0.05$).

There was at least one extreme outlier for each of the nutrients during the study with the exception of calcium and magnesium, which only showed moderate outliers (Figures 6-8). The magnesium data exhibited one season moderate outlier at the P301 site and one event moderate outlier at the Tower site which was co- located with a moderate calcium outlier. The greatest number of extreme outliers were nitrate-N and ammonium-N, both having six. Two of the nitrate-N event extreme outliers were co-located with season ammonium-N outliers for the P301 site, suggesting a large hot spot of inorganic nitrogen. Potassium demonstrated three extreme season outliers and no event outliers. With the exception of one of the sixteen sampling locations at P301, there was no overlap in extreme outliers between event and season probe data for an individual nutrient. No single location was identified in which all nutrient concentrations exhibited an outlier (extreme or moderate) at the same sampling location.

Resin Lysimeters

Average nutrient flux, along with the skew, for the resin lysimeter data are shown in Table 5. The winter seasons for both years were from September to June the following year. The Tower site nutrient fluxes were higher for the 2010-2011 winter season than the 2009-2010 winter season with the exception of ammonium-N. For the P301 site, the 2009-2010 season data demonstrated higher average flux for ammonium-N, calcium, and magnesium. Correlations determining the strength of the relationships were performed comparing the nutrients from the 2009-2010 winter season data to the 2010-2011 winter season data. The coefficients of determination between different nutrient concentrations showed a poor relationship with $r^2<0.5$ for the years compared. None of the correlations were significant ($p\leq0.05$). The only site and time that demonstrated a significant positive data skew for all nutrients was in 2010 at the Tower site. The only nutrients that showed a positive significant skew for both years and locations were ammonium-N and nitrate-N. They were also the only nutrients to show a significant skew during the 2011 water year. In 2010 orthophosphate also had a significant skew for both sites.

Data for individual grid points for the resin lysimeters are illustrated in figures 9-11. In the 2009 -2010 winter season (September –June) data, there were extreme or moderate outliers for calcium, magnesium, and ammonium-N at the Tower site and nitrate-N, ammonium-N, and orthophosphate at the P301 site. For the winter season of 2010- 2011 (September-June), data from both sites exhibited extreme and moderate outliers for nitrate-N and ammonium-N. The grid point locations of the extreme and moderate outliers were not the same from the 2010 year to the 2011 year.

DISCUSSION

Hot spots (extreme and moderate outliers) were identified for some nutrients in all of the resin sampling methods used (resin capsules, PRS^{tm} probes, and resin lysimeters). Ammonium-N demonstrated the highest frequency of outliers for the resin lysimeters and nitrate-N the highest frequency of outliers for the capsules and probes. Nitrate-N and ammonium-N concentrations were also the only nutrients that consistently showed a significant positive skew for all three types of nutrient concentrations.

All four samples from probes taken at point 12 (the two event as well as the two season samples) in the Tower site were hotspots for inorganic nitrogen. Ammonium-N was the main form for the event data and nitrate-N was the main form for the season data (Figure 12). This suggests that there was a large nitrogen hot spot in the soil for point 12 with the probe data. Potentially this pattern could be explained by nitrification converting the ammonium to nitrate between the event and season sampling.

Out of the three types of resin sampling methods, capsule nutrient fluxes were the only ones to show hot spots for all nutrients at the same sample location (Tower sampling point 13, both event capsules). The capsules were placed approximately 20 cm apart, suggesting this location may also have had a larger zone of higher nutrient concentrations (or two smaller hot spots coincidentally close together). Nutrient concentrations derived from event samples at the Tower site all exhibited strong correlations with each other ($r^2 > 0.5$), suggesting interflow as the dominant source for nutrients. If a capsule was in a location of high preferential interflow, then one would expect all nutrient concentrations to be greater than those for a capsule in a location of low preferential interflow. Since rooting is absent in the O-horizons of these sites (because of the dry summers), root uptake should not influence the capsule adsorption or preferential flow in the O-horizons.

Adsorption efficiency of the resin capsule is temperature dependent (Skogley et al, 1996) which may affect nutrient adsorption during the winter season. Research on the adsorption capacity of capsules is typically performed over periods of weeks and not long-term (Schaff et al. 1982; Skogely et al. 1996) which may be another reason for the discrepancies between the different r^2 values between the event and season data.

The data from the PRS™ probes showed hot spots and significant positive skews for some nutrients from both the event and season data. The data from the probes did not show a hot spot that contained all nutrients at one sampling point for either the event or season data. Correlations between nutrients for event probe and capsule data were greater than those for the season data. This suggests the influence of the interflow may be greater in the event nutrient data similar to the capsules.

We speculate that the lower potassium concentrations from the season than from the event data may be due to cation exchange, perhaps displacement of potassium by calcium. The membranes collect ions by electrostatic adsorption. Higher valence ions replacing the lower valence ions is also the likely cause for the significant decrease of the average of ammonium-N at the P301 site (22.0 $\mu mol \cdot cm^{-2}$ for event nutrient fluxes and 4.48 $\mu mol \cdot cm^{-2}$ for the season nutrient flux). With one exception, the ion concentrations did not exceed probe membrane adsorption capacity. The maximum capacity for cation adsorption is approximately 2370 $\mu mol \cdot cm^{-2}$ and for the anions approximately1491

$\mu\text{mol}\cdot\text{cm}^{-2}$ (Western Ag Innovations probe specifications). The P301 site season sample location number 13 had a sum of cation concentrations at 2648 $\mu\text{mol}\cdot\text{cm}^{-2}$ which is 10% higher than the adsorption capacity for the probes. For the event samples the average concentrations for the sum of the nutrient concentrations for cation and anions were 609 $\mu\text{mol}\cdot\text{cm}^{-2}$ and 44 $\mu\text{mol}\cdot\text{cm}^{-2}$, respectively. For the sum of the season nutrient concentrations both cation and anions were 1625 $\mu\text{mol}\cdot\text{cm}^{-2}$ and 98 $\mu\text{mol}\cdot\text{cm}^{-2}$ respectively. The average cation sum of absorption for the probes was 52% lower than the maximum adsorption capacity. The average anion sum of adsorption for the probes was 95% lower than the maximum capacity for the membranes.

The utilization of probes for the determination of hot spots may be useful in a field setting. However, a more efficient method for long term monitoring would be to replace the probes more frequently in the soil to avoid the effects of ion transfer on the membranes. In the Sierra Nevada Mountains, this is not practical due to the persistent winter snowpack.

The resin lysimeter samples detected individual nutrient flux hot spots from the O-horizon. It is noteworthy that not one of these hot spots was in the same location from the first to second year. This suggests that hot spot locations may not last over an extended period of time (multiple years) and biological activity or a change in flow paths may influence duration. McClain et al (2003) describe "hot moments" as hot spots, which occur for shorter durations of time. Therefore, this may indicate that the resin lysimeters demonstrate hot moments as well as hot spots.

CONCLUSIONS

1. The results of this study are consistent with a previous study (Johnson et al., 2011) and indicate that hot spots are present in O-horizons and soils and can be identified by several different resin-based sampling methods. No matter the type of sampling method, inorganic nitrogen, which is the ionic form of the most common limiting nutrient, is the most prominent nutrient hot spot (moderate and extreme outliers) in the King's River soil using resin based sampling methods. Nitrate was the only nutrient to have a consistent significant positive skew for all sampling methods, which supports nitrogen being the most common hot spot found.

2. We have observed evidence of hotspots of varying sizes from the size of a resin capsule (2 cm in diameter) to $40cm^2$; however, the smaller size appears to be more prominent.

3. The resin lysimeter data suggests that the locations of nutrient leaching hotspots are ephemeral (they are hot moments).

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Tables

Table 1: Means and standard errors of concentrations, skew, and t-test P-values for resin capsule data. One set of two capsules were removed after the first precipitation event in early fall (labeled with site name and event) and a final set of two capsules were removed after the entire winter season (labeled with site name and season). The skews that are significant are represented by a (†). The t-tests p-values are comparing event and season nutrient data.

Mean (μmol·cm^{-2})					
Sample Type	Ca^{2+}	Mg^{2+}	NO_3^--N	NH_4^+-N	Ortho-P
Tower Event	3.75 ± 0.69	0.50 ± 0.13	2.98 ± 1.02	1.06 ± 0.33	0.30 ± 0.06
Tower Season	20.36 ± 2.09	2.26 ± 0.26	1.60 ± 0.42	0.86 ± 0.19	0.37 ± 0.06
P301 Event	5.50 ± 0.73	0.70 ± 0.13	1.63 ± 0.61	0.14 ± 0.04	0.31 ± 0.06
P301 Season	22.31 ± 2.08	2.55 ± 0.27	2.61 ± 0.57	0.56 ± 0.06	0.40 ± 0.04
Skew					
Tower Event	†1.48	†1.84	†2.39	†1.82	†1.30
Tower Season	0.740	0.81	†2.27	†1.56	†0.86
P301 Event	†1.22	†2.02	†4.01	†2.79	†2.25
P301 Season	0.31	†1.62	†2.13	0.54	0.53
P-values for t-tests					
Tower	< 0.01	< 0.01	0.11	0.30	0.22
P301	< 0.01	< 0.01	0.12	< 0.01	0.12

Table 2: Coefficient of determination (r^2) for nutrient concentrations from the capsule data. One set of two capsules were removed after the first precipitation event in early fall (labeled with site name and event) and a final set of two capsules were removed after the entire winter season (labeled with site name and season).

Event Capsules

Tower	Ca^{2+}	Mg^{2+}	NO_3^--N	NH_4^+-N	Ortho-P
Mg^{2+}	0.93				
NO_3^--N	0.80	0.83			
NH_4^+-N	0.79	0.84	0.91		
Ortho-P	0.89	0.89	0.77	0.75	
Na^+	0.91	0.86	0.81	0.76	0.80
P301	Ca^{2+}	Mg^{2+}	NO_3^--N	NH_4^+-N	Ortho-P
Mg^{2+}	0.89				
NO_3^--N	0.53	0.74			
NH_4^+-N	0.02	0.02	0.02		
Ortho-P	0.74	0.88	0.80	0.03	
Na^+	0.42	0.38	0.22	0.22	0.35

Season Capsules

Tower	Ca^{2+}	Mg^{2+}	NO_3^--N	NH_4^+-N	Ortho-P
Mg^{2+}	0.81				
NH_4^+-N	< 0.01	0.05			
NO_3^--N	< 0.01	0.01	0.20		
Ortho-P	0.30	0.34	0.30	0.10	
P301	Ca^{2+}	Mg^{2+}	NO_3^--N	NH_4^+-N	Ortho-P
Mg^{2+}	0.65				

NH_4^+-N	0.27	0.66		
NO_3^--N	< 0.01	< 0.01	0.01	
Ortho-P	0.16	0.18	0.13	0.02

Table 3: Means with standard errors, skew, and t-test P-values for the PRS™ probe data. One set of probes (two cation and two anion) were removed after the first precipitation event in early fall (labeled with site name and event) and a final set of two probes were removed after the entire winter season (labeled with site name and season). The skews that are significant are represented by a (†). The P-values for t-tests are comparing event and season nutrient data.

PRS™ Probes	Mean with Standard Error ($\mu mol \cdot cm^{-2}$)					
Site	NO_3^--N	NH_4^+-N	Ca^{2+}	Mg^{2+}	$H_2PO_4^-$-P	K^+
Tower Event	43.37 ± 8.70	19.57 ± 3.28	93.94 ± 11.49	29.70 ± 5.03	5.95 ± 0.62	209.00 ± 26.46
Tower Season	81.64 ± 22.44	26.86 ± 14.0	566.35 ± 27.3	105.87 ± 6.0	13.33 ± 1.43	87.30 ± 20.30
P301 Event	27.11 ± 3.85	22.00 ± 6.54	137.57 ± 9.66	39.39 ± 3.05	6.17 ± 0.61	297.79 ± 25.03
P301 Season	75.17 ± 16.16	4.48 ± 0.38	746.35 ± 24.70	91.33 ± 2.85	19.02 ± 1.54	36.22 ± 7.50
			Skew			
Tower Event	†1.34	†1.96	†1.73	†1.63	0.83	0.51
Tower Season	†2.77	†5.47	-0.39	0.30	†1.66	†2.93
P301 Event	†1.78	†4.05	0.54	0.40	†1.89	0.12
P301 Season	†3.06	†2.20	†0.87	†0.87	†1.06	†2.81
			T-Test P-values			
Tower	0.06	0.31	<0.01	<0.01	<0.01	<0.01

P301	< 0.01	<0.01	<0.01	<0.01	<0.01	<0.01

Table 4: Coefficient of determination (r^2) for nutrient concentrations from the PRS™ probe data. One set of probes (two cation and two anion) were removed after the first precipitation event in early fall (labeled event) and a final set of two probes were removed after the entire winter season (labeled season).

R^2 Values for Event Probes

Tower	NO_3^--N	NH_4^+-N	Ca^{2+}	Mg^{2+}	K^+
NH_4^+-N	0.17				
Ca^{2+}	0.55	0.01			
Mg^{2+}	0.61	0.04	0.89		
K^+	0.39	0.04	0.66	0.81	
$H_2PO_4^-$-P	0.12	0.01	0.23	0.20	0.26
P301	NO_3^--N	NH_4^+-N	Ca^{2+}	Mg^{2+}	K^+
NH_4^+-N	0.06				
Ca^{2+}	<0.01	<0.01			
Mg^{2+}	0.05	0.02	0.77		
K^+	0.13	0.01	0.37	0.65	
$H_2PO_4^-$-P	0.04	0.04	0.15	0.08	0.07

R^2 Values for Season Probes

Tower	NO_3^--N	NH_4^+-N	Ca^{2+}	Mg^{2+}	K^+
NH_4^+-N	<0.01				
Ca^{2+}	0.10	0.01			
Mg^{2+}	0.09	0.04	0.05		
K^+	0.02	0.01	0.40	0.01	
$H_2PO_4^-$-P	0.01	0.01	0.26	0.16	0.04
P301	NO_3^--N	NH_4^+-N	Ca^{2+}	Mg^{2+}	K^+
NH_4^+-N	0.03				
Ca^{2+}	0.01	0.02			
Mg^{2+}	0.13	<0.01	<0.01		
K^+	0.02	0.06	0.20	0.06	
$H_2PO_4^-$-P	0.02	0.00	0.05	0.01	0.05

Table 5: Means, standard errors and skew for resin lysimeter data from the 2009-2010 and 2010-2011 winter seasons (September-June) resin lysimeters nutrient data in $kg \cdot ha^{-1}$. The skews that are significant are represented by a (†).

	Winter Season 2009-2010					Winter Season 2010-2011				
Site	NO_3^--N	NH_4^+-N	Ortho-P	Ca^{2+}	Mg^{2+}	NO_3^--N	NH_4^+-N	Ortho-P	Ca^{2+}	Mg^{2+}
Average with Standard Error										
Tower	3.01 ± 1.02	2.51 ± 0.35	3.38 ± 1.19	83.54 ± 37.59	15.97 ± 4.23	5.79 ± 1.50	2.45 ± 1.65	13.64 ±2.85	106.42 ± 18.21	23.43 ± 3.60
P301	7.50 ± 2.32	6.88 ± 3.45	1.80 ± 0.63	47.92 ± 7.38	18.87 ± 2.62	9.59 ± 3.35	3.62 ± 2.29	6.18 ± 1.33	43.58 ± 7.87	12.66 ± 2.25
Skew										
Tower	†1.48	†1.39	†1.34	†3.26	†1.91	†1.23	†3.92	0.86	0.79	0.77
P301	†1.72	†3.20	†2.70	0.46	0.43	†2.98	†3.72	0.14	0.59	0.72

Figures

Figure 1: Site location map for the King's River Experimental Watershed (KREW). The map was taken from the Southern Sierra Critical Zone Observatory (CZO) website (https://eng.ucmerced.edu/czo/sites.html).

Figure 2: Schematic of the grid layout for sample locations of the UniBest® resin capsules and the PRS™ probes (resin stakes). Four resin stakes (S; two cation and two anion) and four capsules (C) were installed at every other internode along alternating grid rows. Two of the capsules and one each of the cation and anion resin stakes at each sampling point were removed for analysis after the first large precipitation event, totaling 26cm in 48 hours, in October with the remaining removed the following summer.

Figure 3: Nutrient concentrations of ammonium-N and nitrate-N in $\mu mol{\cdot}cm^{-2}$ for the resin capsules from the respective grid point location at each study site. On the x-axis is nutrient concentration, and on the y-axis is sample location. Hot spots are recognized by moderate outliers with a circle (O) above the bar and extreme outliers with an asterisk (*) above the bar. The light grey bars are the season samplers dark grey bars are the event samplers.

Figure 4: Nutrient concentrations for calcium and magnesium in $\mu mol{\cdot}cm^{-2}$ for the resin capsules from the respective grid point location at each study site. On the x-axis is nutrient concentration, and on the y-axis is sample location. Hot spots are recognized by

moderate outliers with a circle (O) above the bar and extreme outliers with an asterisk (*) above the bar. The light grey bars are the season samplers dark grey bars are the event samplers.

Figure 5: Nutrient concentrations for orthophosphate in $\mu mol \cdot cm^{-2}$ for the resin capsules from the respective grid point location at each study site. On the x-axis is nutrient concentration, and on the y-axis is sample location. Hot spots are recognized by moderate outliers with a circle (O) above the bar and extreme outliers with an asterisk (*) above the bar. The light grey bars are the season samplers dark grey bars are the event samplers.

Figure 6: Nutrient concentrations for nitrate-N and ammonium-N in $\mu mol \cdot cm^{-2}$ for the resin PRS™ probes from the respective grid point location at each study site. On the x-axis is nutrient concentration, and on the y-axis is sample location. Hot spots are recognized by moderate outliers with a circle (O) above the bar and extreme outliers with an asterisk (*) above the bar. The light grey bars are the season samplers dark grey bars are the event samplers.

Figure 7: Nutrient concentrations for calcium and magnesium in $\mu mol \cdot cm^{-2}$ for the resin PRS™ probes from the respective grid point location at each study site. On the x-axis is nutrient concentration, and on the y-axis is sample location. Hot spots are recognized by moderate outliers with a circle (O) above the bar and extreme outliers with an asterisk (*) above the bar. The light grey bars are the season samplers dark grey bars are the event samplers.

Figure 8: Nutrient concentrations for phosphate-P and potassium in μmol·cm^{-2} for the resin PRS™ probes from the respective grid point location at each study site. On the x-axis is nutrient concentration, and on the y-axis is sample location. Hot spots are recognized by moderate outliers with a circle (O) above the bar and extreme outliers with an asterisk (*) above the bar. The light grey bars are the season samplers dark grey bars are the event samplers.

Figure 9: Nutrient concentrations for nitrate-N and ammonium-N in kg·ha^{-1} for the resin lysimeters from the 2009-2010 and 2010-2011 winter seasons (September-June) from the respective grid point location at each study site. 16 lysimeters were placed in a 4x4 meter grid and after one year they were removed and a second set was put in the same location for another year to look at temporal variation. On the x-axis is nutrient concentration, and on the y-axis is sample location. Hot spots are recognized by moderate outliers with a circle (O) above the bar and extreme outliers with an asterisk (*) above the bar. The light grey bars are the season samplers dark grey bars are the event samplers.

Figure 10: Nutrient concentrations for calcium and magnesium in kg·ha^{-1} for the resin lysimeters from the 2009-2010 and 2010-2011 winter seasons (September-June) from the respective grid point location at each study site. 16 lysimeters were placed in a 4x4 meter grid and after one year they were removed and a second set was put in the same location for another year to look at temporal variation. On the x-axis is nutrient concentration, and on the y-axis is sample location. Hot spots are recognized by moderate outliers with a

circle (O) above the bar and extreme outliers with an asterisk (*) above the bar. The light grey bars are the season samplers dark grey bars are the event samplers.

Figure 11: Nutrient concentrations for orthophosphate in kg·ha^{-1} for the resin lysimeters from the 2009-2010 and 2010-2011 winter seasons (September-June) from the respective grid point location at each study site. 16 lysimeters were placed in a 4x4 meter grid and after one year they were removed and a second set was put in the same location for another year to look at temporal variation. On the x-axis is nutrient concentration, and on the y-axis is sample location. Hot spots are recognized by moderate outliers with a circle (O) above the bar and extreme outliers with an asterisk (*) above the bar. The light grey bars are the season samplers dark grey bars are the event samplers.

Figure 1

Figure 2

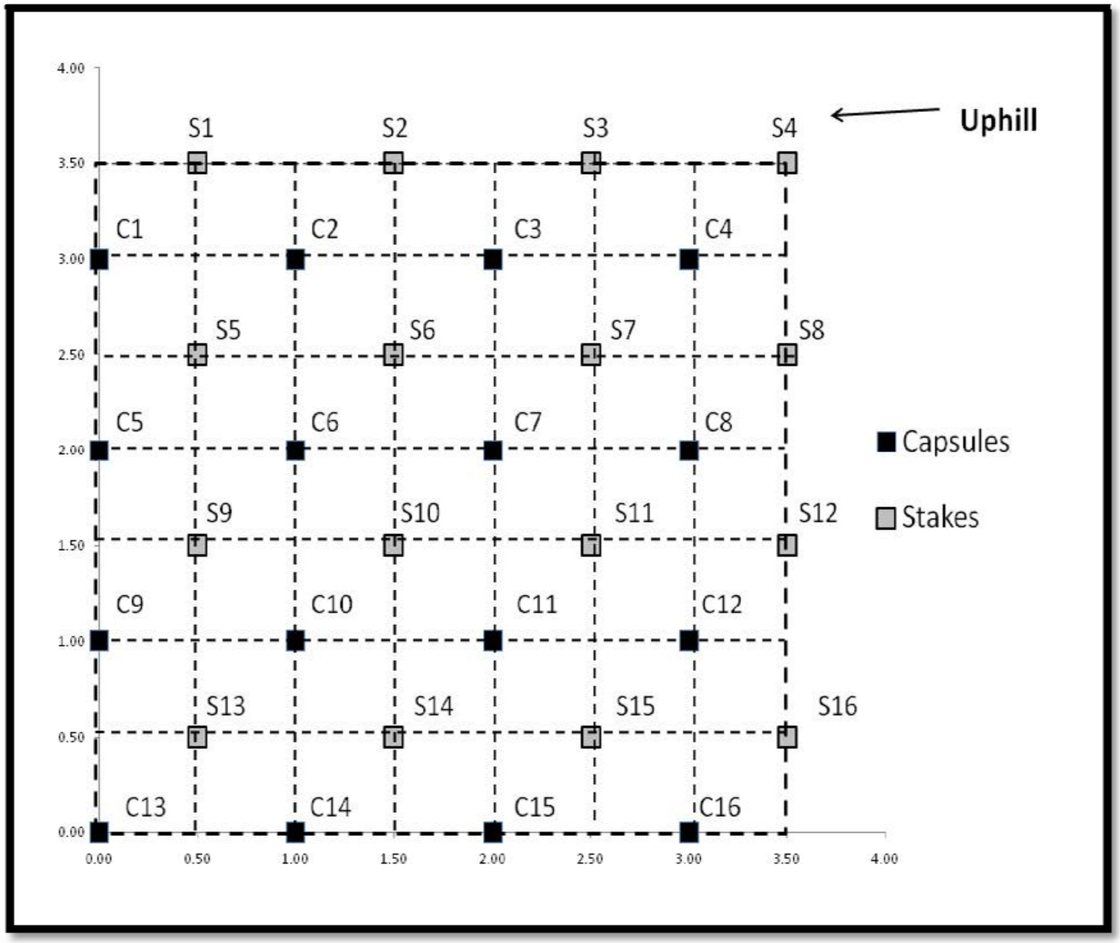

4.00
3.50
3.00
2.50
2.00
1.50
1.00
0.50
0.00
0.00
0.50
1.00
1.50
2.00
2.50
3.00
3.50
4.00
S1
S2
S3
S4
Uphill
C1
C2
C3
C4
S5
S6
S7
S8
C5
C6
C7
C8
Capsules
S9
S10
S11
S12
Stakes
C9
C10
C11
C12
S13
S14
S15
S16
C13
C14
C15
C16

Figure 3

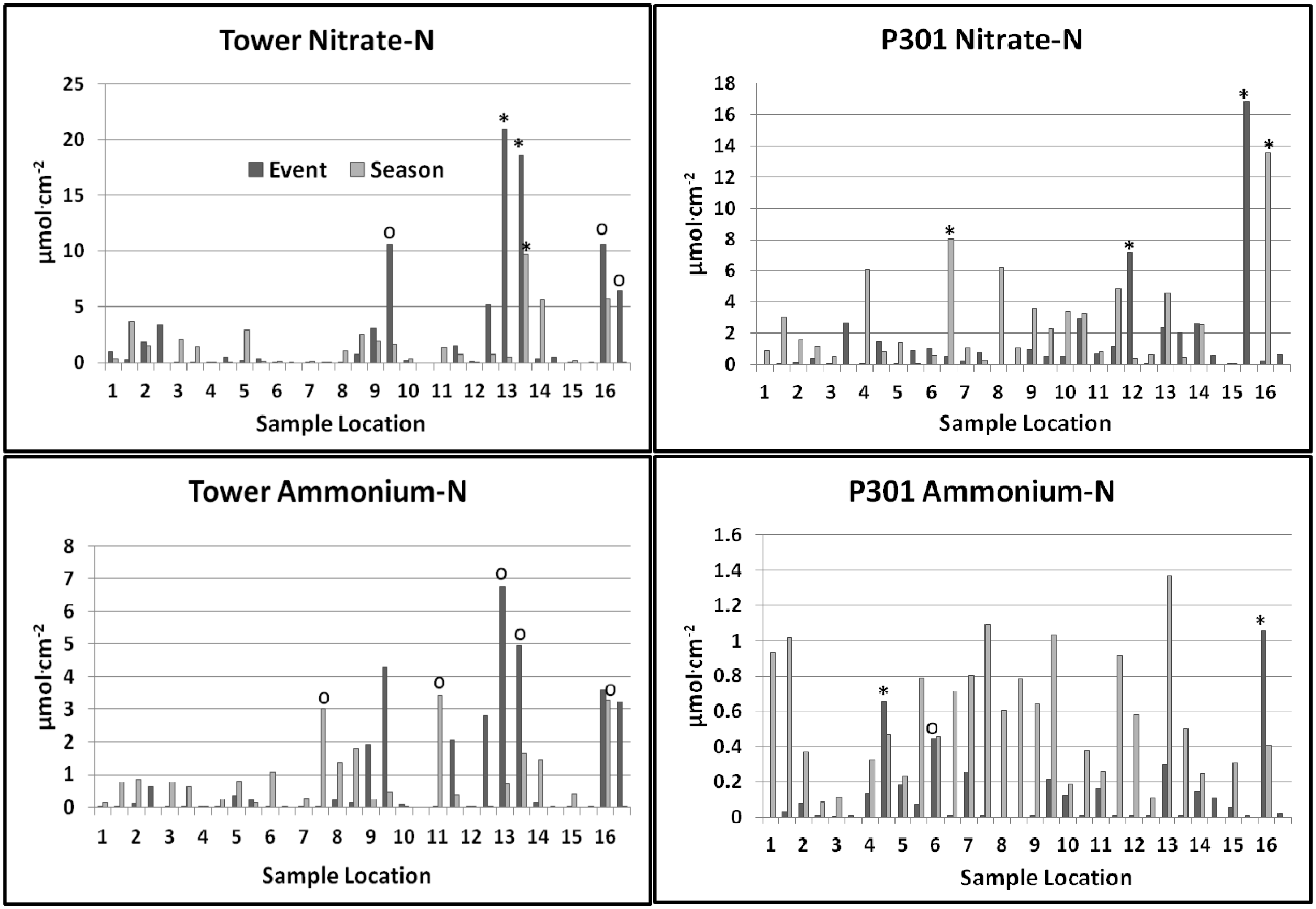

Tower Nitrate-N
25
20
15
10
5
0
µmol·cm^{-2}
Event
Season
*
*
*
o
o
o
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16
Sample Location
P301 Nitrate-N
18
16
14
12
10
8
6
4
2
0
µmol·cm^{-2}
*
*
*
*
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16
Sample Location
Tower Ammonium-N
8
7
6
5
4
3
2
1
0
µmol·cm^{-2}
o
o
o
o
o
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16
Sample Location
P301 Ammonium-N
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
µmol·cm^{-2}
*
*
o
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16
Sample Location

Figure 4

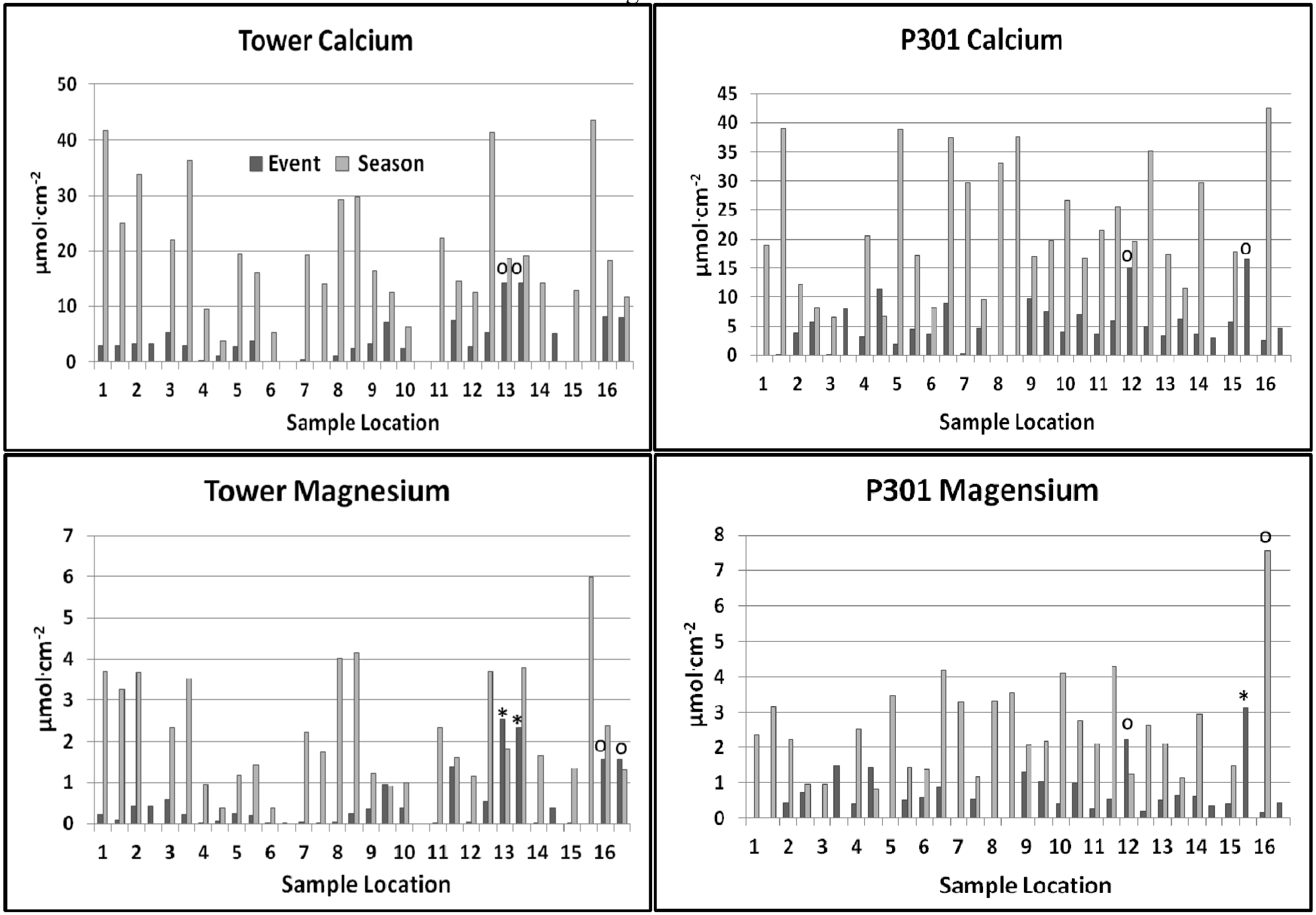

Tower Calcium
μmol·cm⁻²
0
10
20
30
40
50
■ Event ■ Season
o o
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16
Sample Location
P301 Calcium
μmol·cm⁻²
0
5
10
15
20
25
30
35
40
45
o
o
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16
Sample Location
Tower Magnesium
μmol·cm⁻²
0
1
2
3
4
5
6
7
* *
o o
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16
Sample Location
P301 Magensium
μmol·cm⁻²
0
1
2
3
4
5
6
7
8
o
o
*
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16
Sample Location

Figure 5

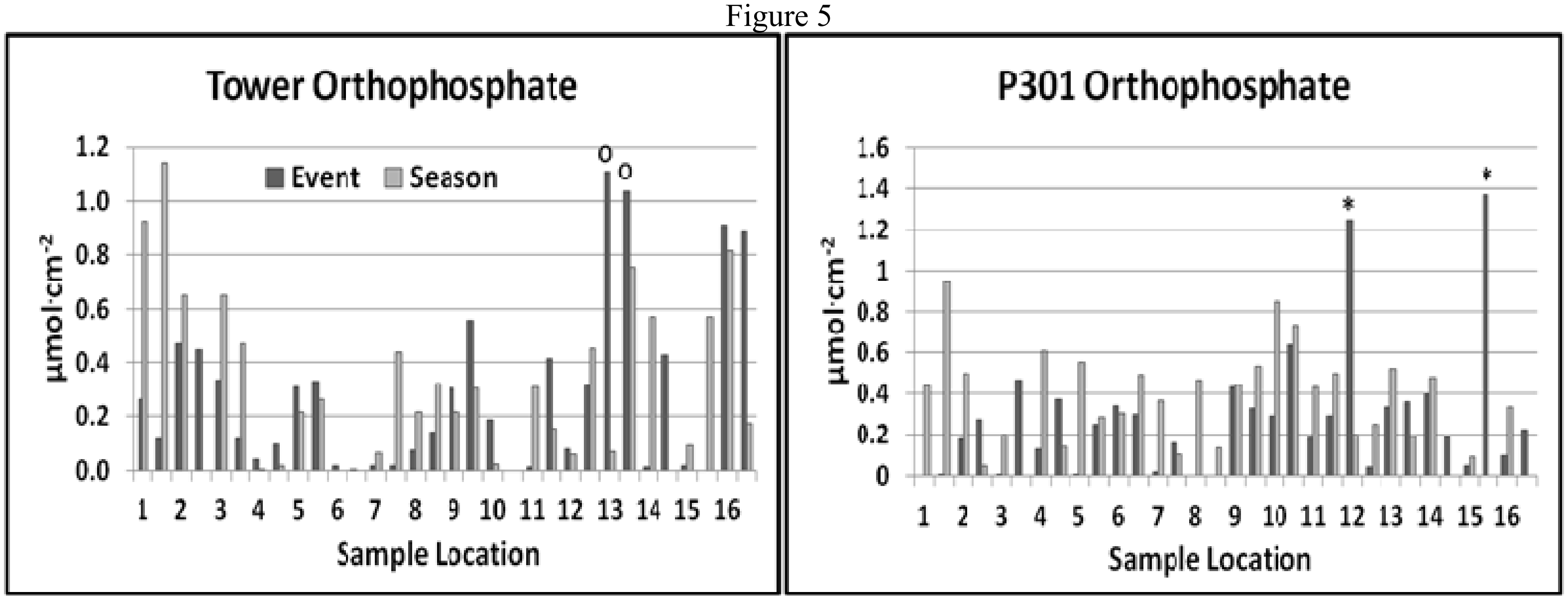

Tower Orthophosphate
Event
Season
µmol·cm⁻²
1.2
1.0
0.8
0.6
0.4
0.2
0.0
o
o
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16
Sample Location
P301 Orthophosphate
µmol·cm⁻²
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
*
*
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16
Sample Location

Figure 6

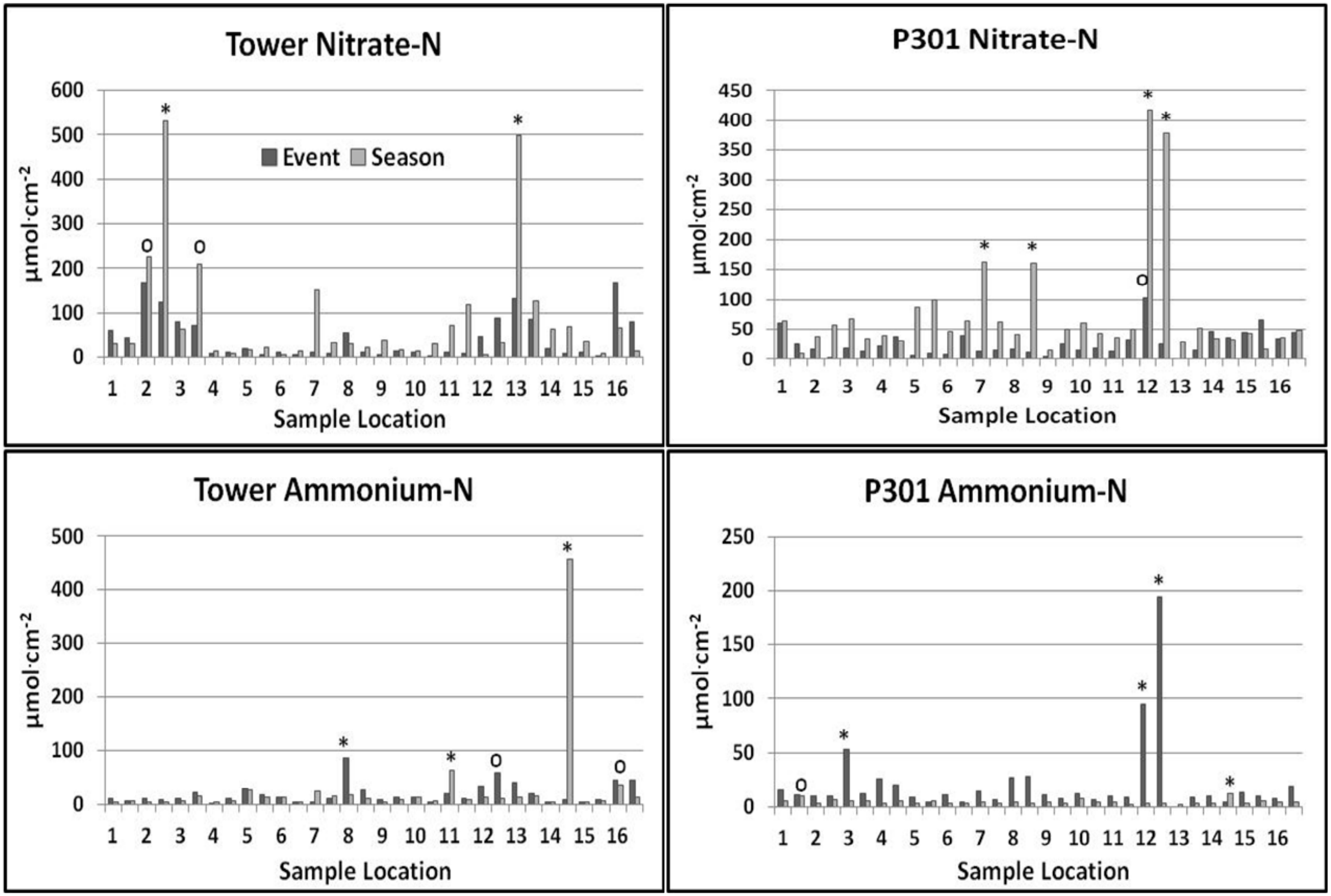

Tower Nitrate-N
µmol·cm-2
600
500
400
300
200
100
0
■ Event ■ Season
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16
Sample Location
P301 Nitrate-N
µmol·cm-2
450
400
350
300
250
200
150
100
50
0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16
Sample Location
Tower Ammonium-N
µmol·cm-2
500
400
300
200
100
0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16
Sample Location
P301 Ammonium-N
µmol·cm-2
250
200
150
100
50
0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16
Sample Location

Figure 7

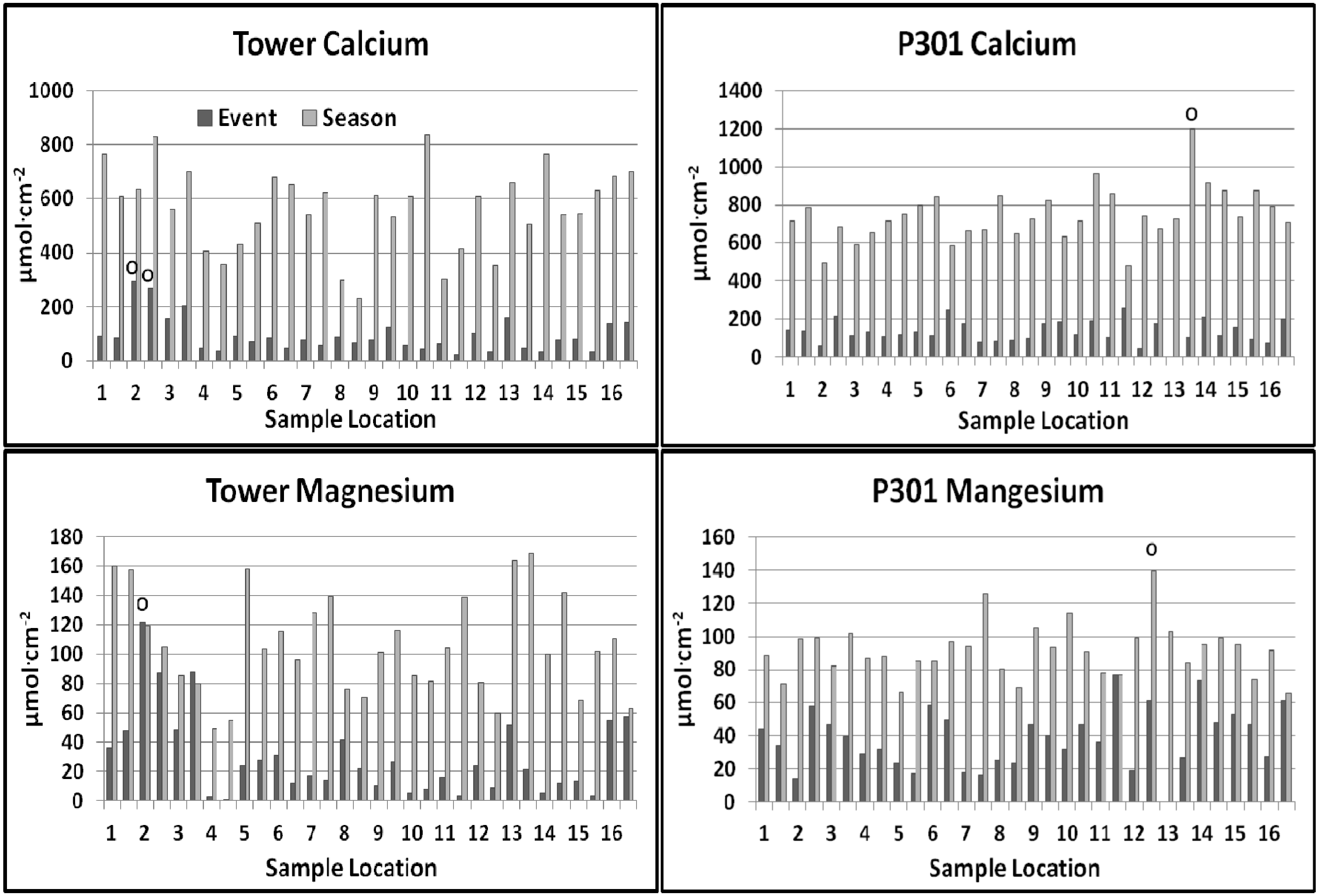
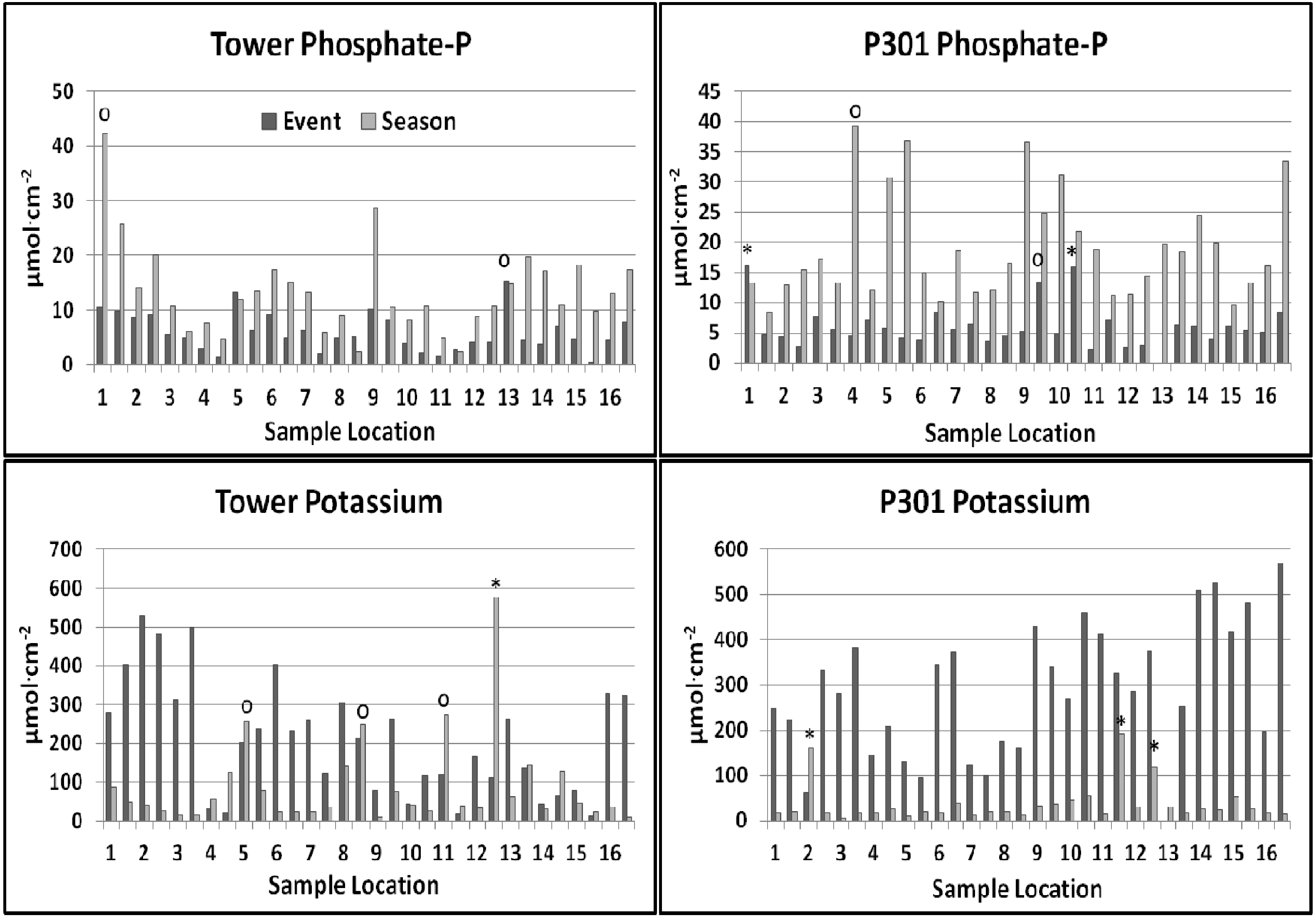

Tower Calcium
Event
Season
1000
800
600
400
200
0
µmol·cm⁻²
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16
Sample Location
P301 Calcium
1400
1200
1000
800
600
400
200
0
µmol·cm⁻²
Sample Location
Tower Magnesium
180
160
140
120
100
80
60
40
20
0
µmol·cm⁻²
Sample Location
P301 Mangesium
160
140
120
100
80
60
40
20
0
µmol·cm⁻²
Sample Location

Figure 8



Tower Phosphate-P

P301 Phosphate-P

Tower Potassium

P301 Potassium

Figure 9

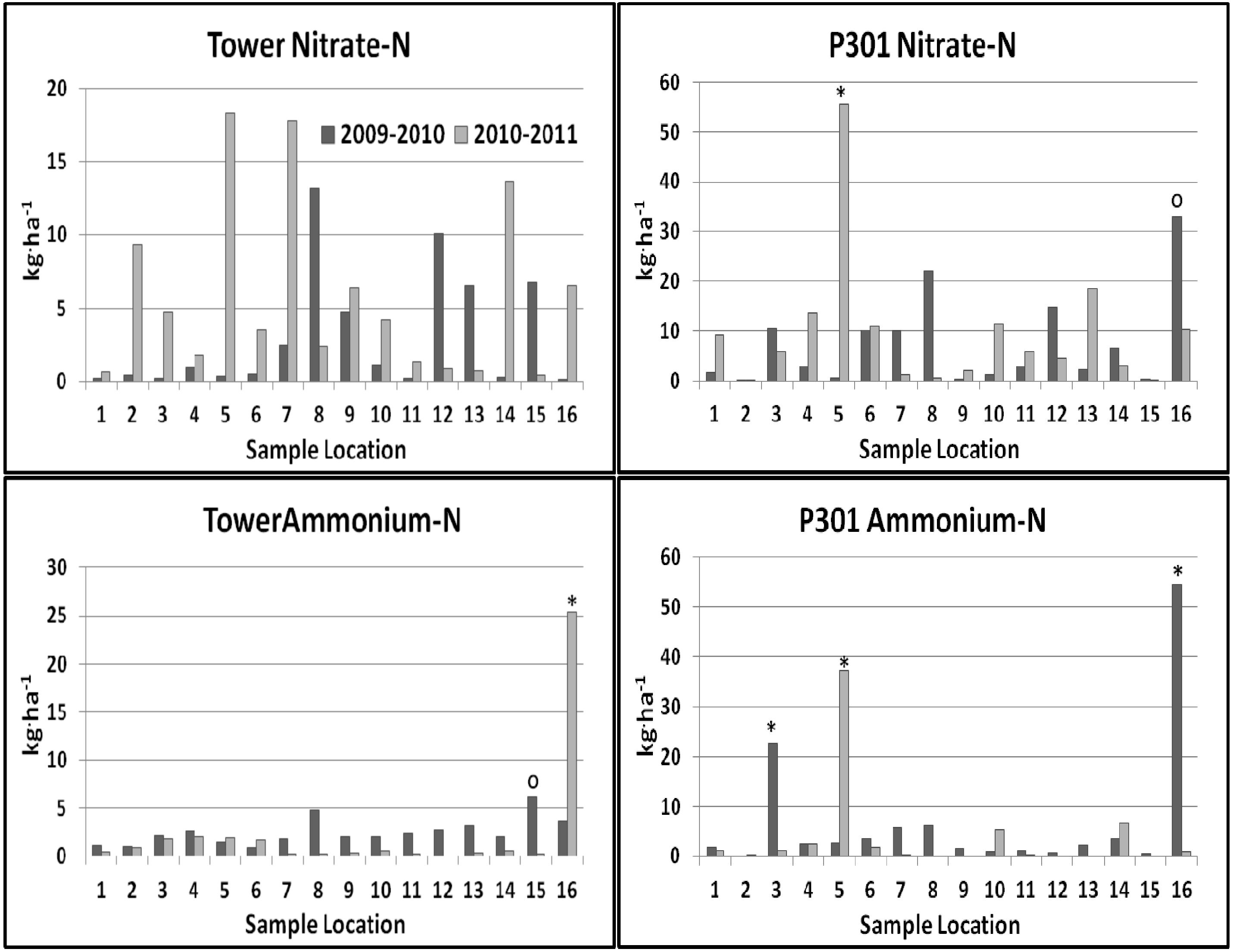

Tower Nitrate-N
kg·ha-1
0
5
10
15
20
2009-2010
2010-2011
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16
Sample Location
P301 Nitrate-N
kg·ha-1
0
10
20
30
40
50
60
*
o
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16
Sample Location
TowerAmmonium-N
kg·ha-1
0
5
10
15
20
25
30
o
*
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16
Sample Location
P301 Ammonium-N
kg·ha-1
0
10
20
30
40
50
60
*
*
*
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16
Sample Location

Figure 10

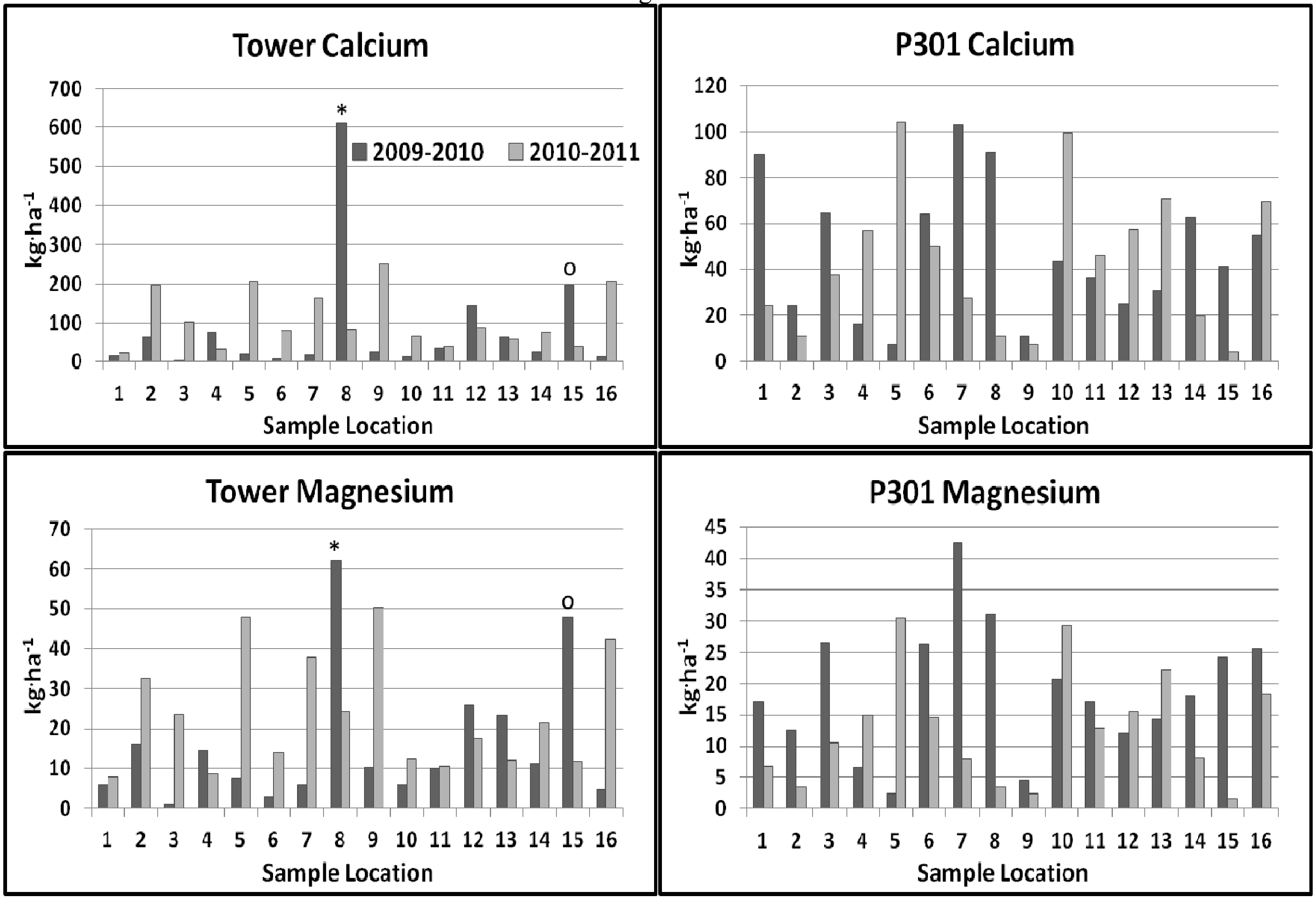
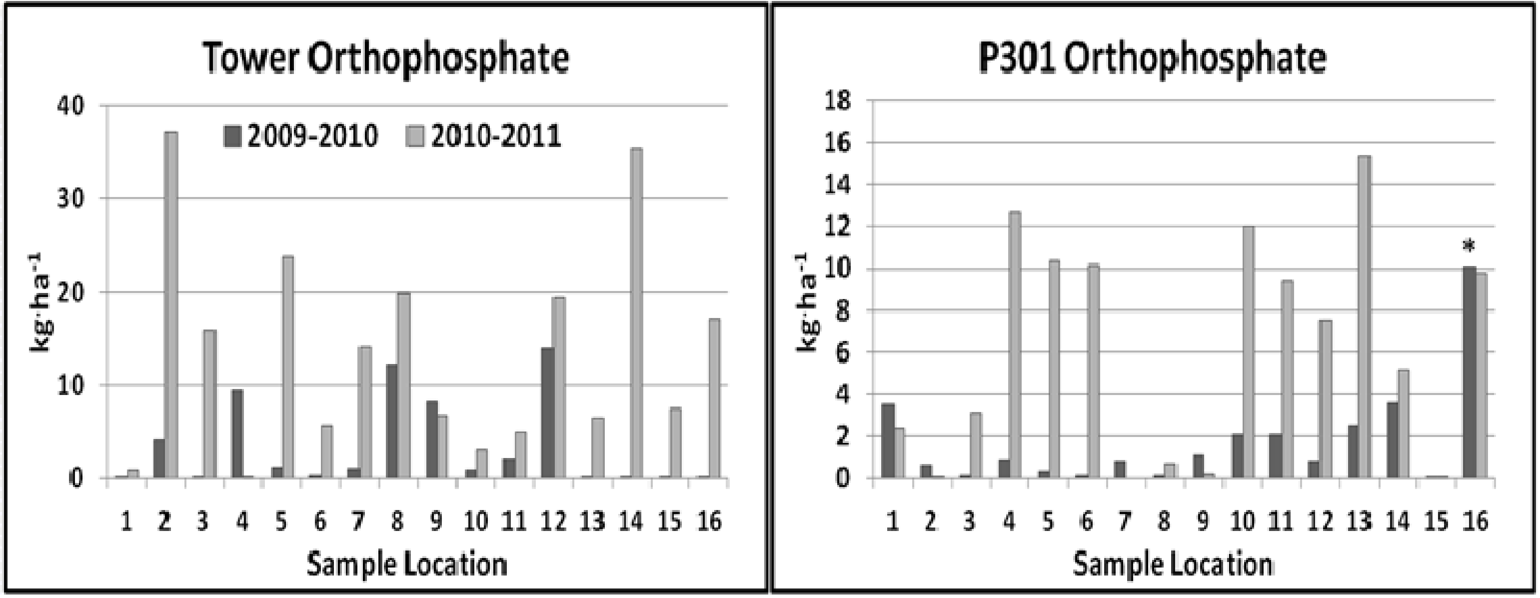

Tower Calcium
700
600
500
400
300
200
100
0
kg·ha^{-1}
*
o
2009-2010
2010-2011
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16
Sample Location
P301 Calcium
120
100
80
60
40
20
0
kg·ha^{-1}
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16
Sample Location
Tower Magnesium
70
60
50
40
30
20
10
0
kg·ha^{-1}
*
o
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16
Sample Location
P301 Magnesium
45
40
35
30
25
20
15
10
5
0
kg·ha^{-1}
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16
Sample Location

Figure 11


Tower Orthophosphate
P301 Orthophosphate
2009-2010
2010-2011
kg·ha-1
0
10
20
30
40
0
2
4
6
8
10
12
14
16
18
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16
Sample Location
*

Chapter Two

Nutrient hot spots in a Sierra Nevada forest soil: II. Relations to microbial communities

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ABSTRACT

Meter scale grids were established at two locations (upper elevation Tower and mid-elevation P301) in the King's River Experimental Watershed on the west side of the Sierra Nevada Mountains to investigate the presence and status of soil nutrient hot spots and microbial communities. Cores of O-horizons and surface mineral soils were taken at each of 16 grid points in two 4 x 4 m plots and analyzed for total C and N, water extractable nutrients and microbial biomass in the mineral soil. Hot spots were identified by positive skew and extreme and moderate statistical outliers. Water extractable nitrate was the most common hot spot found. Nitrate hot spots were commonly observed in locations of lower concentrations for other nutrients. One sample point in the P301 site had hot spots for all the nutrients in the mineral soil with the exception of calcium, but calcium concentrations were highest at this point as well. This particular sample point also had the highest microbial biomass amounts and hot spots for phosphate and magnesium were observed in the O-horizon directly overlying this point as well. No such trend was evident at the Tower site even though nutrient hotspots were observed. Water-extractable nutrient hot spots observed in the O-horizons and mineral soils correlated with microbial biomass at only one site. Thus, we conclude that microbial biomass and nutrient hot spots cannot always account for each other.

Key Words: Soils, Nutrients, Hot Spots, Sierra Nevada Mountains, Microbes

INTRODUCTION

Soil nutrient heterogeneity on a local scale is an important aspect of the soil system and plays crucial roles in maintaining the biodiversity of a landscape (Schimel and Bennet 2004; Johnson 2011). Inorganic nutrient hot spots have been shown to exist in the west side the Sierra mountains (Johnson et al. 2011) and are believed to aid plants outcompete microbes and a key function in the biogeochemical cycling of nutrients (McClain et al. 2003; Schimel and Bennet 2004; Johnson et al. 2011).

The climate for western Sierra Nevada consists of dry warm summers and cold winters, where the precipitation is dominated by snow. The dry summers cause the soils in the Sierra to become hydrophobic leading to preferential flow paths in the mineral soil (Miller et al. 2005). There are three main different types of preferential flow, finger (or column), macropore, and funnel flow. Finger flow, which is the most prominent type of preferential flow, is often caused by spatial heterogeneity of water repellency in a soil (Dekker 1994; Jury et al. 2004; Morales 2010). Hardie et al. (2011) found hydrophobicity-induced finger flow was much more prominent than finger flow produced in soils with higher antecedent moisture content. Organic carbon and nitrogen have been shown to be enriched in preferential flow paths when compared to the surrounding soil matrix (Bundt et al. 2001). The majority of the decomposition of the organic matter for the western Sierra Nevada’s climate takes place beneath the snow pack (Stark 1973). During this process, it is likely that the decomposition is increasing the amount of available nutrients in the soil, which can enhance nutrient transport. The buildup of forest floor organic matter is hypothesized to enrich soil nutrient pools and to be a source for soluble nutrient transport (Miller et al. 2005; Johnson et al. 2009). This suggests that the preferential flow paths could be carrying organic colloids and nutrients from the surface into the mineral soil. These preferential flow paths containing enriched amounts of nutrients could have an influence on the formation of hot spots in the mineral soil.

Much like soil nutrients, microbial communities are also an important component of a soil system. Microbes help with decomposition, mineralizing nitrogen, and they heavily influence the biogeochemical cycles within a soil matrix. Forested systems are more dependent on microbial mediated processes than agricultural systems (Moore-Kucera 2007). This is especially true for forested systems such as the Sierra Nevada's where decomposition and nutrient cycling can be limited to times of snowpack and snowmelt. Therefore, understanding the processes that can influence microbial communities is increasingly important in forested systems. Factors affecting microbial activity in the soil include soil chemistry and preferential flow paths (Williamson et al. 2005; Hackl et al. 2005; Zhang 2005). Preferential flow paths have been shown to stimulate the development of biological zones of elevated activity (hot spots) in the soil (Morlaes 2010). At locations of preferential flow, Bundt et al. (2001) found carbon contents that were 10-70% higher, as well as elevated levels of organic nitrogen, CEC, and base saturation levels compared to the surrounding soil. Since preferential flow paths in the form of finger flow could have an influence on the formation of soil hot spots and microbial activity, there may be observable trends between microbial activity and hot spots in the mineral soil.

In a previous paper, Johnson et al. (2011), reported on the occurrence of nutrient hotspots in soil cores taken from two locations in the King's River Experimental

Watershed (KREW). They found more abundant nutrient hotspots in both O-horizons and soils with water extractions than with stronger extractions, such as KCl, or total analyses showing that water-extractable nutrients are a viable method for hot spot determination (Johnson et al. 2011). They found no correlations between such hotspots and soil organic carbon, nor were hotspots in mineral soils spatially associated with those in overlying O-horizons. They speculated that the presence of a single hotspot for all water-soluble nutrients in the mineral soil was the result of preferential flow from nutrient-rich waters from the overlying O-horizon. In Chapter 1 of the thesis, we found that hotspots for water soluble nutrients were ephemeral; i.e., hotspots for the fall were in different locations than those for the winter season.

An unknown in the previous study was the potential role of microbial activity, and that is one thrust of the current study. The objective of this research was assess the abundance of water extractable nutrient hot spots in the soil and two possible influencing factors, microbes and runoff. To test this, soil core samples were extracted from meter sized grids at each site. The soil cores were analyzed for nutrient hot spots and microbial biomass in the mineral soil at two field sites at KREW. Runoff solute concentrations were measured for one year before soil cores were extracted.

METHODS AND MATERIALS

Study Site Description

The King's River Experimental Watershed (KREW) (located on the western side of the Sierra Nevada Mountains) approximately 105 km northeast of Fresno, California in Fresno County, was established in 2000 to promote the understanding of headwaters in ecosystems and the effects of forest management practices that are used to increase the health of a forest (Figure 1). The Southern Sierra Critical Zone Observatory (CZO) is co-located at KREW and used as an environmental laboratory to study the physical, chemical, and biological processes of the earth's surface. KREW is characterized by warm dry summers and cold winters, where most of the precipitation occurs as snow. The mean annual temperature is 8°C. The mean annual precipitation is ~137 cm and annual snowfall ranges from 100-300 cm for the area (Hunsaker 2012). The vegetation for the site is a mixed conifer forest composed of sugar pine (*P. lambertiana Douglas*), ponderosa pine (*Pinus ponderosa Lawson and C. Lawson*), incense-cedar (*Calocedrus decurrens (Torr.) Florin*) and white fir (*Abies concolor (Gord. & Glend.) Lindl. ex Hildebr*). The understory consists of unidentified brush species, green leaf manzanita (*Arctostaphylos patula Greene*), and squawcarpet (*Ceanothus prostratus Benth*). The soil is a Shaver series; a coarse-loamy, mixed mesic Pachic Xerumbrept derived from granite (Johnson et al 2011).

Two field sites were chosen for study. Site one (Tower site) is at an elevation of 1980 meters, Latitude: 37° 3' 33.626" N Longitude: 119° 10' 56.184" W. Site two (P301) is at a lower elevation, 1910 meters, Latitude: 37° 3' 46.649" N Longitude: 119° 12' 3.844" W. Both sites have similar soil and vegetation; however site two has nearly 100% canopy closure.

Three runoff collectors were installed at each site and collected samples were analyzed for nutrient concentrations at indiscriminate time intervals for one year. After one year soil core samples were taken at 16 grid points one meter apart at each field site near the locations of the runoff collectors (Figure 2). The O-horizon was separated and analyzed for water extractable nutrients and total carbon and nitrogen. The mineral soil was analyzed for microbial communities using phospholipids fatty acids (PLFA) analysis, water extractable nutrients and total carbon and nitrogen.

Sampling and Analysis

Runoff collectors were installed at each site as described by Miller et al (2005). The collectors are designed to collect interstitial flow from the O-horizon, just above the surface of the mineral soil. Soil solution interflow samples were collected when accessible throughout the sampling year. The total amount of solution was extracted from the samplers and recorded. From each collection, an aliquot was frozen and shipped to the University of Nevada Reno soils lab. The aliquot was filtered and analyzed on a Dionex ICS-3000 ion chromatograph for nitrite, sulfate, nitrate, phosphate, sodium, ammonium, potassium, magnesium, calcium and chloride.

Due to site access, runoff collections were randomly obtained. The collection dates for the season were 15th October 2009, 5th January 2010, 23rd March 2010, 4th April 2010, 23rd April 2010, and 8th June 2010. On 23rd of April 2010, only one collector contained solute, which was Tower-3. During the sampling interval between 6th of April, 2010 and 23rd of April 2010, there was about 15 cm of precipitation; however, in spring when the snow melt is the highest, the soils were likely not hydrophobic because the excess snow melt would infiltrate decreasing hydrophobicity. This would decrease O-horizon interflow and allow the precipitation to penetrate directly into the soil.

Soil core samples were taken using the same protocols as in the previous study (Johnson et al., 2011) using a slide hammer auger from a 4x4 meter grid at one meter intervals, for a total of 16 grid points. Nitrile gloves were worn at all times and all equipment was washed with 95% ethanol between samples to prevent sample contamination for microbial analyses. The cores were separated into the O-horizon and mineral soil in the field.

A mineral soil subsample from each of the 16 cores was taken and immediately processed and frozen for microbial analysis. The frozen samples were shipped overnight in dry ice to the Scow Soil Microbial Ecology Lab at UC Davis, CA for Phospholipids Fatty Acid Analysis (PLFA). The remaining soil samples were dried in Lindberg/Blue M Stabil-Therm Mechanical Convection Oven with the organic samples being dried at 45°C and mineral samples at 55°C for a minimum of 24 hours. Once the samples were dried, they were immediately weighed. The mineral samples were sieved to the 2mm fraction and homogenized. Five homogenized grams of each sample were extracted for 1 hour with 40 mL of deionized water on a Sampletek^{tm} programmable vacuum extractor, Model 24VE. The extract was then analyzed in the University of Nevada Reno soils lab using the Dionex ICS-3000 ion chromatograph which runs Chromeleon® software for nitrate, phosphate, ammonium, magnesium, and calcium. Subsamples of the mineral soil were analyzed at Oklahoma State University Soil, Water and Forage Laboratory (SWFAL) on a dry combustion C and N analyzer (LECO) for total carbon and nitrogen concentrations.

Data Analysis

The data was analyzed for extreme and moderate outliers using the program DataDesk (Velleman 1997). Linear regression determining the coefficients of determination (r^2) was done comparing the water flux to individual nutrient concentrations and total microbial biomass to individual nutrient concentrations.

DataDesk defines positive and extreme outliers as:

Extreme outliers:

$X > Q_3 + 3 \times IQR$

Moderate outliers

$X > Q_3 + 1.5 \times IQR$

x = the value

Q_3 = the third quartile value (75th percentile), and

IQR = interquartile range (range from 25th to 75th percentile)

Skewness Values were determined as:

$Skew=M_3/M_2^{3/2}$

where

$M_2=\sum(yi-\bar{y})^2/n$

$M_3=\sum(yi-\bar{y})^3/n$

$\bar{y}$ = sample mean

M_2 = variance

M_3 = third moment of the data

Skewness was calculated in excel and is defined as the characterization of the asymmetry of a distribution around its mean (Brown 1997). A skewness value is considered significant if it is equal to or greater than twice the standard error (Brown 1997). For smaller data sets it is more reasonable to use the standard error of the skewness *(ses)* developed by Routledge, 1997 (Brown 2012). We calculated *ses* using the following equation:

$$SES = \sqrt{\frac{6\mathrm{N}(\mathrm{N}-1)}{(\mathrm{N}-2)(\mathrm{N}+1)(\mathrm{N}+3)}}$$

RESULTS

O-horizon Interflow

O-horizon interflow was observed at both sites during the 2009-10 snow season (September 2009 to June 2010) with interflow collectors which was also noted in the previous study (Johnson et al 2011). The Tower site collected a substantially greater volume of interflow solute than the P301 site (Table 1). This may be due to micro-site differences or the increased canopy cover at the P301 site. There was a high degree of variability in the maximum values for each nutrient. The runoff data for each site showed that the P301 site had significantly higher concentrations for magnesium, and calcium (P-value for t-tests 0.01 and <0.01 respectively). A comparison of the individual nutrient concentrations and water flux show a strong positive correlation ($r^2>0.5$) at the P301 site for ammonium, magnesium, and calcium (Table 2). No such trend was noticed at the Tower site. Multiplying the water flux to the nutrient concentration showed that the Tower site had significantly (t-test $P<0.05$) more nutrients collected over the season due to the significantly higher water flux.

Soil Extraction and Microbial Communities

Extreme or moderate outliers were found for all nutrients except water extractable ammonium and calcium in the O-horizon (Figures 3-9). Water extractable nitrate was the only nutrient with an extreme outlier for both soil types and sites. The water extractable nitrate outliers were not co-located with any other nutrient outlier except at mineral soil point five for the P301 site which also had the most outliers for both the mineral soil and O-horizon data sets. Nitrate outliers were more commonly associated with substantially lower concentrations of the other nutrients. The only extreme ammonium outlier was located in the P301 mineral soil. Tower sample point six nutrient data had a moderate outlier or highest concentration for the phosphate, chloride, calcium, and magnesium data in the O-horizon (Figures 3, 6). The Tower sampling point 11 in the mineral soil had an extreme outlier for total nitrogen, and moderate outliers for total carbon, sodium, chloride, and calcium data (Figure 4, 5). For the P301 site, sampling point five nutrient data had either an extreme, moderate, or highest concentration for all nutrients except for sodium in both soil types, nitrate, chloride, and calcium in the O-horizon, as well as the C:N ratio in the mineral horizon. There appears to be an observable trend of higher nutrient concentrations at sampling point five for the P301 site (Figures 6-9).

There were no nutrients that showed a significant positive skew for both sites and soil type (Table 3). For water extractable nutrient data, nitrate and phosphate had the most significant positive skews at three each. The phosphate data showed significant positive skews for all sites and both the O-horizon and mineral horizon, with the exception of the Tower O-horizon samples. Nitrate in the mineral soil at the Tower site was the only nutrient that did not show a significant positive skew. The calcium data exhibited no significant skews at either site or soil material. The ammonium and magnesium data demonstrated only one significant positive skew each. The significant skew for the ammonium data was located at the P301 site in the mineral soil, which also showed a significant positive skew for nitrate, phosphate, sodium and chloride. The significant skew for the magnesium data was located at the Tower site in the mineral soil. Sodium and chloride both exhibited a negative skew, however they were not significant. Both total carbon and total nitrogen for both sites exhibited significant positive skews for the mineral soils.

The microbial PLFA analysis data showed some extreme and moderate outliers (Figures 10 and 11). For the P301 site there was an extreme and moderate outlier for eukaryotes and one moderate outlier for each of, gram positive and negative bacteria and actinomyces. For the Tower site there were two moderate outliers for eukaryotes. One of the eukaryotes moderate outliers was co-located with an ammonium moderate outlier in the mineral soil at the P301 site. For the Tower site, one of the eukaryotes outliers was co-located with an extreme nitrate outlier in the O-horizon, which also had the highest total microbial biomass for the site. For the Tower site the only significant r^2 values ($P \leq 0.05$) comparing the nutrients to the microbial biomass were for calcium ($r^2 = 0.27$) and nitrate ($r^2 = 0.43$) in the mineral soil. No other discernible trends were identified for the Tower site. For the P301 site, the highest amount of microbial biomass was located at sampling point five which also had the observed trend of higher overall nutrient concentrations. This sampling point also demonstrated moderate outliers for gram positive and gram negative bacteria, and the highest percentage of fungi. The P301 site exhibited significant r^2 values ($P \leq 0.05$) for the C/N and all mineral soil nutrients analyzed except for sodium and nitrate. The highest r^2 values for the P301 site were with ammonium, calcium, and magnesium in the mineral soil (r^2 values 0.39, 0.33, 0.34 respectively).

DISCUSSION

The interflow in the O-horizon was enriched with nutrients relative to water extractable soil solution concentrations which was also noted in the previous study by Johnson et al. (2011). The concentrations of nutrients in the interflow however, were substantially less than found by Johnson et al. (2011). The interflow was highly variable both spatially and temporally at both sites. The mineral soil nutrient concentrations were also highly variable suggesting that interflow may influence hot spots in the soil. The P310 site exhibited considerably lower interflow volume but significantly higher nutrient concentrations for magnesium and calcium suggesting a less diluted interflow. Furthermore, some of the nutrient concentrations correlated with the water flux at P301 albeit this was not evident at the Tower site. The average nutrient concentrations for the O-horizon and mineral soil were higher at P301 than the Tower site which may be related to the nutrient rich interflow. The higher volume of interflow collected at the Tower site may have led to an increased dilution of nutrients in the mineral soil.

The most frequent nutrient parameter exhibiting hot spot characteristics was nitrate in both the O-horizon and mineral soil. Nitrate had a significant positive skew for all soil types with the exception of the Tower mineral soil. This supports nitrogen being the most common nutrient hot spot found (Johnson et al. 2011). The water extractable nitrate hot spots were most frequently situated in locations of lower concentrations for the other nutrients, which was not noted by Johnson et al. (2011). Nitrate tends to be more soluble in the soil than other nutrients and this may be a reason for the different hot spot location. However, chloride which has similar behavioral characteristic as nitrate in the soil did not show the same trend. In fact, high chloride concentrations typically occurred with the other high nutrient concentrations. This could be due to the influence of biological uptake or nitrification on nitrate which does not affect chloride.

Hot spots were identified at both field sites for nutrients and microbial species. For the Tower site extreme and moderate outliers as well as the locations of highest concentrations for the O-horizons and mineral soils were not located at the same sampling point. For the Tower site, sample point location 6 showed the highest frequency of outliers and highest nutrient concentrations in the O-horizon, whereas sampling point eleven for the mineral soil has the highest number of outliers. Johnson et al. (2011) found similar trends of non co-locating hot spots between the mineral and O-horizon. However, for the P301 site, the high nutrient concentrations were mostly co-located at the same sampling point in the O-horizon and mineral soil. There were no hot spots (extreme or moderate outliers) for total microbial biomass; however there were hot spots for individual microbial species.

The P301 site mineral soil demonstrated the most significant skews for the nutrients analyzed and a co-location between nutrient hot spots in the mineral and O-horizon, which was also the same location for the highest amount of microbial biomass. This was an apparent area of higher microbial biomass and nutrient hot spots. This was not the case for the Tower site suggesting that nutrient outliers are inconstantly related to microbial biomass as indicated by PLFA analysis.

Total carbon hot spots were co-located with the sampling points that showed the most nutrient hot spots in the mineral soil for both field sites. This contradicts what was observed at the KREW by Johnson et al. (2011). Thus, we find some evidence of the influence of carbon content in hot spot formation. The contrast between the findings of this study and the previous investigations highlight the problems of studying the potential causes of nutrient hotspots; they are by definition rare, one may or may not find them within a particular sampling scheme, and, if found, the potential causes may not be consistent from one hotspot to another.

In Chapter 1 of the thesis, nutrient hot spots were identified by several different resin based sampling methods. Chapter 2 found water extractable nutrient hot spots in the O-horizon and mineral soil, total carbon and nitrogen hot spots, and zones of high microbial activity in the mineral soil. No one underlying cause can be singled out as the key contributor to the formation of hot spots in the soil. Movement of hot spots across the soil matrix may be influenced by biological uptake or changes in flow paths.

CONCLUSIONS

1. Nutrient hotspots in O-horizons and soils were identified, but differed somewhat from previous work by Johnson et al. (2011) in that a nutrient hot spot for most nutrients did occur at the same location in the O-horizon and mineral soil for the P301 site.
2. As with Johnson et al. (2011), nutrient-rich runoff in the O-horizon was found and the site with higher interflow nutrient concentrations also demonstrated higher O-horizon and mineral soil average nutrient concentrations.
3. Nutrient hotspots in soils and overlying O-horizons were inconsistently related to microbial indices.

4. Inorganic nitrogen was the most common hot spot found (moderate and extreme outliers) in the King’s River soil. Water extractable nitrate hot spots were commonly located with low concentrations of the other soil nutrients.

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Tables

Table 1: The average interflow nutrient concentrations with standard deviation and maximum values for both sites. The collection dates for the season were 15th October 2009, 5th January 2010, 23rd March 2010, 4th April 2010, 23rd April 2010, and 8th June 2010. On 23rd of April 2010, only one collector contained solute, which was Tower-3. Runoff collector P301-2 only had one sample that contained PO_4^- above the detection limit. There is the average interflow nutrient concentrations for individual collectors at each site and then for the site as a whole.

Average Interflow Concentration with Standard Error ($\mu eq \cdot L^{-1}$) and Total Volume for Individual Collectors						
Collector	Total Volume (L)	NO_3^-	NH_4^+	PO_4^-	Mg^{2+}	Ca^{2+}
Tower-1	13.25	132.6 ± 70.7	11.3 ± 4.7	18.2 ± 7.3	51.2 ± 11.1	129.3 ± 29.3
Tower-2	23.93	1.4 ± 0.6	24.1 ±13.6	24.6 ± 11.0	32.3 ± 11.5	53.7 ± 15.5
Tower-3	48.90	2.68 ± 0.7	3.6 ± 1.5	5.18 ± 4.42	18.8 ± 3.9	51.5 ± 10.6
P301-1	2.84	133.4 ± 33.7	9.8 ± 3.1	26.4 ± 6.7	54.2 ± 11.4	258.3 ± 55.6
P301-2	1.35	7.96 ± 1.8	3.0 ± 0.6	2.9 ± 0.8	89.1 ± 20.3	342.5 ± 78.2
P301-3	4.18	1.75 ± 0.7	11.7 ± 6.7	7.5 ± 3.4	49.9 ± 16.2	161.8 ± 53.2
Average Interflow Concentration with Standard Error ($\mu eq \cdot L^{-1}$) and Total Volume for Each Site						
Tower	86.08	30.8 ± 19.3	7.9 ± 3.3	10.5 ± 3.6	24.1 ± 5.4	57.7 ± 13.0
P301	8.37	37.2 ± 18.9	6.9 ± 3.5	10.0 ±3.8	43.0 ± 12.2	168.5± 47.1
Maximum Interflow Values ($\mu eq \cdot L^{-1}$)						
Tower-1		341.3	22.9	35.5	71.9	207.0
Tower-2		2.3	58.0	43.4	52.7	72.9
Tower-3		5.9	7.7	23.1	32.9	100.3
P301-1		200.4	24.1	38.5	68.0	344.2

P301-2	13.8	3.9	5.9	154.3	593.5
P301-3	5.5	51.2	24.1	96.5	323.5

Table 2: Comparison of the interflow nutrient concentrations to the water flux collected. The collection dates for the season were 15th October 2009, 5th January 2010, 23rd March 2010, 4th April 2010, 23rd April 2010, and 8th June 2010. On 23rd of April 2010, only one collector contained solute, which was Tower-3. Runoff collector P301-2 only had one sample that contained PO_4^- above the detection limit.

Correlation coefficients for Comparing Water Flux to Individual Nutrients

Tower	r^2 value	P301	r^2 value
NO_3^-	0.05	NO_3^-	0.01
NH_4^+	0.06	NH_4^+	0.52
PO_4^-	0.01	PO_4^-	<0.01
Mg^{2+}	0.24	Mg^{2+}	0.73
Ca^{2+}	0.41	Ca^{2+}	0.81

Table 3: Mean with standard error and skew for the water extractable nutrients and total nitrogen and total carbon for soil core samples extracted at two filed sites in the King’s River Experimental Watershed. Significant skews are noted by a (†).

Average with Standard Error ($\mathrm{mmol \cdot kg^{-1}}$)

Site	Nitrate	Phosphate	Ammonium	Magnesium	Calcium	Sodium	Chloride	TN	TC
Tower O-horizon	0.053 ± 0.017	0.265 ± 0.057	0.582 ± 0.057	0.433 ± 0.052	1.962 ± 0.235	0.209 ± 0.019	0.561 ± 0.108		
Tower Mineral	0.014 ± 0.005	0.006 ± 0.002	0.071 ± 0.011	0.106 ± 0.015	0.602 ± 0.080	0.205 ± 0.016	0.201 ± 0.015	96.1 ± 6.1	2772.2 ± 262.5
P301 O-horizon	0.065 ± 0.028	0.429 ± 0.118	0.764 ± 0.159	0.560 ± 0.100	2.891 ± 0.509	0.240 ± 0.022	0.560 ± 0.061		
P301 Mineral	0.037 ± 0.018	0.014 ± 0.005	0.343 ± 0.183	0.196 ± 0.021	1.450 ± 0.186	0.226 ± 0.018	0.475 ± 0.170	145.4 ± 13.9	3682.1 ± 418.9

Skew for Soils

Site	Nitrate	Phosphate	Ammonium	Magnesium	Calcium	Sodium	Chloride		
Tower O-horizon	†2.67	0.98	0.09	0.83	0.08	-0.18	†1.82		
Tower Mineral	0.98	†1.99	0.19	†1.18	0.86	0.88	0.15	†1.29	†1.28
P301 O-horizon	†3.08	†1.63	0.56	1.03	0.89	0.94	-0.04		
P301 Mineral	†3.32	†2.89	†3.77	0.90	0.87	†1.52	†3.75	†1.39	†1.13

Figures

Figure 1: Site location map for the King's River Experimental Watershed (KREW). The map was taken from the Southern Sierra Critical Zone Observatory (CZO) website (https://eng.ucmerced.edu/czo/sites.html).

Figure 2: Sample and approximate runoff collectors' locations for each site, not to scale.

Figure 3: Water extractable nitrate, ammonium, phosphate, calcium, and magnesium for the Tower site O-horizon. Sixteen soil cores were taken from the site, separated into the O-horizon and mineral soil and then analyzed for nutrient for soil nutrient extreme and moderate outliers. The data was normalized and extreme outliers are denoted by an asterisk (*) and moderate outliers are denoted by a circle (^{O}).

Figure 4: Water extractable nitrate, ammonium, phosphate, calcium, and magnesium for the Tower site mineral soil. Sixteen soil cores were taken from the site, separated into the O-horizon and mineral soil and then analyzed for nutrient for soil nutrient extreme and moderate outliers. The data was normalized and extreme outliers are denoted by an asterisk (*) and moderate outliers are denoted by a circle (^{O}).

Figure 5: Water extractable sodium and chloride and total carbon, total nitrogen, and C:N for the Tower site mineral soil. Sixteen soil cores were taken from the site, separated into the O-horizon and mineral soil and then analyzed for nutrient for soil nutrient extreme

and moderate outliers. The data was normalized and extreme outliers are denoted by an asterisk (*) and moderate outliers are denoted by a circle (^{O}).

Figure 6: Water extractable sodium and chloride for the O-horizon for both sites. Sixteen soil cores were taken from the site, separated into the O-horizon and mineral soil and then analyzed for soil nutrient extreme and moderate outliers. The data was normalized and extreme outliers are denoted by an asterisk (*) and moderate outliers are denoted by a circle (^{O}). (T) refers to the Tower site and (P) refers to the P301 site.

Figure 7: Water extractable nitrate, ammonium, phosphate, calcium, and magnesium for the P301 site O-horizon. Sixteen soil cores were taken from the site, separated into the O-horizon and mineral soil and then analyzed for nutrient extreme and moderate outliers. The data was normalized and extreme outliers are denoted by an asterisk (*) and moderate outliers are denoted by a circle (^{O}). ND mean there is no data available for that sample location.

Figure 8: Water extractable nitrate, ammonium, phosphate, calcium, and magnesium for the P301 site mineral soil. Sixteen soil cores were taken from the site, separated into the O-horizon and mineral soil and then analyzed for nutrient for extreme and moderate outliers. The data was normalized and extreme outliers are denoted by an asterisk (*) and moderate outliers are denoted by a circle (^{O}).

Figure 9: Water extractable sodium and chloride and total carbon, total nitrogen, and C:N for the P301 site mineral soil. Sixteen soil cores were taken from the site, separated into the O-horizon and mineral soil and then analyzed for nutrient extreme and moderate outliers). The data was normalized and extreme outliers are denoted by an asterisk (*) and moderate outliers are denoted by a circle (^{O}).

Figure 10: Tower site normalized microbial data for the mineral soil. Sixteen soil cores were taken from the field site separated by horizon. The mineral soil was then analyzed for microbial biomass using the PLFA analysis. The data was analyzed for statistical outliers denoted as hot spots in the soil. There were no extreme outliers for the data set and moderate outliers are denoted by a circle (^{O}).

Figure 11: P301 site normalized microbial data for the mineral soil. Sixteen soil cores were taken from the field site separated by horizon. The mineral soil was then analyzed for microbial biomass using the PLFA analysis. The data was analyzed for statistical outliers denoted as hot spots in the soil. Outliers are noted as: asterisk (*) for extreme outliers and moderate outliers are denoted by a circle (^{O}).

Figure 1

Figure 2

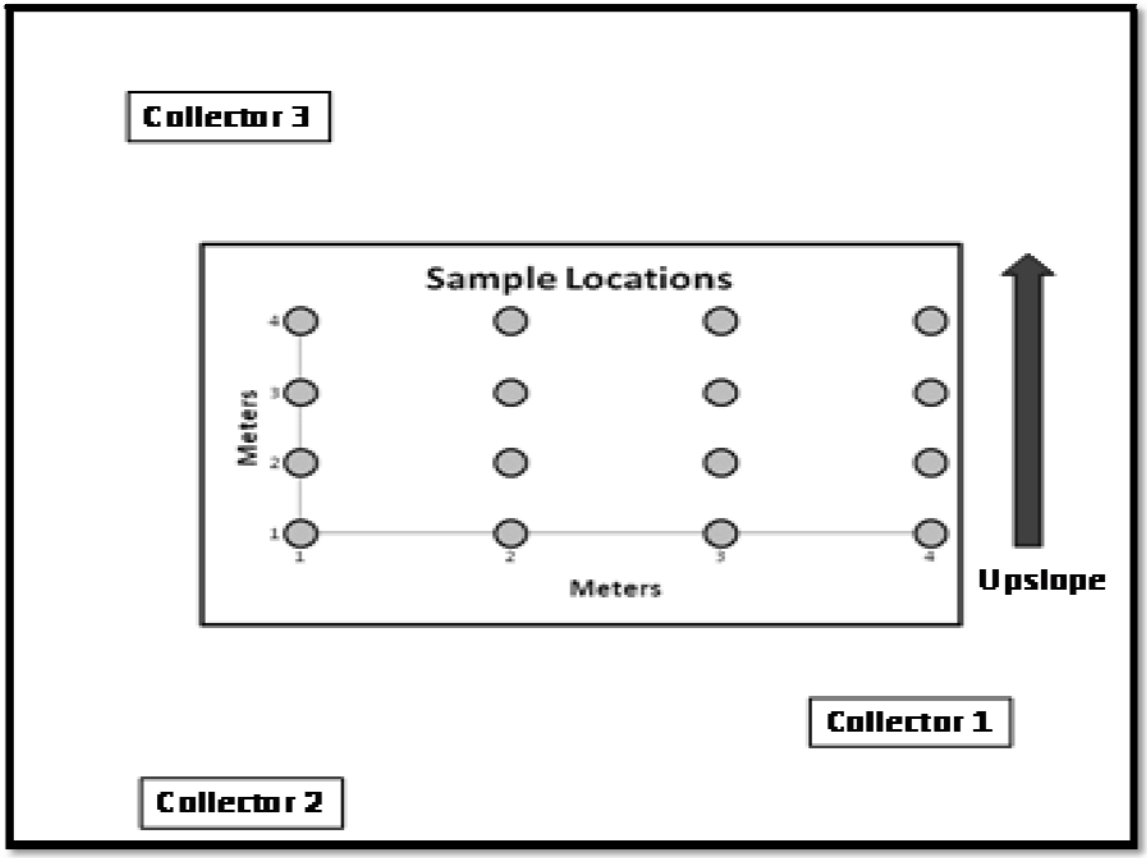

Collector 3
Sample Locations
4
3
2
1
Meters
1
2
3
4
Meters
Upslope
Collector 1
Collector 2

Figure 3

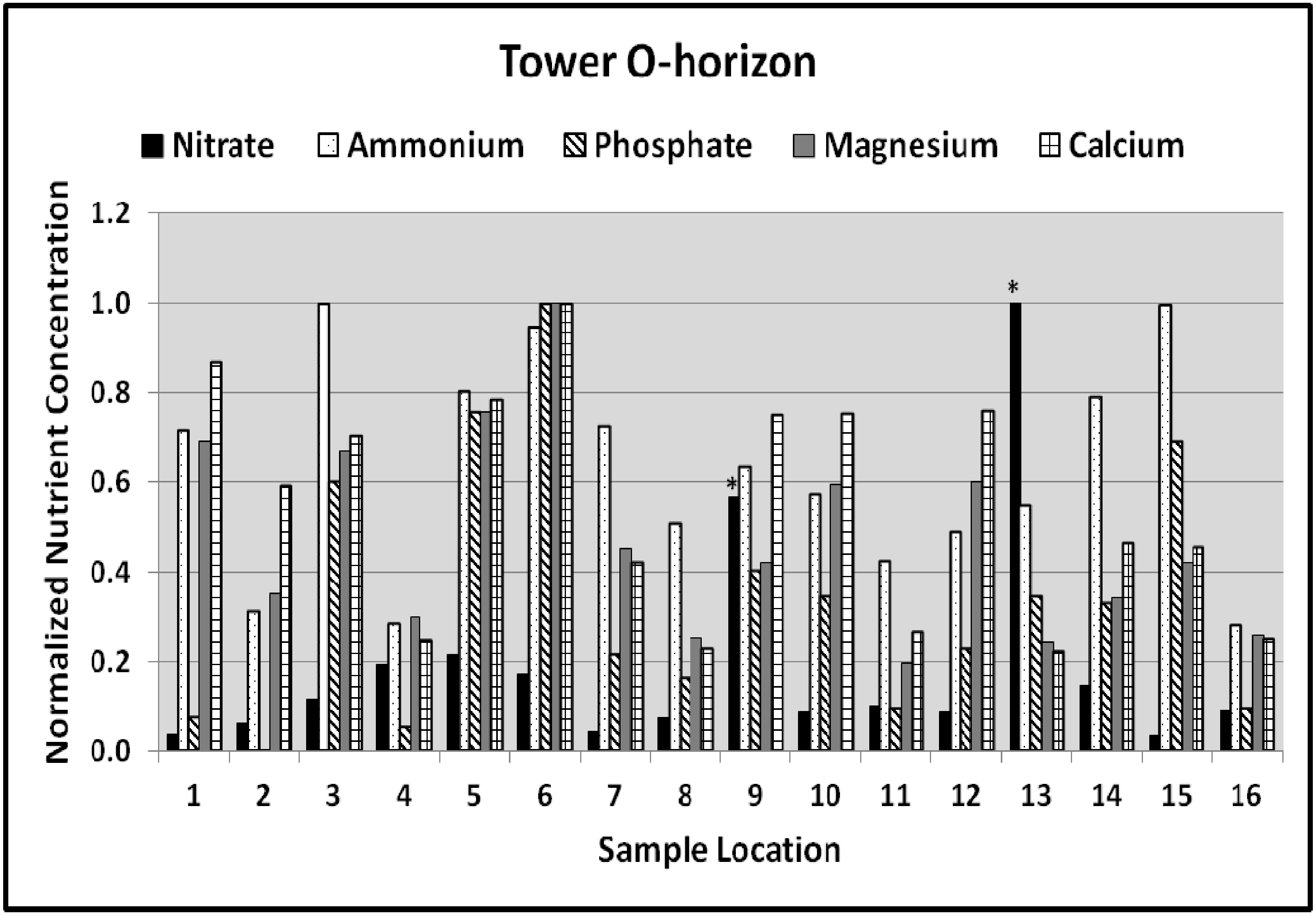

Tower O-horizon
Nitrate
Ammonium
Phosphate
Magnesium
Calcium
Normalized Nutrient Concentration
1.2
1.0
0.8
0.6
0.4
0.2
0.0
*
*
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
Sample Location

Figure 4

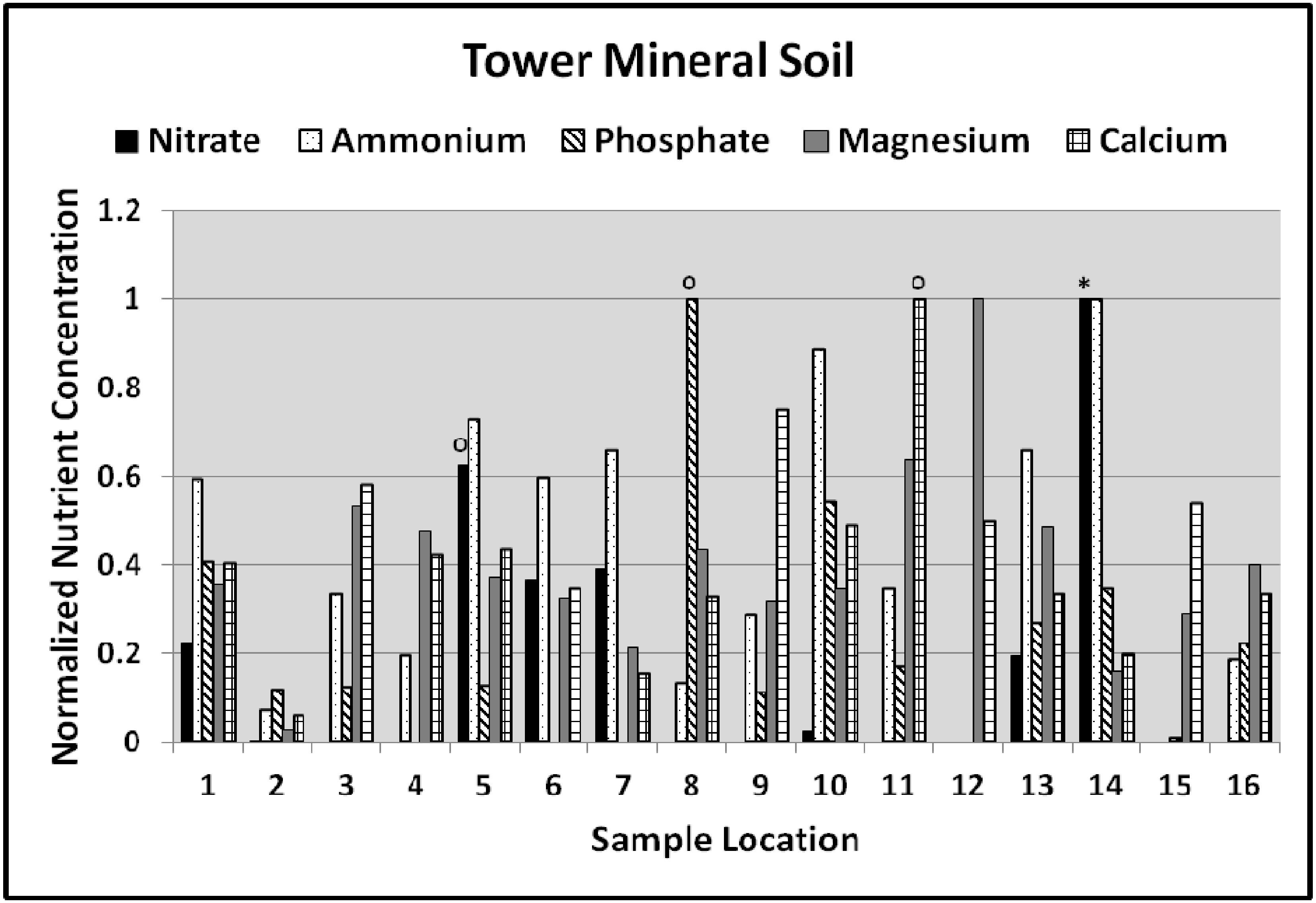

Tower Mineral Soil
■ Nitrate
☐ Ammonium
▧ Phosphate
■ Magnesium
⊞ Calcium
Normalized Nutrient Concentration
1.2
1
0.8
0.6
0.4
0.2
0
o
o
o
*
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
Sample Location

Figure 5

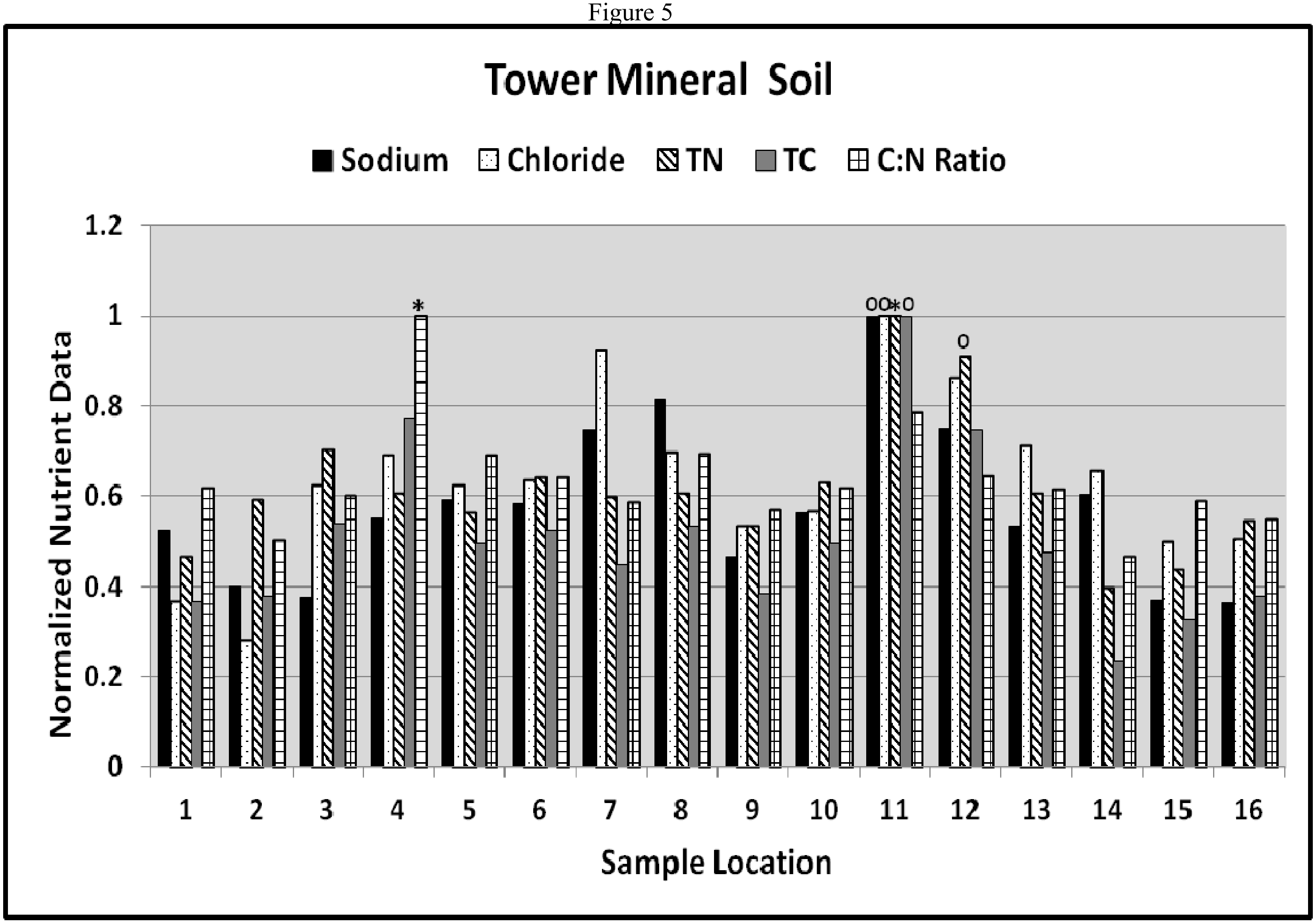

Tower Mineral Soil
■ Sodium ☐ Chloride ▨ TN ■ TC ⊞ C:N Ratio
1.2
1
0.8
0.6
0.4
0.2
0
Normalized Nutrient Data
*
OO*O
O
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
Sample Location

Figure 6

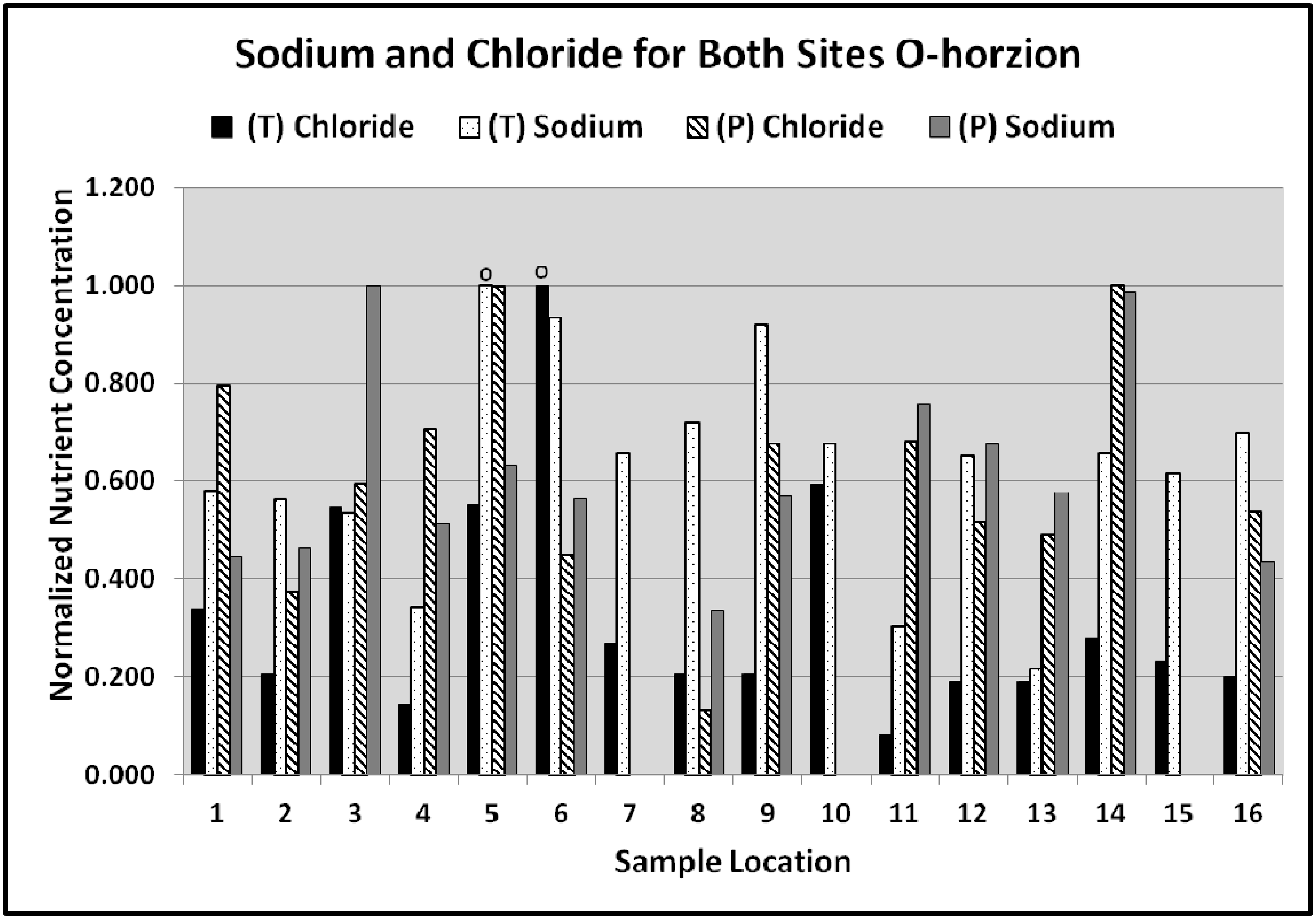

Sodium and Chloride for Both Sites O-horzion
■ (T) Chloride
☐ (T) Sodium
▨ (P) Chloride
■ (P) Sodium
Normalized Nutrient Concentration
1.200
1.000
0.800
0.600
0.400
0.200
0.000
o
o
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
Sample Location

Figure 7

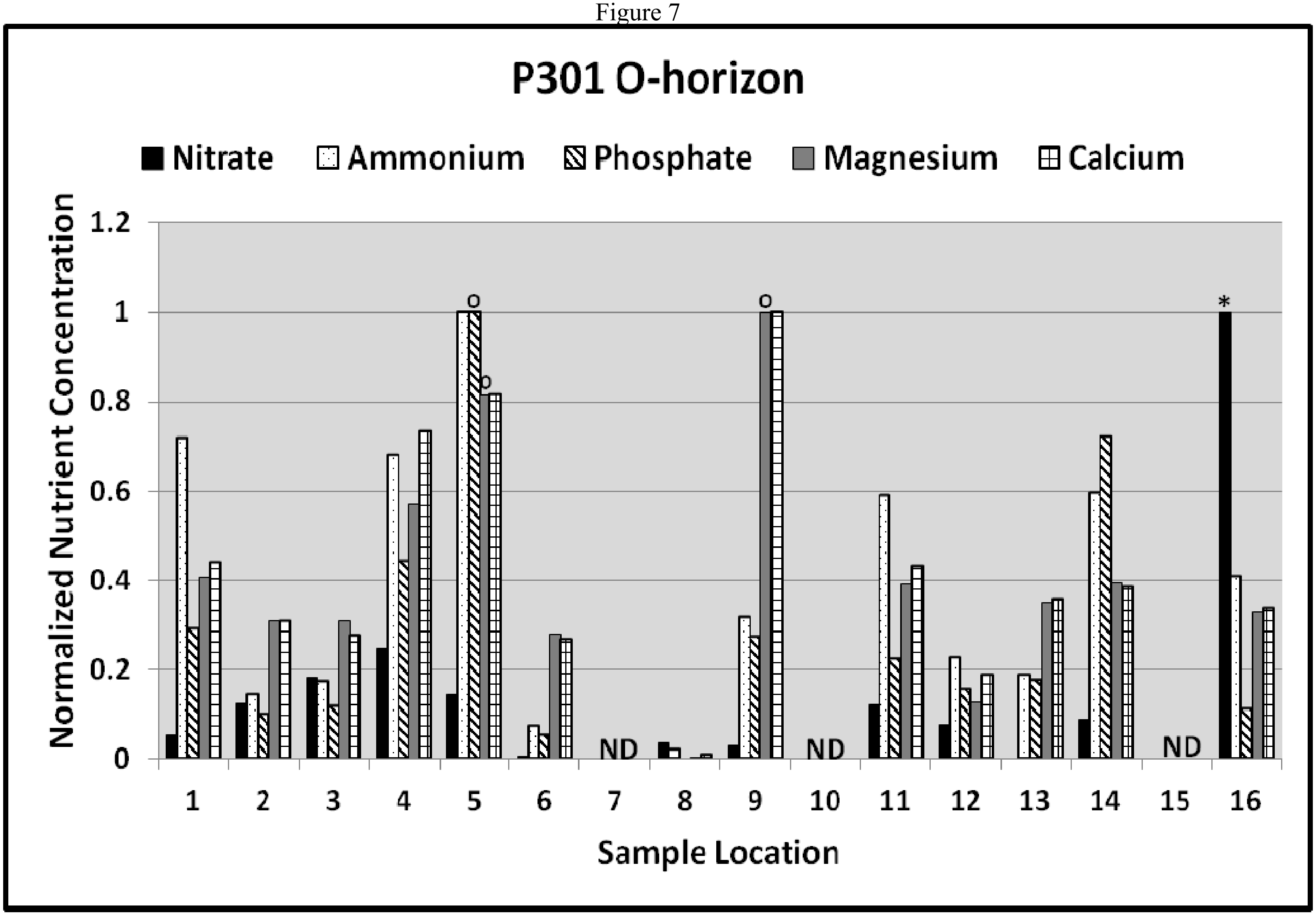
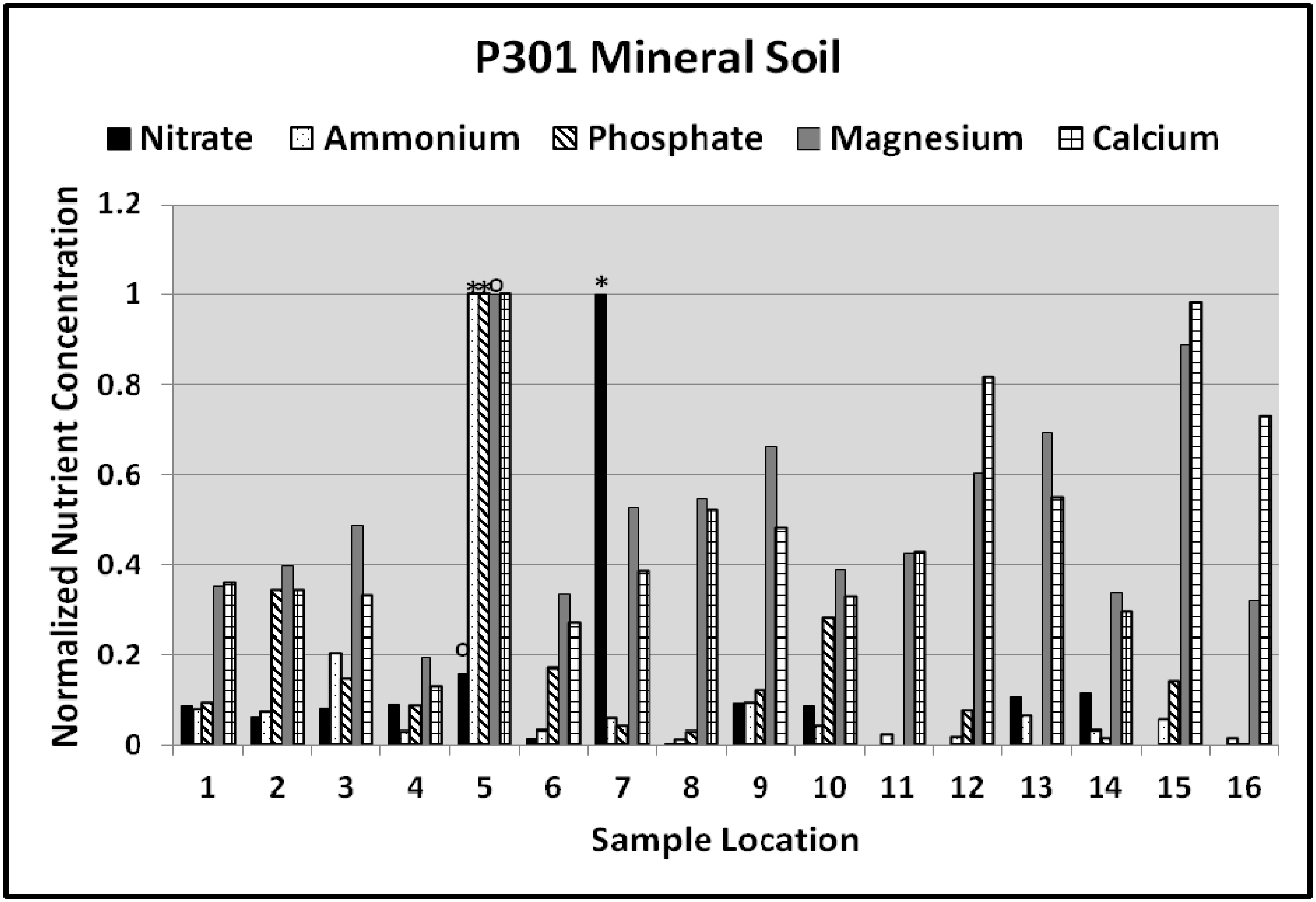

P301 O-horizon
Nitrate
Ammonium
Phosphate
Magnesium
Calcium
Normalized Nutrient Concentration
0
0.2
0.4
0.6
0.8
1
1.2
o
o
o
*
ND
ND
ND
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
Sample Location

Figure 8


P301 Mineral Soil
■ Nitrate
☐ Ammonium
▧ Phosphate
■ Magnesium
⊞ Calcium
Normalized Nutrient Concentration
1.2
1
0.8
0.6
0.4
0.2
0
**o
*
o
1
2
3
4
5
6
7
8
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10
11
12
13
14
15
16
Sample Location

Figure 9

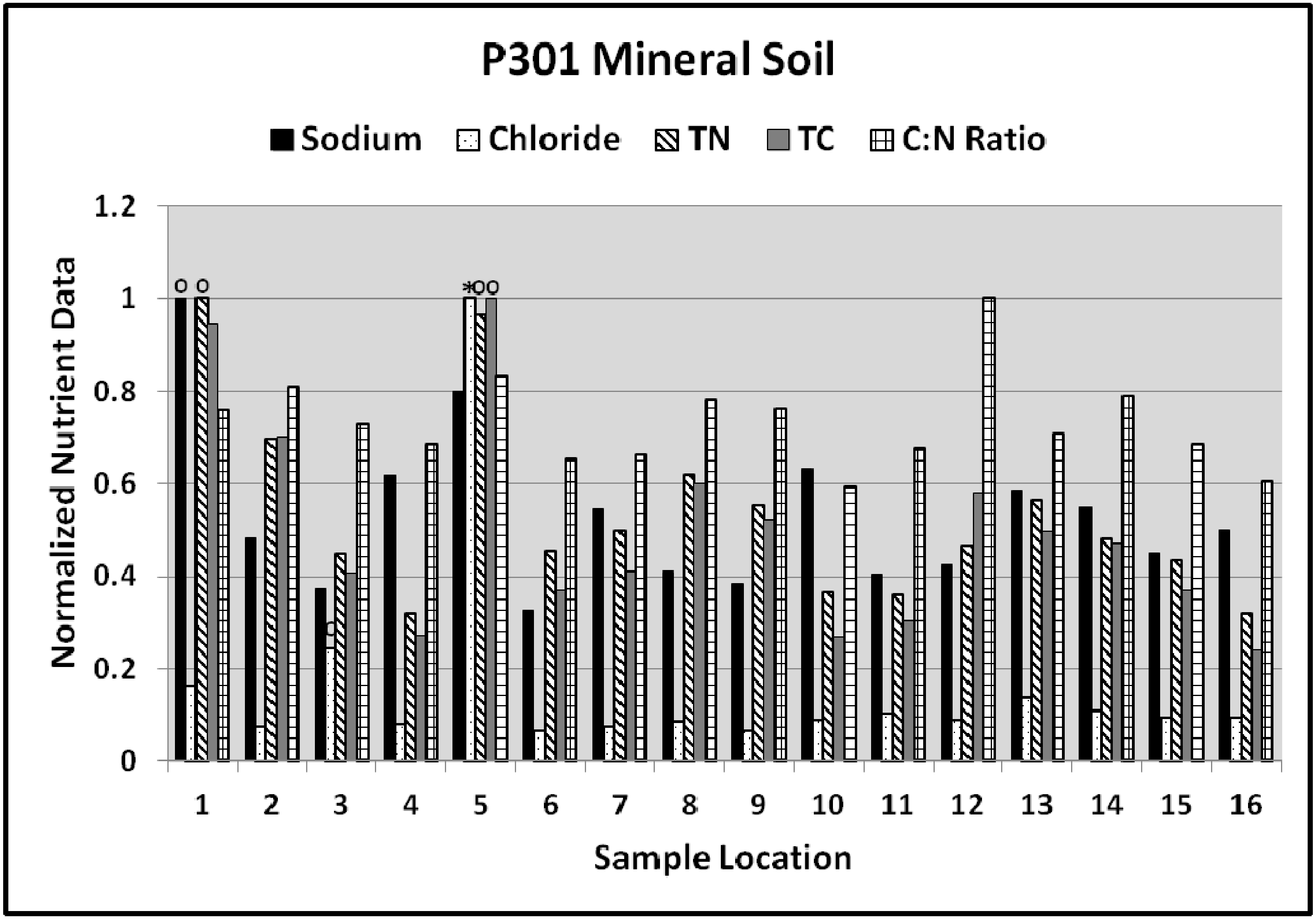

P301 Mineral Soil
■ Sodium
□ Chloride
▨ TN
■ TC
⊞ C:N Ratio
Normalized Nutrient Data
1.2
1
0.8
0.6
0.4
0.2
0
o o
*oo
o
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
Sample Location

Figure 10

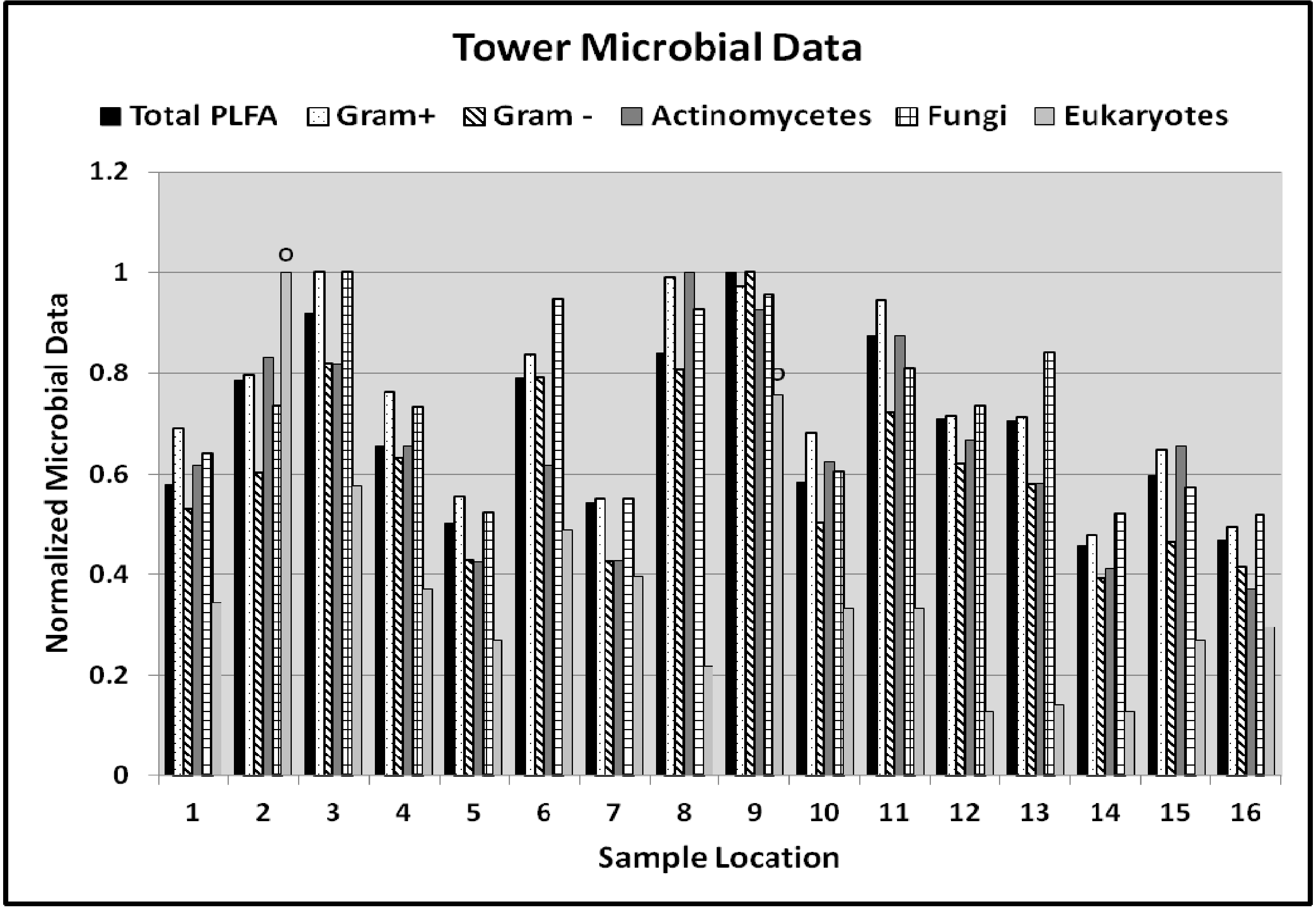
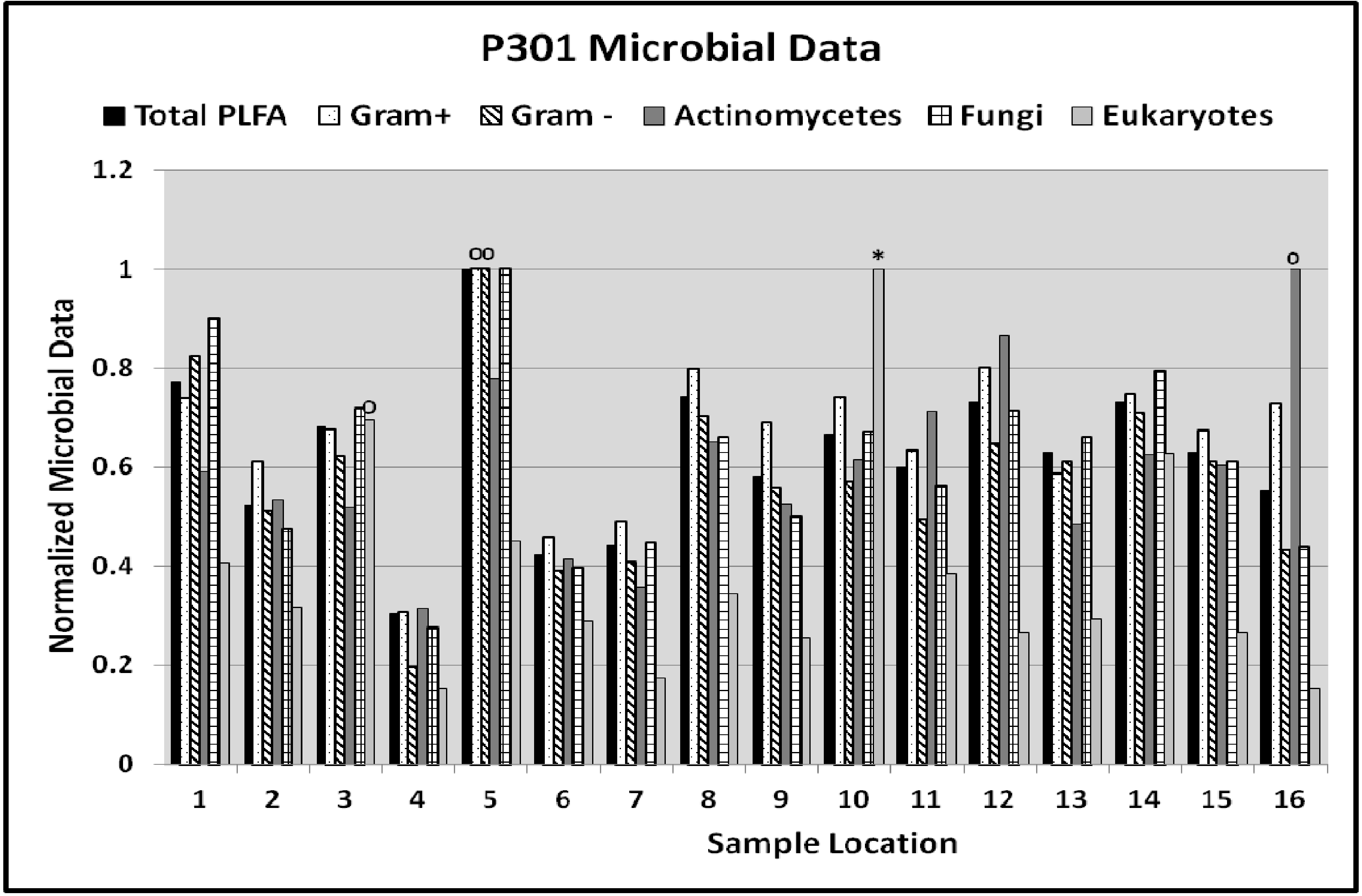

Tower Microbial Data
Total PLFA
Gram+
Gram -
Actinomycetes
Fungi
Eukaryotes
Normalized Microbial Data
1.2
1
0.8
0.6
0.4
0.2
0
o
o
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
Sample Location

Figure 11


P301 Microbial Data
■ Total PLFA
☐ Gram+
▧ Gram -
■ Actinomycetes
⊞ Fungi
■ Eukaryotes
1.2
1
0.8
0.6
0.4
0.2
0
Normalized Microbial Data
oo
o
*
o
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
Sample Location

Chapter 3

Effect of O-horizon interflow on nutrients in a Sierra Nevada forest soil

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ABSTRACT

Meter scale grids were established at two locations (upper elevation Tower and mid-elevation P301) in the King's River Watershed, California to establish if increasing moisture content from O-horizon interflow can increase decomposition and nutrient concentrations in the soil. Three grids were established at each site. One grid was composed of four treatments: 1) a barrier placed in the O-horizon to truncate interflow, 2) a barrier with a cation/anion UniBest® resin capsule, 3) a capsule with no barrier, and 4) a control point. After one year, soil cores were taken at each sampling point and both the organic and mineral horizon were analyzed for nutrient concentrations. A second grid containing 20 sampling points was established for decomposition studies: ten litter bags were placed inside the barriers and ten without barriers. Using a Decagon® soil sensor it was shown that the barriers increased the moisture content in the O-horizon by 17% and the decomposition rates were greater (t-test P=0.09) in the barriers at the Tower site. The 17% increase in soil moisture did not cause an increase on soil nutrient concentrations. A third grid contained PRS™ probes with four probes (two cation and two anion) at each of the 16 sampling points. Two sets of probes were placed perpendicularly with respect to slope to truncate interstitial flow and two were placed parallel. Truncating interstitial flow appeared to increase individual number of hot spots for the PRS™ probes, but did not cause the formation of hot spots for multiple nutrients in one sampling point. Ammonium-N was the only nutrient that appeared to be affected by truncating interstitial flow with resin based sampling methods.

Key Words: Soils, Nutrients, Hot Spots, Runoff, Sierra Nevada Mountains

INTRODUCTION

Part of a soil's biodiversity is inorganic nutrient hot spots which have been shown to exist by several different soil sampling methods (Johnson et al. 2009, Johnson et al. 2010, and Johnson et al. 2011, Woodward et al. in review). Hot spots of inorganic nutrients in a soil matrix are believed to play a pertinent role in the biogeochemical cycling of nutrients, plant nutrition, and water quality (McClain et al. 2003, Schimel and Bennet 2004, Johnson et al. 2011). Soil bulking to reduce variability can eliminate hot spots can very possibly lead to misrepresentations of macronutrients in a soil matrix. Factors that influence hot spot formation are organic content, microbial biomass, and O-horizon interflow.

Chapter 2 investigated the influence of mineral soil carbon content and microbial activity on mineral soil hot spots. We found that high carbon concentration corresponded with a hot spot for multiple nutrients at one grid point, but not the formation of individual nutrient hot spots at others. Microbial biomass was greatest at one hot spot for multiple nutrients but there was no pattern at other nutrient hot spots. Therefore, microbial biomass and nutrient hot spots do not always coincide.

Another possible contributing factor to the formation of hot spots in the soil may be the presence of preferential flow paths. Previous work has demonstrated that O-horizon interflow in the Sierra Nevada Mountains contains nutrient concentrations that were variable and high compared to stream water and mineral soil solutions (Miller et al. 2005, Loupe et al. 2009, Johnson et al. 2011, Woodward et al. in review). In the summer the Sierra Nevada mountain soils tend to become hydrophobic leading to the development of preferential flow paths within the mineral soil (Miller et al. 2005). Finger flow (the most common type of preferential flow) is often caused by spatial heterogeneity of water repellency in a soil (Dekker 1994; Jury et al 2004; Morales 2010). Hydrophobicity-induced finger flow is much more prominent than finger flow produced in soils with higher antecedent moisture content (Hardie et al. 2011). Thus preferential flow paths are likely to occur in the Sierra Nevada mountains and may contribute to the formation of nutrient hot spots in the mineral soil by conducting high nutrient interflow concentrations.

Soil nutrient hot spots have been found in the Kings River Experimental Watershed (KREW) using a variety of different sampling methods (Johnson et al. 2011). The nutrient concentrations in interflow from the KREW have been spatially and temporally variable and can exhibit higher concentrations than water extractable nutrient data in past research (Johnson et al. 2011). The objective of this research was to investigate the potential for formation of nutrient hot spots in soil in response to O-horizon interflow infiltration. Our two hypotheses were:

H_1: Localized interstitial flow will increase nutrient flux and the formation of hot spots in the soil.

H_2: Localizing interstitial flow will increase the decomposition rates of pine leaf litter in the O-horizon and therefore increase nutrient availability.

METHODS AND MATERIALS

Study Site Description

The King's River Experimental Watershed (KREW) (located on the western side of the Sierra Nevada Mountains) approximately 105 km northeast of Fresno, California in Fresno County, was established in 2000 to promote the understanding of headwaters in ecosystems and the effects of forest management practices used to increase forest health (Figure 1). Southern Sierra Critical Zone Observatory (CZO) is co-located at KREW and is a collaborative used as an environmental laboratory to study the physical, chemical, and biological processes of the earth's surface. KREW is characterized by warm dry summers and cold winters, where most of the precipitation occurs as snow. The mean annual summer and winter temperatures are 13.38°C and -0.4°C, respectively. The mean annual rainfall is 94 cm and annual mean snowfall is 514 cm with a mean snow depth of 33 cm. The vegetation for the site is a mixed conifer forest composed of sugar pine (*P. lambertiana Douglas*), ponderosa pine (*Pinus ponderosa Lawson and C. Lawson*), incense-cedar (*Calocedrus decurrens (Torr.) Florin*) and white fir (*Abies concolor (Gord. & Glend.) Lindl. ex Hildebr*). The understory consists of unidentified brush species, green leaf manzanita (*Arctostaphylos patula Greene*), and squawcarpet (*Ceanothus prostratus Benth*). The soil is a Shaver series; a coarse-loamy, mixed mesic Pachic Xerumbrept derived from granite (Johnson et al 2011).

Two field sites were chosen for study. Site one (Tower site) is at an elevation of 1980 meters, Latitude: 37° 3' 33.626" N Longitude: 119° 10' 56.184" W. Site two (P301) is at a lower elevation, 1910 meters, Latitude: 37° 3' 46.649" N Longitude:

119° 12' 3.844" W. Both sites have similar soil and vegetation; however the overstory is denser at site P301.

Instrumentation and Analysis

Runoff and snowmelt collectors were installed at each site. The runoff was measured during the study to investigate the continuing spatial and temporal variability and high nutrient concentrations as noted in previous research (Johnson et al. 2001 and Woodward et al. in review). The runoff collectors were installed as described by Miller et al (2005) and snowmelt collectors as described by Susfalk and Johnson (2002). The collectors are designed to collect interstitial flow from the O-horizon, just above the surface of the mineral soil. The snowmelt collectors are comprised of buried collection bottles attached to above ground open collectors. Soil interflow and snowmelt samples were collected when accessible throughout the sampling year. The collection dates for the season were 10th of October 2010, 4th of November 2010, 13th of January 2011, 11th of February 2011, 20th of April 2011, 24th of May 2011, 2nd of June 2011, and 22nd of June 2011. The total amount of solution was evacuated from the samplers and recorded. From each collection, a subsample was taken, frozen and then shipped to the University of Nevada, Reno soils lab. The subsamples were filtered and analyzed on a Dionex ICS-3000 ion chromatograph which runs Chromeleon® software for nitrite, sulfate, nitrate, phosphate, sodium, ammonium, potassium, magnesium, calcium and chloride.

A 4x4 meter grid was established at the P301 site to measure soil volumetric water content (Figure 2). Fifteen of the sixteen sampling points were instrumented with Decagon Soil Sensor® probes to measure volumetric water content, temperature, and electrical conductivity. Eight of the sampling points containing a probe were located in a barrier designed to intercept O-horizon interflow. The barriers consisted of sections of plastic gutter inserted into the O-horizon to the mineral soil surface. The barriers were composed of a durable plastic cut from rain gutters and had a width at the opening of 10.5 cm, width of 7.5 cm at the base, and a height of 18 cm. The probes took soil measurements every hour from August 2010 to June 2011. The sixteenth sampling point was not instrumented since the data logger only contained probes in sets of 5.

A separate 4x5 meter grid established at both sites had twenty sampling points with barriers located at every other sampling point (Figure 3). Litter bags were placed at each of the twenty sampling points (ten in barriers and ten on the open O-horizon). Litter bags were created using mesh fabric and litter collected in from the field site in June of 2010. The bags were 13cm by 14cm in size and an average of 4.5 grams of litter was placed in each bag and the stapled closed. A set of ten extra litter bags were weighed and then dried in a Lindberg/Blue M Stabil-Therm Mechanical Convection Oven at 45°C for at least 24 hrs, then weighed again. Their moisture content was calculated and used to correct for the initial moisture content of the bags deployed in the field.

A third 4x4 meter, 16 point grid was established at both sites containing 4 Western Ag Innovations PRS^{tm} Probes (two cation and two anion) at each point. There are two probe types both composed of a 17.5 cm^2 surface ion membrane, which is either cation or anion adsorptive. The probes are designed to adsorb ions through electrostatic attraction and are believed to simulate root adsorption making them useful for understanding nutrient supply rates within the soil matrix. Two of the probes (one cation and one anion) were placed parallel with respect to the slope and the other two were place perpendicular with respect to the slope to truncate interstitial flow on a small scale. They were inserted 10cm into the O-horizon. The probes were deployed in August 2010 and removed in June 2011.

A fourth 7x7 meter grid with 64 sampling points was established at both sites and instrumented with barriers and UniBest® resin capsules. Thirty-two of the 64 sampling points were instrumented with a barrier designed to intercept O-horizon interflow was previously described. Sixteen of the barrier grid points were instrumented with UniBest® resin capsules on the downhill side. Resin capsules were used to capture nutrients from the interstitial flow within the O-horizon. The ion exchange resin capsule primarily measures the labile forms of inorganic nutrients (Skogley 1996). Resin capsules without barriers were located at 16 grid points and the final 16 grid points were left with no treatment (controls). The grid was established in the summer of 2010 and in the spring of 2011 resin capsules were removed (Figure 4). After the capsules were removed, a core sample was taken at all 64 points for each site using a slide hammer auger. The depth of the O-horizon was measured and the mineral horizon was sampled to a depth of 10 cm unless the auger hit an obstruction. The samples were separated by horizon, bagged and taken back to the laboratory for processing.

The surface samples collected from the barrier grid were dried in Lindberg/Blue M Stabil-Therm Mechanical Convection Oven with the organic horizon dried at 45°C and mineral soil at 55°C for a minimum of 24 hours. Once the samples were dried, they were immediately weighed. The mineral samples were sieved to the 2mm fraction and homogenized. Five homogenized grams of each sample were extracted for 1 hour with 40 mL of deionized water on a Sampletek^{tm} programmable vacuum extractor, Model 24VE.

The extract was then analyzed at the University of Nevada Reno soils laboratory using the Dionex ICS-3000 ion chromatograph which runs Chromeleon® software for nitrite, sulfate, nitrate, phosphate, sodium, ammonium, potassium, magnesium, calcium and chloride. Subsamples of the mineral soil were analyzed at Oklahoma State University Soil, Water and Forage Analytical Laboratory (SWFAL) on a dry combustion C and N analyzer (LECO) for total carbon and nitrogen concentrations and KCl extractable nitrate and ammonium were analyzed on a Lachat 8000 flow injection analyzer (Hatch co. Loveland, C.O. USA) . Finally, five homogenized samples of both the mineral and O-horizon were analyzed for phosphate using the bicarbonate Olsen method which is believed to represent the phosphate available for biological uptake (Tiessen et al 1993).

The resin capsules were washed free of all debris with deionized water. Care was taken to prevent sample contamination. They were then extracted with 20 mL of 2 M KCl three times, each time being shaken on a platform shaker for 20 minute intervals. The combined 60 mL of extract was then shipped to SWFAL for analysis. The ammonium, nitrate, and orthophosphate were analyzed on a Lachat 8000 flow injection analyzer (Hatch co. Loveland, C.O. USA). The calcium and magnesium were analyzed using a Jarrell Ash inductively coupled plasma spectrophotometer (Thermo Jarrell Ash Corp., Franklin MA).

The PRS™ probes were washed free of all debris using deionized water. They were then shipped to Western Ag Innovations Saskatoon Canada where they were soaked for one hour in 17.5 mL of 0.5 M HCl. The extract was then analyzed for ammonium and nitrate colorimetrically using a Technicon Autoanalyzer II (Seal Analytical, Mequon, Wisconsin). Phosphorus, sulfur, magnesium, calcium, sodium, boron, copper, manganese, and zinc were all analyzed on a Perkin Elmer Optima 3000-DV ICP using an inductive coupled plasma emission spectroscopy.

Data Analysis

The data presented was analyzed for extreme and moderate outliers using the program DataDesk (Velleman 1997). Student t-tests were also used on all the data presented as single tailed and two-sample unequal variance (heteroscedastic). This was done to determine differences between the parallel and perpendicular probe data, the resin capsule data from both inside and outside the barriers and the soil core data from the four different soil types (barrier, no barrier, barrier and capsule, and capsule only). SAS® was used to perform ANOVA analysis on all the soil samples to assess the effect of the capsule, barrier and capsule*barrier interaction using PROC GLIMMIX (Delwiche and Slaughter 1998). All capsule*barrier p-values were >0.05 and are therefore not presented. DataDesk defines positive and extreme outliers as:

Extreme outliers:

$x > Q_3 + 3*IQR$

Moderate outliers

$x > Q_3 + 1.5*IQR$

x = the value

Q_3 = the third quartile value (75th percentile), and

IQR = interquartile range (range from 25th to 75th percentile)

Due to the small amount some soil samples, not all were subjected to the entire suite of analyses and therefore have different n values. Data desk constructs box plots using the lowest n value presented in the data set. Therefore, the samples had to have each nutrient run in data desk individually and not all nutrients plotted on the same graph. Therefore, figures of the box plots are not available for the soil data.

RESULTS

Litter Decomposition and Soil Moisture

The litter bags from inside the barriers for both sites (Figure 3) showed greater weight loss than those located outside the barriers. For the Tower site the mean weight loss for the litter bags located inside the barriers was 29.22% greater (7.23%) than for those not in a barrier (5.15%) (t-test p=0.09). For the P301 site the mean weight loss for the littler bags located inside the barriers (6.14%) was not significantly different than those outside the barriers (6.05%).

The decagon soil moisture probes indicated higher moisture content in the soil located inside the barriers. The mean volumetric water content (VMC) 0.155 and that from outside the barriers was 0.128 for the 2010-2011 sampling year (September 2010 to June 2011). Soil inside the barriers sites had a 17% higher moisture content 99.75% ($P<0.001$) of the time compared to the soil outside the barriers. Soil inside the barriers exhibited a mean temperature of 7.05 ˚C, whereas the soil outside the barriers had a mean temperature 7.09 ˚C which was not significantly different.

Plant Root Simulator™ (PRS) Probes

Extreme and moderate outliers were observed for the data from both the perpendicular and parallel probes at each site (Figure 5). No single sample point at either site exhibited outliers for all the nutrients analyzed. The parallel probe data demonstrated outliers for mineral nitrogen, nitrate-N, phosphate-P, iron and zinc at the Tower site. The iron and zinc outliers were moderate while the others were extreme. The Tower site perpendicular probes demonstrated outliers for magnesium, potassium, iron, zinc, and aluminum (2). The P301 parallel probes exhibited outliers for ammonium, potassium, iron, and manganese in which the ammonium and potassium were extreme outliers. The P301 site perpendicular probes exhibited outliers for all the nutrients analyzed with the exception of sulfate and aluminum. Calcium showed both a high and low moderate outlier. In total there were nine outliers (5 extreme and 4 moderate) for the parallel probe data for both sites and 17 outliers (4 extreme and 13 moderate) for the perpendicular probe data. P301 perpendicular probe data exhibited the most outliers 11, with two of them being extreme.

The mean nutrient values for the probes did not show consistent significant differences between those placed perpendicular to the slope and those placed parallel to the slope (Table 1). The mean data from perpendicular probes at the Tower site were higher than from the parallel probes for ammonium-N, magnesium, potassium, phosphate, iron, manganese, sulfur, and aluminum, with ammonium-N being significantly different(t-test P=0.04). The Tower mean data from parallel probes were higher for mineral nitrogen, nitrate-N, calcium, and zinc, none statistically significant. The mean data for the perpendicular probes at the P301 site were higher than the parallel probe data for ammonium-N, potassium, manganese, and zinc. Parallel probe mean data were higher at the P301 site for mineral nitrogen, nitrate-N, calcium, magnesium, phosphate, iron, sulfate, aluminum with sulfur being significantly different (t-test

P=0.04). At the P301 site the differences in the calcium data were different between the parallel and perpendicular probes (t-test P=0.06). The perpendicular probe ammonium data was higher than the parallel probe data at both sites. Potassium and manganese also had higher nutrient concentrations for both sites from the perpendicular probe data. The differences in the manganese data from both types of probes from the P301 site had a t-test p-value of 0.07.

UniBest® Resin Capsules

Outliers were observed in the data from both sites and sampling methods (Figure 6). No single grid point demonstrated outliers for all the nutrients in either site or sample type. Capsules located inside the barrier demonstrated outliers for all the nutrients analyzed at various sampling points at the Tower site with extreme outliers for orthophosphate, ammonium, and calcium and moderate outliers magnesium, nitrate-N (2), and ammonium-N. There was only one moderate outlier (ammonium-N) from the capsule, no barrier data for the Tower site. In contrast, P301 demonstrated only two moderate outliers, magnesium and ammonium-N, for data from the capsule barrier data whereas; capsule data from outside the barriers exhibited outliers for all nutrients analyzed except ammonium. The barrier capsule data for both sites exhibited a total of nine outliers with three being extreme outliers. The data from the capsules without a barrier for both sites demonstrated a total of eight outliers with three of them being extreme outliers.

The averaged capsule data were variable at both sites when comparing the data from the capsules placed in barriers and those placed in the open O-horizon (Table 2).

For the Tower site, ammonium-N was the only nutrient higher in the capsule barrier data than the capsule non-barrier data and the difference was significant (t-test P=0.04). All of the other nutrient data for the Tower site showed higher concentrations from the non-barrier capsule data with significant differences for magnesium (P=0.05). The P301 site exhibited higher nutrient concentrations in the barrier capsules for orthophosphate, calcium, and magnesium. None of the data differences in barrier and non-barrier capsules for the P301 site demonstrated low enough p-values to suggest a significant difference.

Soil Results

The soil cores collected were separated by site, two horizons (O-horizon and mineral soil), and four different sample types:

1. Barrier (B); soil cores extracted from inside the barriers after they were in place for one year
2. No barrier (NB); soil cores extracted from locations where there had been no alteration to the soil (control points)
3. Barrier with a capsule (BC); soil cores extracted from inside a barrier that housed a capsule in the O-horizon for one year
4. Capsule only (C); soil cores taken from the locations that had a capsule in the O-horizon for one year.

Due to the different "n" values for the samples collected the outliers for the soil data are presented in tables rather than figures (see methods). Water extractable nutrient outliers were found at each site for the four different soil samples (barrier, no barrier, barrier with a capsule, and capsule only) in both the O-horizon and mineral soil (Tables

3-4). For KCl extractable nitrate and ammonium, bicarbonate phosphate, and C:N ratio there were outliers but not for all sample types and sites. The mineral soil NB data and BC data only demonstrated moderate outliers for the P301 site. The B samples for sites, O-horizon, and mineral soil showed the highest amount of outliers, 48, with 14 of them being extreme outliers. The NB samples exhibited 42 outliers with 10 being extreme outliers and C samples demonstrated 36 outliers with 10 of them extreme outliers. BC demonstrated the lowest amount of outliers 33, with 10 that were extreme outliers. For an individual soil horizon (organic and mineral) and site, the Tower site O-horizon B samples exhibited the most outliers, 17, with 4 of them being extreme outliers. One sample point from Tower site O-horizon B demonstrated an outlier or highest concentration for all types of nutrients analyzed except for water and KCl extractable nitrate, C:N ratio, and bicarbonate phosphate.

Mean nutrient concentrations were compared between the different sampling methods and are presented in Table 5. The B data was compared to the NB data and the BC data was compared to the C data for the t-tests. For the Tower site O-horizon data the mean nutrient concentrations were higher more often from the NB and C data compared to the B and BC data. The only B data higher than the NB data were for potassium, C/N, and KCl extractable ammonium and the only BC data that was higher than the C data was nitrate, sodium, and KCl extractable ammonium. For the Tower mineral soil, the mean data were higher for the B and BC for sulfate, sodium, ammonium, KCl extractable ammonium, and bicarbonate phosphate. The P301 O-horizon data demonstrated higher means for the B and BC more often than the NB and C data. The NB data exhibited higher means only for nitrate, KCl extractable ammonium, and KCl extractable nitrate.

The mean data for the C samples were only higher for the total carbon data in the P301 O-horizon. For the P301 mineral soil data the NB demonstrated higher mean concentrations that the B soil data. The B soil data for the P301 mineral soil was only higher for sulfate, phosphate, chloride, and bicarbonate phosphate. With the exception of the Tower O-horizon nutrient data bicarbonate phosphate mean nutrient concentrations were higher from the B and BC data compared to the NB and B.

T-test p-values comparing the B to NB and CB to C are given in Table 6. Bicarbonate phosphate showed low ($P \leq 0.1$) p-values for the O-horizon data from both sites which means the NB and C nutrient data were higher than that from the B and BC for the Tower site and that the B and BC were higher for the P301 site. Sulfate and sodium all exhibited significant differences between the C and CB samples with the CB nutrient data being higher for the P301 O-horizon ($P \leq 0.05$). Potassium showed a significant difference between the P301 CB and C data with the C being higher. For the P301 mineral soil the nitrate was significantly higher for the BC samples compared to the C samples and KCl nitrate was significantly higher for the NB samples compared to the B data in the O-horizon.

To test the possibility of the effects of the barrier or capsule on individual nutrient concentrations a two way ANVOA analysis was performed comparing different sample types (Table 7). For the Tower site, the barrier treatment did not have any significant affect on the nutrients analyzed for either the O-horizon or mineral soil. The Tower site did show some significant differences ($p<0.05$) for the capsule's effect on the nutrients in the O-horizon. The P301 site showed some effects of the barrier and the capsule on the O-horizon and mineral soil. Sulfur and ammonium in the O-horizon exhibited a significant effect ($p<0.05$) from the capsules at both sites. The effects of the capsules on the O-horzion for the P301 site were significant most often. P-values characterizing the affect of the capsule on a nutrient concentration were all <0.05 for the O-horizon sulfur, nitrate, phosphate, sodium, ammonium, potassium, and mineral soil nitrate for the P301 site. Sulfate was the nutrient that was affected the most by the treatments. The nutrients that showed significant ($P<0.05$) p-values for the barrier treatment beside sulfur were O-horizon sodium and mineral soil potassium for the P301 site.

O-horizon Interflow and Snowmelt

The mean nutrient concentrations with standard error ($\mu eq \cdot L^{-1}$) and total volume (L) collected is presented in Table 8. The mean nutrient concentrations in snowmelt were greater than those in interflow for all nutrients except calcium at the Tower site and nitrate was the only nutrient that had a significant difference (t-test P= 0.04). Snow grab samples were collected in June 2012 at each site; one near Tower-3S and P301-2S. With the exception of some sodium and chloride concentrations all the snowmelt samples collected were higher than the 2 snow grab samples. This may be due to through fall or some other source of nutrients (such as leaf litter in the collector) in the snowmelt collectors. The P301 interflow nutrient data had higher mean concentrations than the snowmelt for sulfate, nitrate, sodium, potassium, magnesium, and calcium with calcium being significantly higher (t-test $p<0.05$). For phosphate and ammonium, the snowmelt concentrations were significantly higher (t-test $p<0.05$) than the interflow.

The mean concentrations were highly variable among individual collectors. The highest mean amount of nitrate collected was from Tower snowmelt 1, which also had the highest mean of chloride and one of the highest for potassium. The highest mean concentrations occurred at P301 snowmelt 1 for sulfate, phosphate, and ammonium. Both calcium and magnesium concentrations had the highest mean data at P301 runoff collector 2. The highest concentration of any one nutrient collected was ammonium at 1022.13 $\mu eq \cdot L^{-1}$ for the P301 snowmelt collector 1.

DISCUSSION

The perpendicular PRS™ probe data exhibited almost twice the number of hot spots as the data from parallel alignment (mostly moderate outliers); suggesting that truncating the interflow increased the amount of nutrient collection. Ammonium was higher for the perpendicular probes at both sites; significantly at the Tower site. Ammonium was also significantly higher for the capsule data located inside the barriers at the Tower site. Ammonium-N was the only nutrient that appeared to be affected with the resin samplers. There was no other data for the capsules where the barrier data was significantly higher than the no barrier data. Although the barriers increased moisture content by 17 % in the O-horizon and decomposition at the Tower site they demonstrated no effect on the numbers of outliers in the capsule data. For the probe data it appears that truncating runoff flow may have increased the overall number of apparent hot spots.

The greatest number of apparent hot spots in the O-horizon and mineral soil for both sites combined was from the B data, whereas the fewest were from the BC data. This may have been an effect of the capsule on the O-horizon as shown from the ANOVA analysis (Table 7). Capsules caused more significant ($P<0.05$) effects than the barriers in O-horizon nutrient concentrations (Table 7). There were two locations in the

O-horizon that exhibited trends of highest concentrations and hot spots, one at each site. These multiple hot spot locations in the O-horizon only correlated with the capsule data ammonium-N hot spots at the Tower site. There were two grid points in the mineral soil that showed trends of multiple nutrient hot spots and each exhibited either an extreme outlier (P301) or the highest concentration (Tower) of total carbon, suggesting that organic matter influences hot spots in the mineral soil. The means and t-tests showed no consistent observable trends in the soil data for the individual nutrients when comparing the four treatments. This may be due to dilution of soil nutrients because of higher water flux.

The runoff and snowmelt showed high and variable nutrient concentrations which have been seen previously for the runoff at the field site (Johnson et al. 2011, Woodward et al. in review). For the Tower site, the concentrations in the snowmelt were more often higher in nutrient concentration than the runoff with nitrate being significantly different, which may be due to leaching from the dense forest canopy. This was not prevalent at the P301 site. Increased volume tended to be associated with lower nutrient concentrations which suggest dilution in the nutrient concentrations. Loupe et al. (2009) found that runoff concentrations at a North Tahoe site had similar average concentrations for ammonium and phosphate collected under the canopy, as at the KREW. Mean nitrate runoff concentrations were lower for the KREW than what was found in North Tahoe by Loupe et al. (2009) as was sulfate.

The KREW snowmelt phosphate nutrient concentrations (P301 3.35 mg L^{-1} and Tower 1.15 mgL^{-1}) were higher than that reported by Loupe et al. (2009) (Open 0.21 mgL^{-1} and canopy 0.40 mgL^{-1}) and Miller et al. (2005) (0.21 mgL^{-1} and 0.31mgL^{-1}). The ammonium snowmelt concentrations were also higher at the P301 site and nitrate at the Tower site than that observed by Loupe et al. 2009. The snow grab samples collected at each site also had higher concentrations for ammonium (P301 12.0 mg L^{-1} and Tower 5.2 mgL^{-1}) and nitrate (P301 1.5 mg L^{-1} and Tower 1.0 mgL^{-1}) that what was seen by Loupe et al. 2009 (ammonium 0.34 - 0.38 mg L^{-1} and nitrate 0.30 - 0.31 mgL^{-1}). The snowmelt collector P301-1S had the highest concentrations of ammonium and phosphate collected from the whole data set, including both sites. The 2010-2011 winter season was a wet year with a greater than 100% of normal snowpack for most of the season. Snowpack can collect debris which can presumably increase nutrient concentrations. The wet year also may have had an influence on the infiltration of snowmelt and runoff, increasing moisture and decreasing hydrophobic induced interflow.

CONCLUSIONS

The results of our data show that hypothesis 1, increasing moisture content in the soil would increase soil nutrient hot spots was not satisfied, (but not disproved) and that hypothesis 2, increasing soil moisture content increases decomposition, was satisfied for the Tower site only.

1. Truncating interstitial flow appeared to increase individual number of hot spots for the PRS™ probes, but did not cause the formation of hot spots for multiple nutrients in one location.
2. Ammonium-N was the only nutrient that appeared to be affected by truncating interstitial flow with both resin based sampling methods with the exception of the P301 capsule data.

3. Capsules had a greater effect on some individual O-horizon nutrient concentrations (especially sulfate and ammonium) than did the barriers even though the barriers caused a 17% increase in moisture content.
4. The 17% increase in moisture content caused by the barriers in the soil did not increase the mean nutrient concentrations or the formation of hot spots in the O-horizon or mineral soil.

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Tables

Table 1: Average concentrations in µmol·cm^{-2} and P-values for t-tests of the nutrients extracted from the PRS™ probes. Four probes (two cation and two anion) were placed in the soil at 16 different sampling points along a 4x4 meter grid. Two probes (one cation and one anion) were placed parallel (Pa) with respect to the slope and two probes (one cation and one anion) were placed perpendicular (Pe) with respect to the slope on a local scale. The perpendicular probes exposed more membrane surface area to interstitial flow. The higher average nutrient flux concentration between the probes that were placed vertically and the probes that were placed horizontally are shaded. T-tests were performed comparing the vertical probes to the horizontal probes. A low p-value number is represented by a (*), which suggests a significant difference (= or <0.1) between nutrient concentrations from the vertical and horizontal probe data.

PRS™ probes average nutrient flux concentrations in µmol·cm^{-2} and P-values for t-tests												
Average	**Mineral-N**	**NO3-N**	**NH4-N**	**Ca**	**Mg**	**K**	**P**	**Fe**	**Mn**	**Zn**	**S**	**Al**
Tower (Pa)	1107.5	1060.2	47.3	24763.8	2393.1	989.2	903.4	14.9	245.6	21.7	564.4	62.0
Tower (Pe)	909.3	851.0	58.3	24888.3	2508.7	1022.6	911.2	18.0	256.5	19.5	567.6	92.2
P301 (Pa)	1681.0	1642.3	38.7	22835.3	2945.5	577.8	531.3	37.8	111.1	14.3	532.1	93.2
P301 (Pe)	1598.7	1557.2	41.5	22080.9	2853.4	678.6	491.7	25.8	146.4	15.7	447.3	83.7
T-tests	**P-values for t-tests**											

Tower	0.22	0.21	0.04	0.43	0.20	0.43	0.46	0.13	0.36	0.28	0.47	0.13
P301	0.37	0.37	0.34	0.06	0.20	0.20	0.18	0.10	0.07	0.14	0.04	0.20

Table 2: Average nutrient concentrations in $\mu mol \cdot cm^{-2}$ and P-values for t-tests of the nutrient concentrations extracted from the UniBest® resin capsules at both sites. Sixteen capsules were placed in a barrier (B) to truncate interstitial flow in the O-horizon and 16 capsules were located in the open O-horizon (NB). The average higher nutrient flux concentrations extracted from the capsules located inside the barrier (B) compared to those in the open horizon (NB) are shaded. The p-values for t-test comparing the data from the capsules located inside the barriers to those in the open O-horizon are located below the averages.

UniBest® resin capsules average concentrations in $\mu mol \cdot cm^{-2}$ and P-values for t-tests					
Average	**Ortho-P**	**NH_4^+-N**	**NO_3^--N**	**Ca^{2+}**	**Mg^{2+}**
Tower (B)	0.41	2.48	1.30	8.48	2.75
Tower (NB)	0.59	0.77	1.91	10.15	4.06
P301 (B)	0.43	1.93	2.82	12.17	3.80
P301 (NB)	0.34	1.99	2.84	11.64	3.20
T-Tests	**P-values for t-tests**				
Tower	0.16	0.04	0.06	0.26	0.05
P301	0.23	0.46	0.49	0.44	0.29

Table 3: Extreme and moderate outliers for all nutrients analyzed at both sites in the O-horizon. Barriers were placed in the soil at 32 sampling points in a 64 point grid to truncate interstitial flow in the O-horizon at both sites. Sixteen of the 32 barriers contained a UniBest® resin capsule to measure nutrient fluxes and 16 of the 32 grid points without barriers had a capsule placed in the O-horizon. After one year the capsules were removed and a soil core sample was taken at all locations. The Table reads as Follows: B=soil core extracted from a barrier, NB= soils core extracted from a control point (no barrier) BC= soil core extracted from a barrier with a capsule located in it, C= capsule only at that location, n=the number of samples, E=extreme outliers and M=moderate outliers.

O-horizon Outliers

	$\mathbf{S0_4^-}$			$\mathbf{NO_3^-}$			$\mathbf{PO_4^-}$			$\mathbf{Na^+}$			$\mathbf{NH_4^+}$			$\mathbf{K^+}$			$\mathbf{Mg^{2+}}$			$\mathbf{Ca^{2+}}$		
Tower	n	E	M	n	E	M	n	E	M	n	E	M	n	E	M	n	E	M	n	E	M	n	E	M
B	16		1	16	1	2	16	1		16		3	16		1	16	1		16		1	16		1
NB	16	1		16	1		16	1	1	16	1		16		1	16		1	16		1	16		1
BC	16	1		16	1	1	16			16		1	16		1	16			16		1	16		1
C	16			16	1		16		1	16			16			16			16			16		
P301																								
B	14	1	1	14		1	14			14		1	14		1	14		1	14		1	14		

NB	16			16	1	1	16			16			16		2	16		1	16	1		16	1	
BC	15		1	15			15		2	15			15		2	15			15	1	2	15	1	
C	16			16		1	16			16		1	16			16		1	16	1		16	1	

	Cl$^-$			**Total N**			**Total C**			**C/N**			**KCl NH$_4^+$**			**KCl NO$_3^-$**			**Bicarb-P**			**Total Outliers**
Tower	n	E	M	n	E	M	n	E	M	n	E	M	n	E	M	n	E	M	n	E	M	
B	16			15			15			15	1		15		2	15	1	1	16			17
NB	16			15		1	15			15		2	14		1	14		1	16			14
BC	16		1	15			15			15			15	1		15			16			9
C	16		1	16			16			16	1	1	15	1		15	1	1	16			8
P301																						
B	14		1	15			15			15	1		15			15			14		2	11
NB	16			16			16			16			16		2	16		2	16		1	12
BC	15			15			15			15	1		13		2	13	1		14	1		14
C	16		1	15			15			15	1	1	15			15		2	15			10

Table 4: Extreme and moderate outliers for all nutrients analyzed at both sites in the mineral soil. Barriers were placed in the soil at 32 sampling points in a 64 point grid to truncate interstitial flow in the O-horizon at both sites. Sixteen of the 32 barriers contained a UniBest® resin capsule to measure nutrient fluxes, and 16 of the 32 grid points without barriers had a capsule placed in the O-horizon. After one year the capsules were removed and a soil core sample was taken at all locations. The Table reads as Follows: B=soil core extracted from a barrier, NB= soils core extracted from a control point (no barrier) BC= soil core extracted from a barrier with a capsule located in it, C= capsule only at that location, n=the number of samples, E=extreme outliers and M=moderate outliers.

Mineral Soil Outliers																								
	$S0_4^-$			**NO_3^-**			**PO_4^-**			**Na^+**			**NH_4^+**			**K^+**			**Mg^{2+}**			**Ca^{2+}**		
Tower	n	E	M	n	E	M	n	E	M	n	E	M	n	E	M	n	E	M	n	E	M	n	E	M
B	16		1	16	2		16	1	1	16			16		1	16			16			16		
NB	13			13		1	13	2		13	1		13		1	13			13			13		
BC	15			15			15			15	1	1	15			15		1	15	1		15		
C	16			16	1	1	16	1		16			16		2	16			16		1	16		1
P301																								
B	15	1	1	15			15	1	2	15			15			15		1	15		1	15		1

NB	16			16			16			16		1	16			16		2	16		1	16		2
BC	16		1	16		1	16			16			16			16			16			16		
C	16			16			16		1	16			16			16			16			16		1

	Cl$^-$			**Total N**			**Total C**			**C/N**			**KCl NH_4^+**			**KCl NO_3^-**			**Bicarb-P**			**Total**
Tower	n	E	M	n	E	M	n	E	M	n	E	M	n	E	M	n	E	M	n	E	M	**Outliers**
B	16			16	1		16	1		16			16		1	16			16			9
NB	13		1	13		1	13		1	13			13			13	1		13		1	10
BC	15	1		15			15			15			15		1	15			15			6
C	16			16	1	1	16		1	16		1	16	1		16	1		16		1	14
P301																						
B	15		1	15		1	15	1	1	15	1		15			15			15			13
NB	16			16		1	16		1	16		1	16			16			16			9
BC	16		2	16			16		1	16			16			16			16			5
C	16		1	16		1	16	1		16			16		1	16			16			6

Table 5: The average water extractable nutrients, KCl extractable nitrate and ammonium, total carbon and nitrogen, and bicarbonate phosphate for the mineral soil and O-horizon for both sites. Barriers were placed in the soil at 32 sampling points in a 64 point grid to truncate interstitial flow in the O-horizon at both sites. Sixteen of the 32 barriers contained a UniBest® resin capsule to measure nutrient fluxes, and 16 of the 32 grid points without barriers had a capsule placed in the O-horizon. After one year the capsules were removed and a soil core sample was taken at all locations. The comparison of which average nutrient concentration was high is as follows: comparing barrier to no barrier soils samples and comparing barrier and capsule to capsule only soil samples. The number with the shaded coloring means that average is higher than the average concentration to which it was compared. The gray color is comparing NB to B and the orange is for comparing C to CB.

Average concentrations for soils (mmol·kg^{-1})

Site	Type	$S0_4^-$	NO_3^-	PO_4^-	Na^+	NH_4^+	K^+	Mg^{2+}	Ca^{2+}	Cl^-	Total N	Total C	C/N	KCl NH_4^+	KCl NO_3^-	Bicarb-P
Tower O-horizon	B	0.052	0.069	0.229	0.041	0.630	0.994	0.139	0.746	0.174	482	23404	52	6.534	0.123	292.6
	NB	0.055	0.098	0.269	0.054	0.921	0.961	0.164	0.903	0.206	551	26856	50	5.947	0.141	353.6
	BC	0.079	0.088	0.265	0.063	1.073	1.080	0.180	0.917	0.238	451	24608	54	5.994	0.171	316.1
	C	0.080	0.043	0.432	0.059	1.218	1.531	0.252	1.112	0.282	515	25663	56	5.457	0.221	408.7
Tower Mineral	B	0.047	0.015	0.041	0.133	0.116	0.835	0.236	1.618	0.178	135	4675	34	1.153	0.097	331.39
	NB	0.042	0.070	0.043	0.114	0.072	0.705	0.232	1.505	0.179	151	5462	35	1.118	0.098	309.55
	BC	0.055	0.058	0.039	0.137	0.178	0.823	0.239	1.557	0.221	132	4441	33	1.242	0.106	343.08
	C	0.050	0.049	0.042	0.112	0.117	0.918	0.263	1.806	0.185	125	4407	35	1.046	0.119	306.08

P301 O-horizon	B	0.189	0.155	0.756	0.113	2.065	2.165	0.388	2.366	0.489	715	28493	41	9.490	0.281	625.7
	NB	0.146	0.194	0.587	0.103	1.911	2.129	0.364	2.142	0.445	634	25705	42	9.590	0.550	502.9
	BC	0.298	0.108	3.048	0.176	0.960	3.888	0.402	3.953	0.502	646	24589	39	9.227	0.310	565.1
	C	0.187	0.089	1.955	0.127	0.770	3.629	0.243	2.663	0.412	642	24808	39	8.707	0.306	456.1
P301 Mineral	B	0.070	0.073	0.056	0.095	0.196	0.927	0.298	2.238	0.171	150	3810	25	1.014	0.103	417.9
	NB	0.065	0.077	0.053	0.109	0.215	1.228	0.332	2.305	0.160	151	3904	26	1.054	0.123	390.8
	BC	0.073	0.071	0.042	0.111	0.197	1.029	0.352	2.244	0.200	152	4296	28	1.164	0.120	406.6
	C	0.062	0.037	0.051	0.112	0.209	1.247	0.385	2.480	0.206	155	4235	27	1.143	0.112	398.9

Table 6: The p-values for t-tests comparing the four different soil cores; barrier, no barrier, capsule and barrier and capsule only. Barriers were placed in the soil at 32 sampling points in a 64 point grid to truncate interstitial flow in the O-horizon at both sites. Sixteen of the 32 barriers contained a UniBest® resin capsule to measure nutrient fluxes, and 16 of the 32 grid points without barriers had a capsule placed in the O-horizon. After one year the capsules were removed and a soil core sample was taken at all locations. A shaded number indicates a low p-value, which suggests a significant difference (≤0.05) between nutrient concentrations. B is for soil cores extracted from within the barrier, NB is for soil cores extracted from a point which had not been altered, CB is for soil cores extracted from a barrier that housed a capsule, and C is for soil cores extracted from a location that had a capsule for one year. TN refers to the total nitrogen and TC for the total carbon.

P -values for t-tests																
Site	Type	$S0_4^-$	NO_3^-	PO_4^-	Na^+	NH_4^+	K^+	Mg^{2+}	Ca^{2+}	Cl^-	Total N	Total C	C/N	KCl NH_4^+	KCl NO_3^-	Bicarb-P
Tower O-horizon	B and NB	0.41	0.28	0.30	0.13	0.11	0.45	0.30	0.27	0.19	0.17	0.13	0.35	0.36	0.37	0.10
	CB and C	0.47	0.12	0.12	0.38	0.32	0.08	0.11	0.18	0.23	0.13	0.37	0.45	0.39	0.22	0.05
Tower Mineral	B and NB	0.27	0.16	0.43	0.26	0.27	0.12	0.45	0.27	0.49	0.27	0.23	0.26	0.43	0.48	0.29
	CB and C	0.31	0.40	0.42	0.19	0.17	0.21	0.28	0.14	0.24	0.34	0.48	0.10	0.14	0.33	0.13
P301 O-	B and NB	0.18	0.29	0.15	0.27	0.37	0.46	0.40	0.32	0.30	0.13	0.10	0.45	0.48	0.03	0.08
	CB and C	0.03	0.29	0.09	0.03	0.15	0.34	0.14	0.17	0.07	0.48	0.47	0.42	0.42	0.49	0.09

horizon																
P310	B and NB	0.37	0.41	0.43	0.15	0.41	0.08	0.27	0.43	0.31	0.48	0.44	0.30	0.37	0.11	0.21
Mineral	CB and C	0.14	0.02	0.21	0.44	0.44	0.05	0.19	0.19	0.43	0.43	0.46	0.32	0.43	0.32	0.43

Table 7: ANOVA p-values for the effects of the barrier and capsule on the soil samples for both sites. Barriers were placed in the soil at 32 sampling points in a 64 point grid to truncate interstitial flow in the O-horizon at both sites. Sixteen of the 32 barriers contained a UniBest® resin capsule to measure nutrient fluxes, and 16 of the 32 grid points without barriers had a capsule placed in the O-horizon. After one year the capsules were removed and a soil core sample was taken at all locations. A two way ANOVA analysis was done determining the affects of the barriers and capsules on the soil samples. A shaded number indicates a low p-value, which suggests a significant difference (≤0.05) between nutrient concentrations.

ANOVA P-values				
	Tower Site		**P301 Site**	
O-Horizon	**Effect of Barrier**	**Effect of Capsule**	**Effect of Barrier**	**Effect of Capsule**
Sulfur	0.77	0.03	0.03	0.04
Nitrate	0.48	0.08	0.80	0.050
Phosphate	0.26	0.19	0.12	<0.0001
Sodium	0.39	0.29	0.05	0.01
Ammonium	0.16	0.04	0.48	<0.0001
Potassium	0.48	0.08	0.69	<0.0001
Magnesium	0.19	0.25	0.28	0.53
Calcium	0.26	0.34	0.28	0.14

Chloride	0.23	0.23	0.19	0.84
Total N	0.21	0.21	0.42	0.57
Total C	0.61	0.75	0.44	0.16
C/N	0.84	0.42	0.87	0.24
KCl-ammonium	0.56	0.70	0.87	0.70
KCl-nitrate	0.17	0.17	0.16	0.25
Bicarb-P	0.16	0.15	0.05	0.36
Mineral Soil				
Sulfur	0.46	0.29	0.35	1.00
Nitrate	0.34	0.69	0.20	0.07
Phosphate	0.72	0.84	0.79	0.48
Sodium	0.20	0.71	0.25	0.39
Ammonium	0.79	0.78	0.78	0.97
Potassium	0.68	0.19	0.04	0.62
Magnesium	0.36	0.36	0.31	0.11
Calcium	0.82	0.39	0.50	0.69
Chloride	0.90	0.15	0.92	0.08

Total N	0.77	0.15	0.87	0.78
Total C	0.44	0.55	0.97	0.37
C/N	0.51	0.32	0.78	0.13
KCl-ammonium	0.30	0.39	0.75	0.23
KCl-nitrate	0.87	0.13	0.80	0.98
Bicarb-P	0.20	0.41	0.53	0.95

Table 8: Average nutrient concentrations with the standard error, maximum concentrations, and maximum volume collected for interflow and snowmelt for both sites. Three runoff and three snowmelt collectors were placed at two field sites in the King's River Experimental Watershed to monitor nutrient concentrations in the snowmelt and runoff. Due to site access, samples were randomly obtained. The collection dates for the season were 10th of October 2010, 4th of November 2010, 13th of January 2011, 11th of February 2011, 20th of April 2011, 24th of May 2011, 2nd of June 2011, and 22nd of June 2011. The samples are by site name, either R for runoff or S for snowmelt, then the number of the collector.

Average Interflow and Snowmelt Concentrations with Standard Error and Total Volume Collected for Individual Collectors (µeq·L^{-1})

Collector	**Volume (L)**	**$S0_4^-$**	**NO_3^-**	**PO_4^-**	**Na^+**	**NH_4^+**	**K^+**	**Mg^{2+}**	**Ca^{2+}**	**Cl^-**
Tower-1R	7.15	12.03 ± 2.26	27.06 ± 12.97	30.71 ± 11.16	5.16 ± 3.49	22.50 ± 21.51	68.66 ± 43.88	18.20 ± 11.72	76.96 ± 63.37	102.72 ± 18.23
Tower-2R	2.51	10.38 ± 1.98	5.72 ± 1.93	23.61 ± 6.50	22.45 ± 8.88	11.24 ± 6.62	79.17 ± 36.35	35.46 ± 17.78	93.37 ± 47.58	83.23 ± 15.83
Tower-3R	21.79	10.19 ± 2.38	18.42 ± 5.55	10.76 ± 2.46	10.05 ± 8.48	14.80 ± 11.17	19.42 ± 12.11	8.09 ± 3.89	29.85 ± 16.22	88.80 ± 18.31
Tower-1S	0.33	24.68 ± 5.56	205.03 ± 86.71	49.71 ± 12.11	9.71 ± 6.61	35.58 ± 35.11	118.43 ± 68.04	29.37 ± 15.70	96.68 ± 73.62	202.25 ± 129.02
Tower-2S	5.97	11.29 ± 2.47	69.66 ± 27.38	40.45 ± 7.65	31.27± 16.98	25.51 ± 18.58	118.54 ± 57.16	28.69 ± 14.31	52.95 ± 23.37	96.78 ± 26.87
Tower-3S	4.51	5.03 ± 1.79	12.45 ± 3.22	1.97 ± 1.46	17.34 ± 9.26	16.82 ± 12.54	10.05 ± 4.00	10.97 ± 3.73	37.21 ± 13.85	118.24 ± 39.55

P301-1R	4.79	7.43 ± 3.53	38.93 ± 32.8	23.44 ± 1.38	50.34 ± 23.16	82.63 ± 5.77	105.31 ± 26.74	31.98 ± 2.54	143.06 ± 21.78	79.49 ± 36.26
P301-2R	2.33	7.64 ± 1.10	25.84 ± 5.21	16.48 ± 3.51	32.81 ± 26.08	38.82 ± 20.65	89.89 ± 31.05	36.31 ± 13.21	155.93 ± 53.48	52.40 ± 26.51
P301-3R	11.37	6.25 ± 1.45	76.86 ± 40.28	50.44 ± 17.23	18.76 ± 7.54	19.98 ± 10.01	81.91 ± 38.14	23.04 ± 8.08	89.74 ± 34.09	87.24 ± 16.34
P301-1S	7.30	52.71 ± 20.54	30.16 ± 17.62	250.46 ± 68.72	37.66 ± 14.70	380.35 ± 151.01	90.86 ± 24.40	24.88 ± 8.91	61.60 ± 21.85	118.66 ± 25.94
P301-2S	11.23	8.92 ± 1.86	27.63 ± 10.25	7.32 ± 3.21	15.46 ± 9.25	24.50 ± 7.77	13.40 ± 5.29	11.23 ± 4.34	25.11± 7.04	89.31 ± 19.46
P301-3S	11.80	11.92 ± 2.37	26.60 ± 12.09	20.84 ± 5.69	25.66 ± 9.85	64.07 ± 23.71	60.89 ± 17.64	17.88 ± 5.80	37.72 ± 7.85	84.35 ± 19.13

Average Interflow and Snowmelt Concentrations with Standard Error and Total Volume Collected for Each Site (μeq.L^{-1})

Tower R	31.45	10.90 ± 1.22	17.59 ± 5.29	22.41 ± 4.69	12.68 ± 4.32	16.25 ± 8.19	57.57 ± 20.11	21.21 ± 7.61	68.57 ± 27.41	91.73 ± 9.73
Tower S	10.80	12.88 ± 2.81	80.57 ± 33.01	36.46 ± 7.90	20.13 ± 7.07	25.94 ± 12.46	79.76 ± 29.56	22.55 ± 6.78	59.82 ± 21.99	137.49 ± 41.21
P301 R	18.48	6.90 ± 1.00	53.53 ± 20.94	33.76 ± 8.86	29.54 ± 9.35	38.22 ± 10.79	89.20 ± 20.72	28.75 ± 5.43	120.08 ± 23.34	75.33 ± 12.76
P301 S	30.32	25.06 ± 8.13	28.20 ± 7.63	105.63 ± 37.92	26.78 ± 6.84	160.32 ± 61.34	54.79 ± 11.96	18.00 ± 3.89	41.64 ± 8.62	98.01 ± 12.54

Maximum Interflow and Snowmelt Values (μeq·L^{-1})

Tower-1R		0.20	23.50	99.43	83.33	24.09	151.53	250.20	83.59	455.52
Tower-2R		15.35	12.27	45.64	51.43	38.08	270.92	131.75	344.89	128.85
Tower-3R		17.12	42.14	17.05	52.06	69.69	67.25	20.49	105.67	127.39
Tower-1S		37.60	298.30	75.40	28.28	140.90	243.28	61.36	315.03	575.07
Tower-2S		15.81	122.55	55.90	78.75	95.82	268.10	71.55	116.39	144.81
Tower-3S		11.57	24.16	3.42	41.31	53.64	17.80	20.81	82.41	251.91

P301-1R	12.53	71.73	25.22	93.57	88.41	154.64	34.71	171.95	115.75
P301-2R	10.13	35.32	23.44	110.73	93.42	140.22	61.20	258.70	121.70
P301-3R	11.79	249.96	109.23	55.84	55.60	282.96	59.97	265.91	136.19
P301-1S	185.67	151.30	501.97	122.74	1022.13	176.38	75.11	191.93	227.11
P301-2S	20.07	82.10	21.59	66.26	57.91	44.45	40.87	68.59	147.43
P301-3S	21.72	88.80	43.24	59.89	170.32	115.32	44.56	70.76	141.88

Figures

Figure 1: Site location map for the King's River Experimental Watershed (KREW). The map was taken from the Southern Sierra Critical Zone Observatory (CZO) website (https://eng.ucmerced.edu/czo/sites.html).

Figure 1: Decagon® grid layout for the P301 site. This grid was established to measure soil water content using Decagon® soil moisture probes. Fifteen of the sixteen sampling points were instrumented with a probe. Eight of the sampling points containing a probe were located in a barrier designed to intercept O-horizon interflow. The symbol X is a sample point with a barrier, a letter (ABC) refers to the data logger ID positioned on the tree and P refers to the probe ID.

Figure 2: Schematic of the 4x5 meter litter bag grid established for one year at both sites (Tower and P301). Litter bags were placed at each of the twenty sampling points (ten in barriers and ten on the open O-horizon).

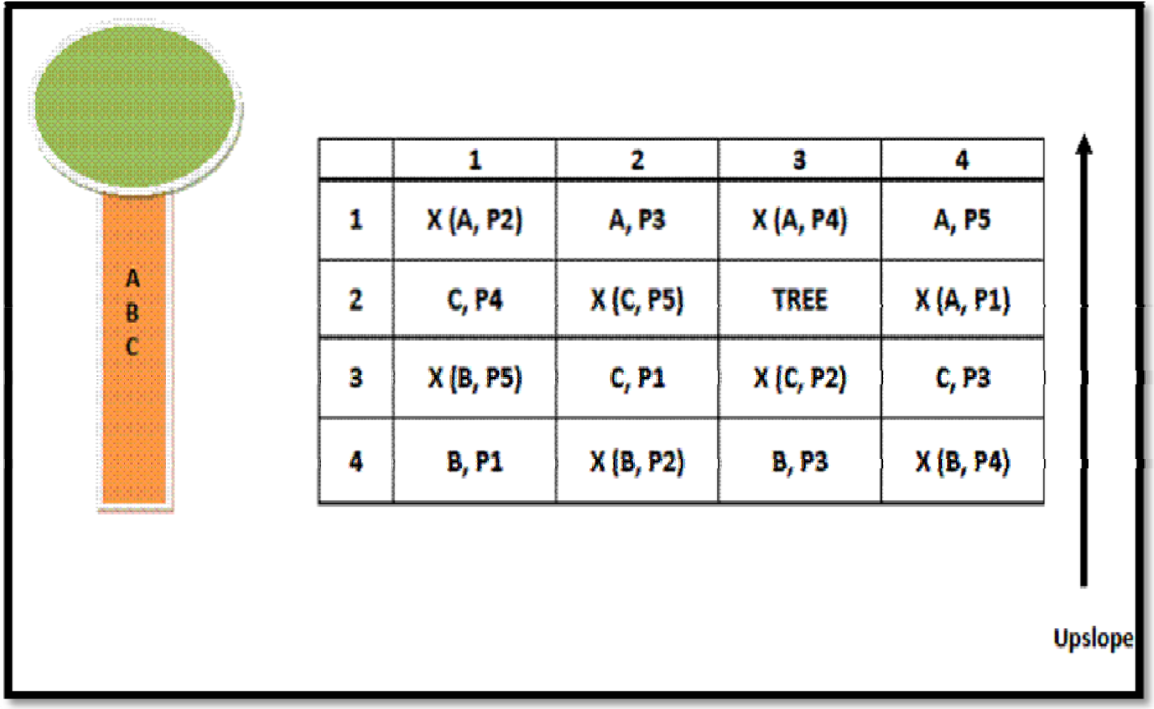
Figure 3: Schematic of the barrier sampling grid located at both field sites (Tower and P301). Barriers were used to truncate interstitial flow in the O-horizon. The grid was 7x7 meters and consisted of 64 sampling points at one meter intervals with 4 different types of points; barrier only, UniBest® resin capsule only, a barrier with a UniBest® resin capsule, and a control point marked by a flag. After one year the resin capsules were removed and a soil core sample was taken from each of the 64 sampling points.

Figure 4: Box plots of the PRS™ probe data. Four probes (two cation and two anion) were placed in the soil at 16 different sampling points along a 4x4 meter grid. Two probes (one cation and one anion) were placed parallel (Pa) with respect to the slope and two probes (one cation and one anion) were placed perpendicular (Pe) with respect to the slope on a local scale. The perpendicular alignment exposed more membrane surface area to interstitial flow.

Figure 5: Box plots of the resin capsule data. Sixteen capsules were placed in a barrier that truncated interstitial flow in the O-horizon and 16 capsules were located in the open O-horizon.

Figure 1

Figure 2



	1	2	3	4
1	X (A, P2)	A, P3	X (A, P4)	A, P5
2	C, P4	X (C, P5)	TREE	X (A, P1)
3	X (B, P5)	C, P1	X (C, P2)	C, P3
4	B, P1	X (B, P2)	B, P3	X (B, P4)

Figure 3

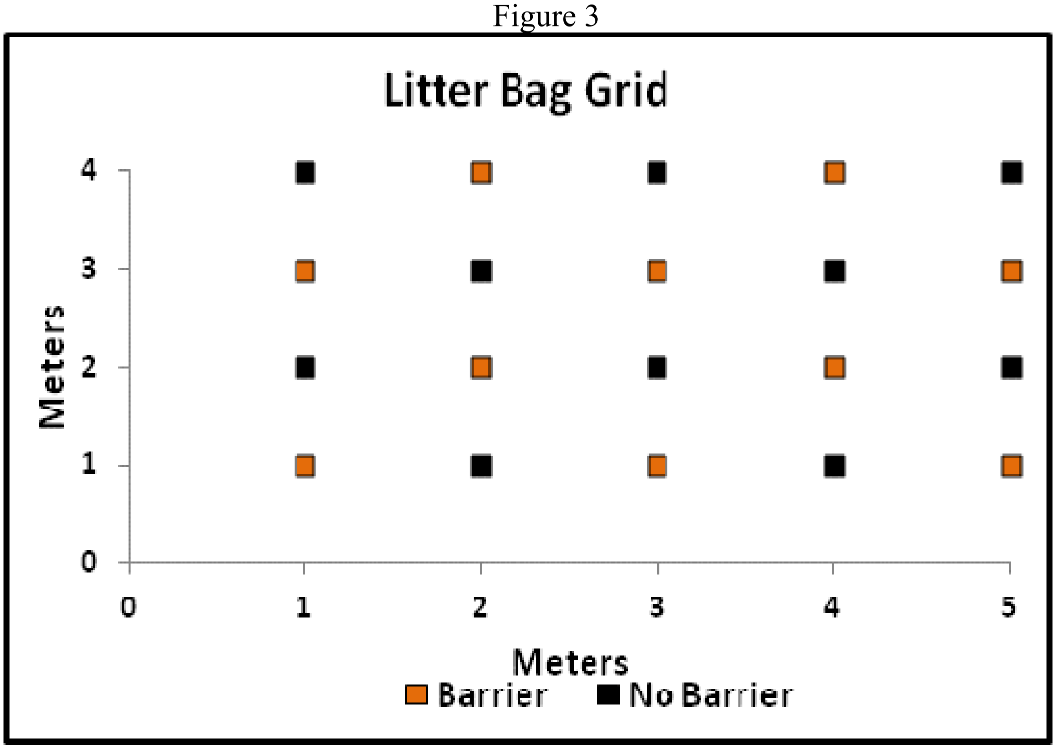

Litter Bag Grid
Meters
4
3
2
1
0
0
1
2
3
4
5
Meters
Barrier
No Barrier

Figure 4

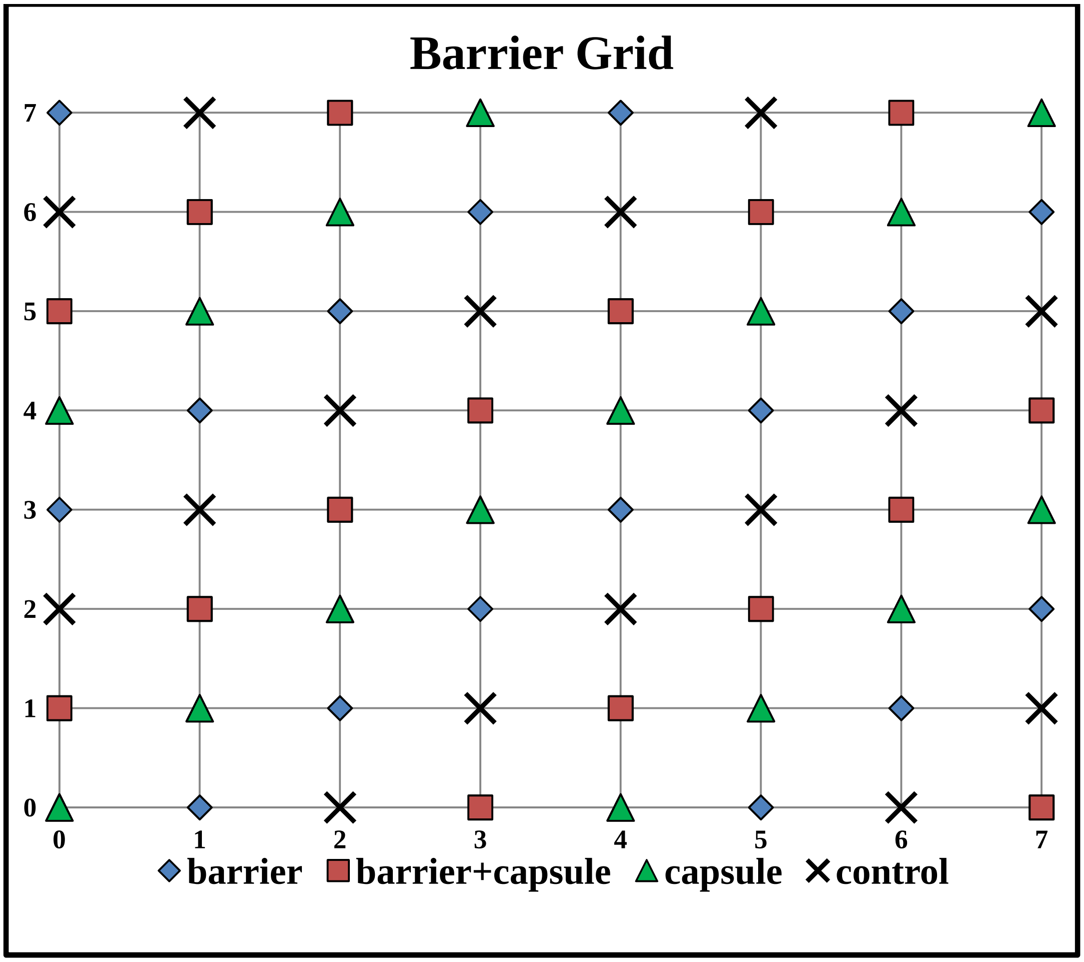

Barrier Grid
0
1
2
3
4
5
6
7
barrier
barrier+capsule
capsule
control

Figure 5

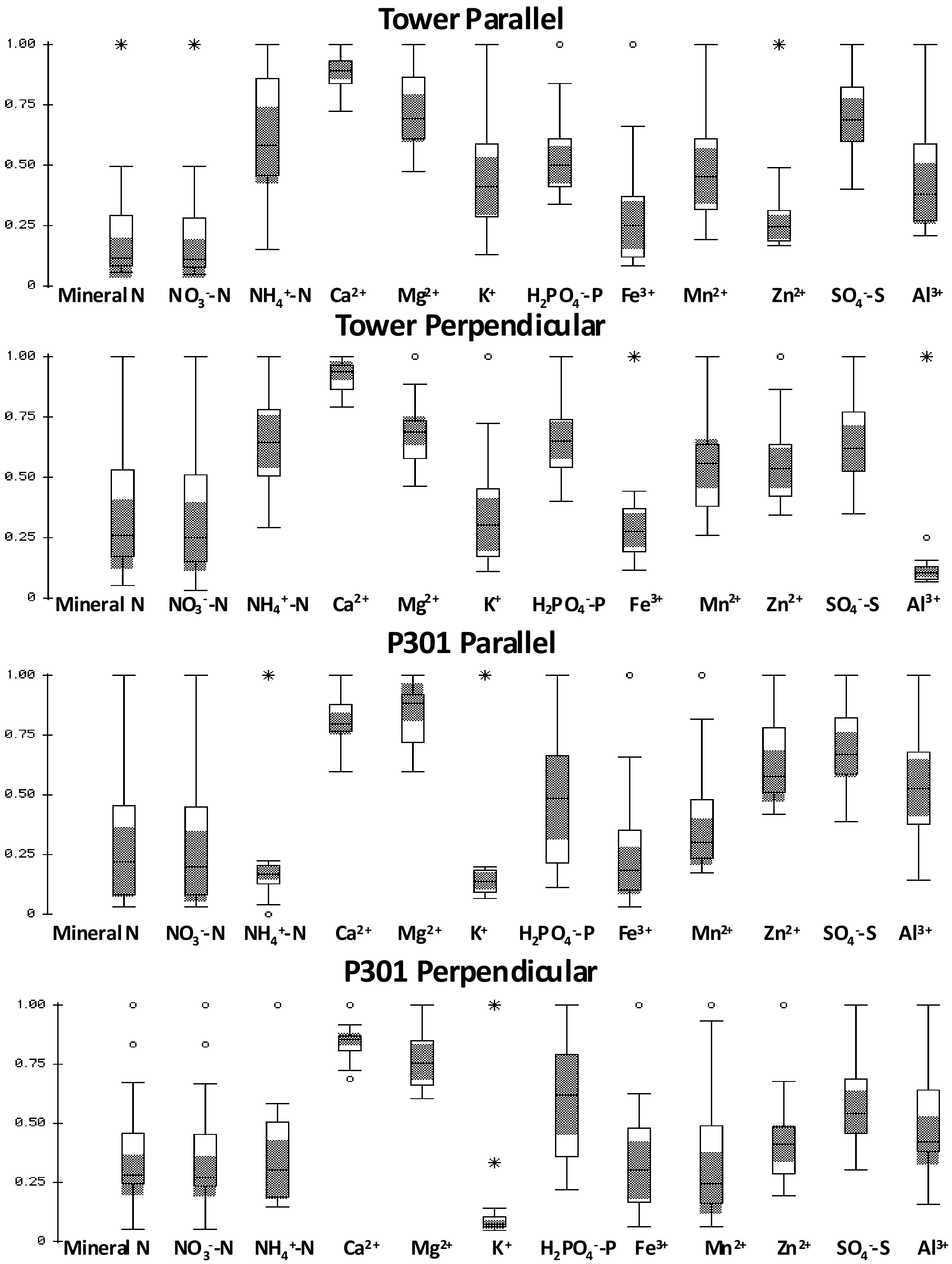
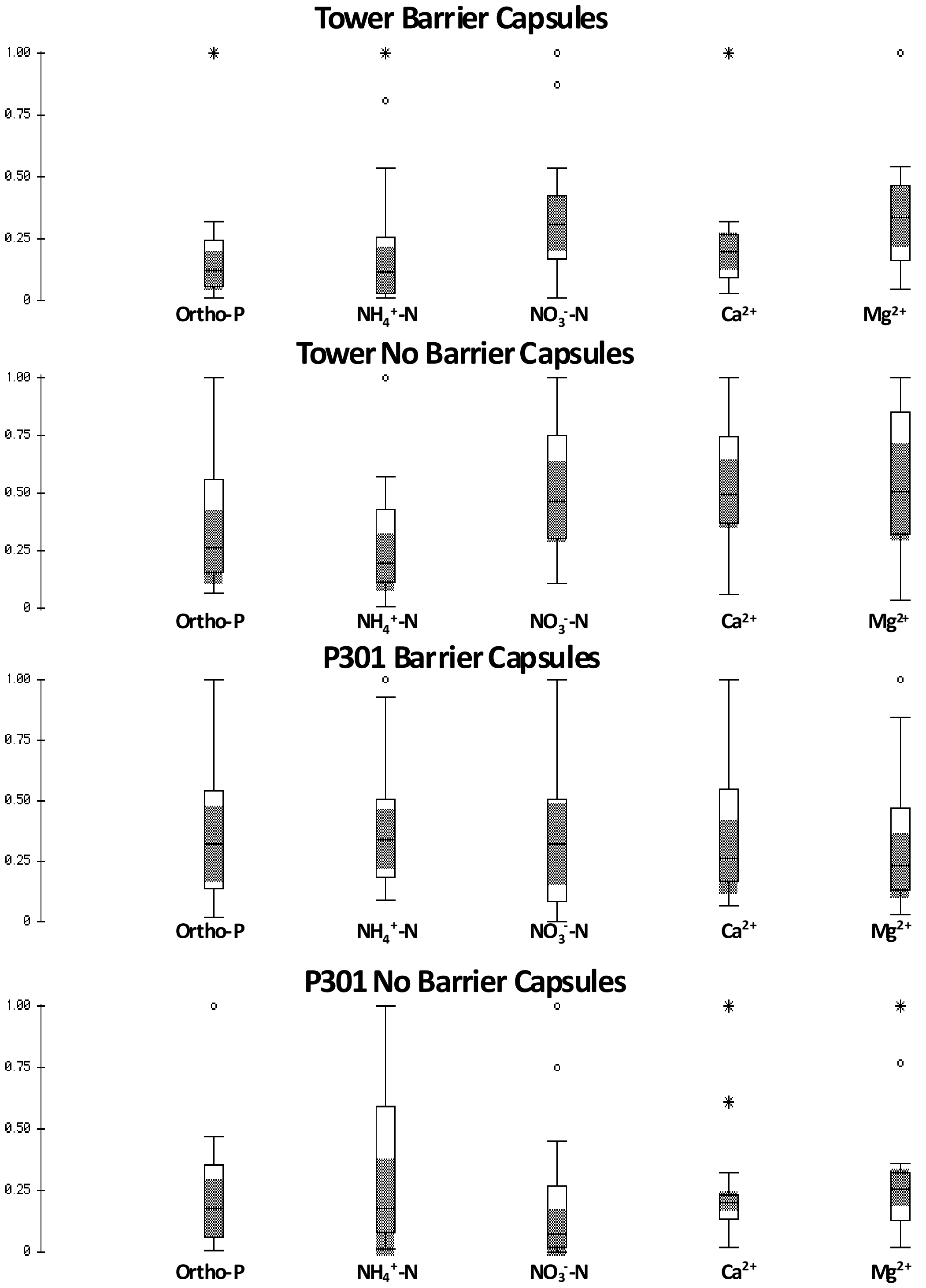

Tower Parallel
Tower Perpendicular
P301 Parallel
P301 Perpendicular
1.00
0.75
0.50
0.25
0
Mineral N
NO_3^--N
NH_4^+-N
Ca^{2+}
Mg^{2+}
K^+
$H_2PO_4^-$-P
Fe^{3+}
Mn^{2+}
Zn^{2+}
SO_4^--S
Al^{3+}

Figure 6


Tower Barrier Capsules
1.00
0.75
0.50
0.25
0
Ortho-P
NH_4^+-N
NO_3^--N
Ca^{2+}
Mg^{2+}
Tower No Barrier Capsules
1.00
0.75
0.50
0.25
0
Ortho-P
NH_4^+-N
NO_3^--N
Ca^{2+}
Mg^{2+}
P301 Barrier Capsules
1.00
0.75
0.50
0.25
0
Ortho-P
NH_4^+-N
NO_3^--N
Ca^{2+}
Mg^{2+}
P301 No Barrier Capsules
1.00
0.75
0.50
0.25
0
Ortho-P
NH_4^+-N
NO_3^--N
Ca^{2+}
Mg^{2+}

THESIS CONCLUSIONS

Although the conclusions are summarized following each chapter, a brief thesis conclusion will be summarized here. A greater understanding of hot spot formation on a local scale is important in the Sierra Nevada Mountains due to the changing landscape. Fire suppression has caused an increase in the build-up of O-horizon on the forest floor. This leads to an increase in nutrient availability and a likely increase to nutrient hot spot formation in the mineral soil. These hot spots are a probable mechanism for plants to outcompete microbes for nutrients, therefore increasing nutrient availability in the soil, and subsequently increasing above ground vegetation. Furthermore, increased nutrient concentrations in preferential flow paths could also increase nutrient stream loads and decrease water clarity. Having an increased understanding of nutrient hot spots in the soil can help gain a greater understanding to changing landscapes and lead to better management practices.

1. Nutrient hot spots in a Western Sierra Nevada soil do exist and can vary in size from 2 cm to 40cm^2.
2. One should proceed with caution when using resin based sampling methods for nutrient hot spots determination and realize the sampling methods limitation for under snow sampling.
3. Inorganic nitrogen was the most frequent hot spot found regardless of sampling method. Furthermore, nitrate water extractable hot spots in the

mineral soil were most commonly located in locations of low concentrations for the other nutrients.

4. Microbial biomass may or may not show a hot spot location suggesting that microbial activity is not necessary for hot spot formation.
5. Finally, a 17% increase in moisture content in the O-horizon caused by truncating interflow did not increase the formation of hot spots or mean nutrient concentrations in the mineral soil; however it did increase decomposition rates in the O-horizon at one of the two field sites.