Spatial and Temporal Variation of Forest Floor, Throughfall, and Stemflow Properties Associated with Bigleaf Maple in a Mixed Conifer Forest of Coastal British Columbia

by

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Abstract

Bigleaf maple (*Acer macrophyllum* Pursh) is a large deciduous tree that is abundant in western North America. This study addressed whether the predicted increase in abundance of bigleaf maple because of climate change could influence forest hydrology and site fertility due to species-specific effects on incident rainfall distribution and nutrient cycling. The study examined the spatial and temporal variation of forest floor, throughfall, and stemflow properties associated with bigleaf maple in a forest dominated by conifers.

In bigleaf maple plots, the throughfall enrichment ratio of major chemicals was highest for NO_3 during the leafed period and for P, K, Ca, and Mg during the leaf senescence period. The fluxes of DOC, total-N, DON, P, K, Ca, Mg, S, and SO_4 in throughfall were higher in the leafless period than the leafed period. Compared to conifer trees, throughfall was larger for bigleaf maple and had a higher pH, and concentrations and fluxes of P and K. Similarly, stemflow of bigleaf maple had higher pH, and K concentration. The under-canopy and near trunk forest floor associated with bigleaf maple trees showed higher pH, total exchangeable bases, cation exchange capacity and concentrations of exchangeable Ca and Mg compared to Douglas-fir. The application of the PCNM method enabled us to segregate the broad and fine spatial patterns and to extract the main factors impacting forest floor pH and possibly other soil properties at multiple scales. It revealed that topography mainly acts broadly and canopy cover, canopy density and moisture content act at a finer scale. A random design has a higher accuracy in mapping the spatial distribution of forest floor pH and NH_4 compared to stratified random and systematic cluster designs, and a sample size of 50 seems to be adequate for mapping the spatial structure of both variables.

This study contributes to the understanding of species-specific impacts on soil properties in a mixed forest and suggests that bigleaf maple has a positive effect on site quality. This would enable it to have legacy effects on soil fertility, enhance overall ecosystem resilience, and promote conifer productivity later in succession following mortality of bigleaf maple.

Keywords: Bigleaf maple, spatial variation, temporal variation, throughfall, stemflow, forest floor, soil fertility

To

the

Soul

of

My

Father

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List of Acronyms

AES	Atomic Emission Spectrometer
%	Percentage
Al	Aluminum
B	Trunk basal area (m^2)
B	Boron
BS	total S content, TEB, BS, and CEC were significantly higher (Pg65)
C	Carbon
C:N	Carbon to nitrogen ratio
Ca	Calcium
$CaCl_2$	Calcium Chloride
CEC	Cation Exchange Capacity
Cl	Chlorine
cm	Centimetre
CO_2	Carbon Dioxide
Cu	Copper
CV	Coefficient of Variation
CWHdm	Coastal Western Hemlock subzone
ºC	Degrees Centigrade
D	Distance
DBH	Diameter at Breast Height
DOC	Dissolved Organic Carbon
DON	Dissolved Organic Nitrogen
EXCH	Exchange
F	Foliage
Fe	Iron
G -Test	Goodness-of-prediction Test
H^+	Hydrogen Ion
H	Hydrogen
HNO_3	Nitric Acid
ICAP	Inductively Coupled Argon Plasma
ICP	Inductively Coupled Plasma

IP	Influence potential
K	Potassium
Kg	Kilogram
KS	Kolmogrov-Smirnov
Li	Lithium
LISA	Local Indicators of Spatial Association
LNCSR	Lebanese National Council for Scientific Research
LS	Leaf Senescence
LSD	Least Significant Difference
m	Metre
MAX	Maximum
Mm	Millimetre
Mg	Magnesium
MIN	Minimum
MKRF	Malcolm Knapp Research Forest
Mn	Manganese
MSE	Mean Square Error
MEM	Moran's eigenvector maps
N	Nitrogen
N	Population Size
Na	Sodium
NH_4	Ammonium
$NH_4 - N$	Ammonium
NO_3	Nitrate
$NO_3 - N$	Nitrate
Nugget/Sill	Nugget to Sill variance ratio
ON	Ontario
P	Phosphorus
P	Depth equivalent of gross incident precipitation (mm)
PASSAGE	Pattern Analysis Spatial Statistics and Geographic Exegis
PCNM	Principal Coordinate analysis of Neighbour Matrices
PCoA	Principal Coordinate Analysis
pH	Potential Hydrogen

P1	Period 1
P2	Period 2
P3	Period 3
P4	Period 4
P5	Period 5
P6	Period 6
P7	Period 7
P8	Period 8
P9	Period 9
P10	Period 10
Q-Q Plots	Quantile-Quantile Plot
RDA	Redundancy Analysis
RF	Rainfall
S	Sulfur
SD	Standard Deviation
SF	Stemflow
Si	Silicon
SO_4	Sulfate
spp	Species
SPSS	statistical package for the social sciences
TER	Throughfall Enrichment Ratio
TEB	Total Exchangeable Bases
TOC – V	Total organic carbon
Total – N	Total nitrogen
UK	United Kingdom
USDAFS	United States Department of Agriculture Forest Service
Zn	Zinc

Preface

In Chapter 2, I co-designed the study design and I conducted the field work, lab analysis, statistical analysis, and manuscript writing. Dr. Margaret Schmidt helped initiate the project, proposed the initial study design, and assisted in manuscript preparation. Dr. Ilja van Meerveld also assisted with designing the study.

In Chapter 3, I co-designed the study design and I conducted the research, including the field data collection, lab analysis, statistical analysis, and manuscript writing. Dr. Margaret Schmidt helped initiate the project, and assisted in manuscript preparation.

In chapter 4, I co-designed the study and conducted the research, including the data collection, statistical analysis, and manuscript writing. Dr. Margaret Schmidt assisted with the analytical analysis and manuscript preparation. Dr. Marie-Josée Fortin assisted with the experimental analytical analysis.

In chapter 5, I designed the study and conducted the research, including the data collection, statistical analysis, and manuscript writing. Dr. Margaret Schmidt assisted with the manuscript preparation.

Chapter 1.

Introduction

There is a direct impact of forest structure on ecosystem function. For instance, leaf area influences interception and distribution of incident rainfall; gaps in dense canopies facilitate the regeneration of trees, shrubs, and herbs; and large live and dead trees provide specialized habitats for many species (Spies, 1998). Forest structure is shaped by several factors including climate, wind, fire, succession, and forest management (Gitay, Brown, Easterling, & Jallow, 2001; Spies, 1998). Climate is considered the major factor controlling global patterns of vegetation structure and plant and animal species composition (Gitay et al., 2001). The change in climate is predicted to cause a shift in ecosystem structure, including predominant vegetation, age class distribution, and species composition (Gayton, 2008).

In forest ecosystems, species-specific effects of vegetation on soil fertility and forest hydrology have been reported (Alexander & Arthur, 2010; Gast, 1937; Levia & Frost, 2003; Sabau, Schmidt, & Krzic, 2010; Turk, Schmidt & Roberts, 2008; Zinke, 1962). Species-specific variation in morphological characteristics of trees influences incident rainfall interception and distribution, evaporation, water status, understory microclimate, nutrient inputs, and leaching (Levia & Frost, 2003). Species-specific differences in leaf litter quantity and quality influence decomposition rates and nutrient availability (Turk, 2006). Therefore, a shift in forest structure and species composition will lead to a shift in ecosystem function, including forest hydrology, decomposition and nutrient cycling, and site fertility and productivity (Gayton, 2008).

In coastal forests of British Columbia, several naturally occurring deciduous species are expected to increase in abundance and distribution because of climate change (Hamann & Wang, 2006). The effects of these changes remain unclear. How would this affect forest hydrology at a plot scale? Does this affect water and nutrient

redistribution through the tree canopy (throughfall) and along the tree stem (stemflow)? Do throughfall and stemflow affect forest floor properties? To what spatial extent do these processes affect forest floor properties? Are the observed spatial patterns of forest floor properties related to individual trees? What sample size is needed to detect the spatial patterns of forest floor properties? There is no easy way to address these questions, given the inherent variability of soil properties and the uncertainties associated with climate change (Gayton, 2008; Trangmar, 1985). Hence, a detailed examination of the temporal and spatial variation of throughfall, stemflow, and forest floor properties associated with existing deciduous and coniferous trees may provide insights about current and future species-specific effects on forest hydrology and nutrient cycling.

Background Literature

Species-Specific Effects on Site Fertility

Conifer Trees

A number of studies have assessed the pattern of influence of individual trees on soil properties. One of the first studies (Zinke, 1962) measured soil properties at different distances from individual forest trees (all conifers). Zinke (1962) found that the pattern of soil properties under the individual trees had generally radial symmetry to the tree such that, there was a regular change in pH, N content and exchangeable bases away from the tree. Soil pH was lowest near the tree stem and increased with distance from the tree, while N content and exchangeable cations decreased with distance from the trunk. Zinke (1962) stated that the pattern in soil properties was related to the effects of leaf litter, bark litter, and the neighbouring tree or adjacent opening, and suggested that stemflow and throughfall would yield rain water with different solute concentrations which may lead to differences in soil properties. Zinke (1962) concluded that there is a general predictable pattern in soil chemistry surrounding individual trees.

This pattern is a set of rings influenced by an inner ring of bark litter, an outer ring of leaf and twig litter, and the adjacent marginal effect of an opening or the corresponding influence ring of a nearby tree. Another paper by the same author (Zinke & Crocker, 1962), studied the spatial influence of giant Sequoia (*Sequoia gigantean*

(Lindl.) decne) on soil properties. Zinke & Crocker (1962) found that the bulk density and the amount of clay content per unit volume decreased with distance from the tree trunk to a minimum of 3 m. For the C and N concentrations, there was an increasing trend till a distance of 3 m, where they reached the maximum. The N content of the samples decreased at greater distance. The trend beyond the crown projection varied, perhaps depending upon adjacent conditions. There was little change in pH with distance from the tree, although some of the studied sites showed some tendency toward a more acidic condition near the tree trunk. Similarly to Zinke (1962), the conclusion was that soil properties develop a typical radial or lateral variation till a distance of 3 m from the bole of the tree. Based on this, Zinke (1962) suggested that the variation in soil properties (bulk density, clay content per unit volume, N content, and pH) is related to the properties and amounts of surface humus, modified canopy drip and stemflow.

The early studies by Zinke (1962) and Zinke & Crocker (1962) were the basis for the emergence of a framework for species-specific effects on soil properties, which is expressed as "single-tree influence circles" as quoted by Boettcher et al. (1990) or “tree influence potential (IP)” as quoted by Saetre (1999). Many studies have investigated the validity of this framework in different ecosystems, exhibiting different forest covers (conifer vs. deciduous trees) or topography (Crampton, 1982; Crampton, 1984; Boettcher & Kalisz, 1990; Escudero & Hernandez, 1991; Amiotti, Zalba, Sanchez, & Peinemann, 2000; Rhoades & Binkley, 1992; Eldridge & Wong, 2005).

A number of studies investigated the soil patterns surrounding individual conifer trees. For instance, Crampton (1982; 1984) studied soils at varying distances (near tree stem, mid-canopy, periphery of tree canopy) from individual Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco), western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) and western redcedar (*Thuja plicata* Donn.), and found the lowest pH near tree stems. The pH increased towards the mid-canopy and decreased at the periphery of the tree canopy. He suggested that this variation in pH could be attributed to throughfall and stemflow. Crampton (1982, 1984) argued that rain water passing through the canopy and along the stem of conifer trees becomes acidified, and although the amount of acidified water reaching the soil from throughfall is greater than that from stemflow, stemflow water is more acidified.

Boettcher and Kalisz (1990) examined the influence of *Tsuga canadensis* L. and *Liriodendrom tulipifera* L. on soils on the steep slopes of the Appalachian Mountains in the eastern USA, and found that the pH and the element concentrations of Ca, K, and Mg were higher under *L.tulipifera* trees. This was attributed to the more basic nature of the *L.tulipifera* foliage. They concluded that the single tree influence is valid even on mountainous steep slopes.

Escudero et al. (1991) studied spatial patterns in soil properties around pine trees (*Pinus pinea* L.) growing in an open canopy. They found that measured soil properties (pH, organic matter and total N concentration) were lowest at the base of a tree stem and increased away from the stem. Litterfall from pine had acidifying effects especially near the base of the trunk. They found the most apparent effects on soil properties at the base of the stems with the influence decreasing outward to the edge of the crowns. Amiotti et al. (2000) studied the validity of the single tree influence of *Pinus radiata* D.Don on grassland soil properties in Argentina, and found that soil pH and concentrations of Ca, and Mg increased with distance from the tree trunk, whereas the concentrations of H and Al decreased with distance from the trunk.

Broadleaf Trees

In contrast to conifers, broadleaf trees are known for their rapidly decomposing litter that is more basic in nature than that of conifers. Hence one would expect a different pattern of influence of deciduous trees on the surrounding forest floor. Rhoades and Binkley (1992) studied the spatial effect of red alder (*Alnus rubra* bong.) in a conifer stand. Samples were collected based on the belt transect method from two stands, one with an alder-conifer mix and the other pure conifer. They found an increase in the concentration of ammonium (NH_4) in the alder-conifer strip, being lower at the extremities of the strip and increasing toward the middle of the strip. The extent of the spatial influence of the ammonium was found to be greatly affected by the slope, where it extended to a distance of 8-12 m down slope with no effect up slope. As for the pH, their study indicated no pattern along the transects; however, it was noticed that the pH in the conifer stand was higher than in the alder-conifer strip, with no impact of the slope on pH. In their discussion they do not provide an interpretation of how it is possible for a conifer stand with acidic litterfall to have a less acidic soil than the mixed stand, in which the basic leaves of the alder trees are expected to decrease the acidity of the soil. One

possibility for the increase in soil acidity in the alder-conifer stand is H production during nitrification (Binkley & Sollins, 1990).

Escudero et al. (1991) studied spatial patterns in soil properties around individual oak trees (three species) growing in an open canopy. They found that measured soil properties (pH, organic matter and total N concentration) were greatest at the base of oak stems and decreased away from the stems, and stated that stemflow was an important process influencing soils surrounding oak trees. Eldridge and Wong (2005) studied the spatial influence of clumped (20-30 m separating the tree trunks) and isolated Eucalyptus trees in Australian temperate box woodland. They found clear patterns in soil properties corresponding to increasing distance from the tree trunk. In both tree configurations: pH, electrical conductivity, available P, soluble Ca and Mg were higher near the tree trunk and decreased with distance outward from the tree stem. However, no clear pattern as a function of distance from the trunk was observed for C, N, and S. They explained their findings by the fact that the bark of Eucalypt spp. contains high concentrations of Ca; hence, bark can increase Ca concentrations near the tree trunk.

Chandler et al. (2008) examined soil properties in two 36 x 36 m grids centred at bigleaf maple trees and found that most soil chemical properties had higher concentrations in locations adjacent to stem. In addition, Chandler (2006) studied the spatial influence of bigleaf maple on soil pH, along six transects extending upslope and to a greater extent down slope from the trunk of bigleaf maple. She found that bigleaf maple stems increased the pH up to a distance of 1.5 m upslope of the stem and this pattern of influence extended to a distance of 2.5 m down slope. Results from both studies were explained by suggesting that this could be a response to the flow of water, carrying base cations from the tree foliage and tree bark down the tree branches and stem into the surrounding forest floor. In addition, her results indicated that the forest floor pH within the stem influence and beneath canopy extent was higher than outside the canopy extent.

Processes Responsible for Species-Specific Effects on Site Fertility

There is a general agreement in the literature that the differences and variations in soil chemical properties (pH, N content, and exchangeable cations) with respect to

distance from tree stems can be attributed to barkfall, litterfall, stemflow and throughfall (Zinke, 1962; Zinke & Crocker, 1962; Crampton, 1982; Crampton, 1984; Escudero & Hernandez, 1991; Boettcher & Kalisz, 1990; Rhoades & Binkley, 1992).

Litterfall and Barkfall

Some generalizations have been made concerning the impacts of conifer and broadleaf tree litterfall on soil properties. Broadleaves, generally (with some exceptions), have litter with higher pH, that decays faster and has higher element concentrations compared to conifer litter (Fisher & Binkley 2000; Augusto, Ranger, Binkley, & Rothe, 2002).

The higher pH and element concentrations of broadleaves are well documented in a number of old and recent studies (Augusto et al., 2002). A recent study by Turk (2006) showed that bigleaf maple canopies have greater litterfall, containing higher elemental concentrations (almost all macronutrients, as well as the micronutrients Mn, B, Zn, and Cu), compared to Douglas-fir, western hemlock, and western redcedar. This is in agreement with a previous study conducted by Fried (1985) on the same species; he found that bigleaf maple had greater litterfall weight and nutrient content compared to Douglas-fir. Another study conducted on vine maple in British Columbia revealed that the litter from vine maple had a higher pH, and higher concentrations of Ca, Mg, and K in the forest floor relative to the conifer dominated forest floor (Ogden & Schmidt, 1997).

The nutrient rich litter of broadleaf trees has a fast decomposition rate under favourable temperature, moisture, and oxygen availability conditions (Van Breeman, 2002). The minimum time required to decompose the litter of almost all conifers (needles) is twice the time required by broadleaf litter to decompose (Van Breeman, 2002, Waring, 2002). This low decay rate is partially explained by the fact that, in general, the leaf litter of conifers contains twice the amount of C in relation to N than broadleaved litter (Waring, 2002) and the relatively high lignin content in conifer litter compared to broadleaves (Taylor et al., 1989). Thus, differences in litter inputs and decomposition rates between broadleaves and conifers can lead to differences in forest floor properties (greater accumulation of forest floor under conifers) and possibly nutrient availability (Waring, 2002).

It is logical to assume that the barkfall would accumulate at the bottom of the stem. Hence, its decomposition contributes to characterizing the soils near the trunk. However, barkfall and decomposition are slow processes and barkfall did not accumulate to a significant level in most of the reviewed studies. Nevertheless, bark is expected to affect soil properties by affecting stemflow solute concentrations and acidity (Mina, 1967).

Throughfall and Stemflow

Throughfall and stemflow are important components of nutrient cycling in forest ecosystems. Throughfall is the component of precipitation that falls directly to the ground between openings in the forest canopy or as water droplets that drip from the canopy. Throughfall, generally, has higher cation concentrations compared to incident rainfall; however, contradictory findings have been reported about the pH (Reynolds, Cape & Paterson, 1989; Amezaga, Gonzalez, Domingo, Echeandia, & Onaindia, 1997; Andersson, 1990). Reynolds et al. (1989) investigated several ion concentrations (Na, Cl, Mg, Ca, K, and H cations) in throughfall of *Larix decidua* Mill. (larch) and *Pinus sitchensis* Bong. (sitka spruce). They found that the concentrations of all measured ions in throughfall were relatively higher than their corresponding concentrations in the incident rainfall. Amezaga et al. (1997) investigated the variation in the elemental concentration of bulk precipitation passing through the canopies of conifer and broadleaf trees. They found that, in general, intercepted precipitation by conifers was higher than broadleaves (33% and 16% respectively). In addition, the interception in the broadleaves was not affected by the presence or absence of leaves. They attribute this to the structure of the canopy and to the higher density of the conifer canopies compared to broadleaves. In their study (not in all sites), they found that the pH in throughfall was significantly lower than that of rainfall water. These findings are contradicted by the results of Andersson (1990), who evaluated the influence of throughfall from *Quercus robur* L. on soil chemistry on the Swedish west coast. He found that concentrations of Mg and Ca were 3-5 times and of K 10-16 times higher in throughfall than in incident rainfall. The pH of throughfall was also higher than that of incident rainfall.

Stemflow, which differs significantly in terms of solute concentrations from throughfall, is the precipitation which flows along tree branches and down the trunk. The percentage of precipitation that reaches the soil via stemflow varies according to the

bark characteristics of the tree species. When the bark is smooth and dense, the amount of stemflow is expected to be high; however, the concentration of the separate elements and the acidity would be lower (Mina, 1967). The opposite is expected to be true for trees with rough and corky bark, which exhibit less stemflow (Franklin, Gersper & Holowaychuk, 1967). An uneven flow of water may occur along a stem leading to non-uniform distribution of water into the surrounding soils (Gersper & Hollowaychuk, 1970) and hence stemflow may exhibit anisotropic behaviour. Factors that might affect the composition of stemflow are the amount of stemflow during a rainstorm and the length of the dry period interval prior to rainfall (Mina, 1967). As the dry period increases then dry deposition is expected to increase also, hence it would increase the solute concentrations during the subsequent stemflow event.

Gersper and Hollowaychuk (1970) investigated the effects of stemflow from trees on chemical properties of soils. They found that stemflow water is more enriched in elements (K, Ca, Mg, Na, P, Al, Fe, and Mn) compared to rainwater. They concluded that stemflow had an impact on soil properties surrounding American Beech, where soils near the stem of these trees had higher exchangeable K concentrations and lower pH than soils away from the stem.

Chang et al. (2000) investigated the spatial effect of beech stemflow and throughfall on patterns of soil solution chemistry in a mixed beech/oak stand by sampling soil near a beech trunk and at a certain distance from the trunk. Stemflow averaged around 6.6% of the total soil water input into the surrounding soils (total water input from stemflow and throughfall) over the two year study period, and peaked to 16% during large rainfall events. Stemflow and throughfall had much higher concentrations of H, K, and SO_4 compared to rainfall water due to leaching and accumulation of these solutes from plant tissues or washing off dry deposition. K and SO_4 concentrations were 60% higher in stemflow than throughfall, while H concentration was 150% higher. The concentrations of K decreased with distance from the tree stem while the concentrations of Na, Mg, Cl and SO_4 increased. They concluded that stemflow contributed to the formation of spatial heterogeneity in soils surrounding the tree stem where the soils proximal to the tree bole exhibit different ion concentrations than those at distal.

Spatial Heterogeneity: a Consequence of Species-Specific Effects

Spatial heterogeneity is defined as the spatially structured variability of a property of interest (Wagner & Fortin, 2005). In the case of a single tree's influence on surrounding soil chemical properties and due to species-specific effects, spatial heterogeneity is obvious in the pattern of increasing pH, and decreasing N content, and exchangeable cations with distance from a tree trunk (Zinke, 1962). Many processes including, litterfall, throughfall, and stemflow act at a local scale to produce this pattern. Many of the processes of soil formation are scale-dependent as well (Trangmar, 1985). They show different degrees of variability for different scales (Prasolova, Xu, Saffigna, & Dieters, 2000). The local patterns surrounding individual trees are also affected by other processes that are occurring at larger spatial scales such as climate, and topography, or larger temporal scale, such as weathering of parent materials (Jenny, 1941). In fact most of the observed patterns result from several processes that interact with each other (Wagner & Fortin, 2005). Therefore, the nature of soil and its chemical properties are scale dependent and the detected variability in spatial studies of soils depends on the scale of observation (Trangmar, 1985), which in turn depends on the sampling design. More precisely, any detected spatial patterns depend on the layout and the dimensions of the grain, the lag, and the extent of the study (Fortin & Dale, 2005).

The Effect of Sampling Design on the Spatial Pattern Detected

Sampling design plays an important role in detecting the spatial patterns of the variables of interest (Fortin & Dale, 2005). Sampling designs have several components, including sample size, configuration, and scale (Fortin & Dale, 2005; Dungan et al., 2002). Generally, a minimum sample size of n= 30 is required to detect significant spatial autocorrelation (Legendre & Fortin 1989), and reliable estimation of spatial structure may require 100 or more sampling locations. In exceptional cases, where the spatial structure is very strong, a sample size of n= 20 may detect the spatial pattern (Fortin & Dale, 2005).

Sampling Configuration

Sampling configuration can be considered as the layout of the sampling points. Sampling configurations can be categorized into four broad categories: pure random sampling, stratified sampling (along transects with regular or irregular spacing), square

grid sampling, and nested grid sampling (grids with sampling at some shorter spacing in some window areas) (Chiles & Delfiner, 1999; Trangmar et al., 1985). Grid sampling provides more insights to the structure of the spatial patterns. However, it requires more data collection and there is higher cost and more time associated with examining chemical and biological variables of soils. Nevertheless grid sampling may be necessary in certain scenarios (Bond-Lamberty et al., 2006). In the absence of previous knowledge about the spatial structure, scientists usually implement random or systematic sampling (Legendre et al., 2002). However, a study by Fortin et al. (1989) showed that random sampling is more powerful than systematic sampling in detecting spatial structure. This is attributed to the fact that there are many different lag steps which may reflect several different harmonics of the spatial pattern. Nevertheless, to avoid the difficulties in implementing random sampling, a systematic cluster sampling design is recommended. Such a design allows capturing the different lag harmonics of the spatial structure (Fortin et al., 1989). Moreover, a systematic cluster design is favoured for analyzing data containing a broad-scale gradient (Legendre et al., 2002). When there is previous knowledge about the structure of the spatial pattern (no deterministic structure in the environmental variable, gradient in the environmental variable, large patch in the environmental variable, waves in the environmental variable, or two clearly separate zones in the environmental variable) due to previous studies or preliminary pilot studies, then sampling designs that show low type I error and good test power, are recommended for each spatial structure (Legendre et al., 2002). For instance, a systematic sampling design is recommended for spatial structure exhibiting waves in the environmental variable, while simple random, aggregated or systematic sampling is suggested for spatial structures exhibiting large patches in the environmental variable (Legendre et al., 2002).

Scale

In addition to sampling configuration, scale is an important parameter of sampling design that could affect the detected spatial structure. The scale component includes the dimensions of the grain, the lag and the extent (Fortin & Dale, 2005; Dungan et al., 2002).

Grain

The grain is the size of the sampling unit, sometimes referred to as support or footprint depending on the discipline; it sets the smallest spatial resolution at which data is measured and to which spatial structure can be characterized (Fortin & Dale, 2005; Skøien & Bloshil, 2006b; Dungan et al. 2002). Large grains, relative to the underlying variability, will lead to decreased variability (Fortin & Dale, 2005) and the data will appear much smoother than the true spatial distribution of the variable of interest (Skøien & Bloshl, 2006b). As grain gets larger, in general, the variable will have a smaller variance and a more systematic distribution (Dungan et al., 2002). Hence, quadrat size should be chosen carefully. For example, quadrats with large sizes may lead to a decrease of Moran's *I* coefficient sensitivity and may not detect the spatial structure (Fortin, 1999).

When the variable exhibits random distribution, the size of the grain will not affect the ability of detecting the presence/absence of spatial pattern (Fortin & Dale, 2005). In this case, and based on the principles of traditional statistics, the variance of the mean will decrease as the grain size increases, and hence, the precision of estimating the population mean will increase (Dungan et al., 2002). This is why scientists were taught to increase the grain size in their sampling design. In the presence of a spatial pattern and with spatially autocorrelated data, the decrease in the variance with an increase in the grain size is not as influential as in case of spatially random data (Dungan et al., 2002). Hence, for characterizing the spatial pattern of a given variable, it is recommended to favour a smaller sampling unit because small units can be aggregated into larger ones without a loss of information, but the reverse is not true (Dungan et al., 2002; Fortin & Dale, 2005). For soil science, most of the variables of interest, such as nutrient concentrations, pH and other physical and chemical properties, only have values at points. Though a physical sample with definite dimensions is used to obtain measurements of variables, these measurements are reported as if they represent point values (Franklin & Mills, 2007).

Lag

The sampling interval, known as lag, is another important parameter of the sampling design. Lag refers to the spacing between neighbouring sampling units. Lag may represent the distance for the centroids of two sampling units or the distance from

edge to edge of the sampling units (Dungan et al., 2002; Fortin & Dale, 2005; Skøien & Bloshil, 2006a). The sampling lag is affected by the size of the grain and the extent of the study area. As grain size increases, lag gets smaller and as the extent is increased then the lag gets larger (assuming a constant number of sampling units) (Fortin & Dale, 2005). In the absence of previous knowledge about the spatial structure, the selection of the sampling interval can be problematic. In studies concerned with soil chemical properties, it is common to have the sampling interval within the 1-4 m. The spatial range (the distance of spatial autocorrelation) of many soil chemical properties, induced by the influence of single trees does not exceed 16 m (Gallardo, 2003; Buscaglia & Varco, 2003; Chandler, 2006).

Gallardo (2003) studied the spatial dependency of several soil properties surrounding Holm oak (*Quercus ilex* L.) in a Mediterranean Dehesa ecosystem. Grid sampling was applied, and samples were collected in a 20x20 m grid surrounding the tree, with a sampling interval of 2 m. Three nested grids, 2x2 m each, were sampled at a finer scale (0.5 m) within the original one. The spatial ranges of organic matter content, mineral N, P, Na, K, and Li were respectively 9.7, 9.5, 13.4, 13, 3.8, and 2.8 m. A lag that is larger than the spatial scale of investigated pattern may not detect the spatial structure. This is why a nested sampling design with several sampling intervals is preferred to detect the spatial pattern (Fortin & Dale, 2005; Gallardo, 2003).

Extent

The extent is the overall size of the domain sampled. It may range from centimetres to hundreds of kilometres. The extent is often selected as the area of interest but sometimes it can be much smaller. (Skøien & Bloshl, 2006b). It is defined as the total length, area, or volume that exists or is observed or analyzed (Dungan et al., 2002). In studies concerned with the spatial influence of individual trees on soil properties, the extent ranges between 20 and 40 m (the area underneath the canopy cover) (Gallardo, 2003; Chandler, 2006). In other cases, where the spatial structure of forest floor and mineral soil properties of an ecosystem are investigated irrespective of the vegetation cover, the extent can reach up to 60 m (Gross, Pregitzer, & Burton, 1995; Gonzalez, 1994; Lister, Paul, Mou, Jones, & Mitchell, 2000). If the extent is too small, the spatial pattern will not be detected properly and if it is too large then many processes will be included in the data and violate the assumption of stationarity (Fortin & Dale,

2005). Therefore, for a given sampling design, no spatial structure can be detected that is smaller than the grain size or larger than the extent of the study (Franklin & Mills, 2007).

The Role of Bigleaf maple in the Pacific Northwest Forest Ecosystem

In the Pacific Northwest, it is predicted that many of the naturally occurring broadleaf tree species will benefit from climate change (Hamann & Wang 2006). Bigleaf maple (*Acer macrophyllum* Pursh) is a large broadleaf tree that is abundant in western North America. Its native range extends from northern Vancouver Island south into California, and within 300 km of the Pacific Ocean (Fig. 1.1) (Peterson, E.B, Peterson, N.M Comeau, & Thomas, 1999; USDAFS, 2004). Bigleaf maple is one of the most naturally abundant broadleaf species in the Coastal Douglas-fir and Coastal Western Hemlock biogeoclimatic zones of British Columbia (Peterson et al., 1999). It is predicted that bigleaf maple will have a frequency increase of 97% by 2085 because of climate change (Hamann & Wang, 2006). Bigleaf maple can grow freely towards canopy gaps and a single tree can consist of multiple stems. Bigleaf maple can grow up to 30 m in height with a diameter at breast height of up to 2.5 m (Haeussler et al., 1990).

Forest managers in the Pacific Northwest traditionally view many broadleaf trees, including bigleaf maple, as weeds that compete with conifers for resources. Current management strategies employ several methods to control its presence, including mechanical site preparation, uprooting of maple stumps, or overstory removal, manual sprout cutting, and prescribed burning, as well as chemical treatment with herbicides (Peterson et al., 1999). The effect of this would be a loss in species diversity and could impair resilience to natural disturbances, including fire, pest infestation and climate change. Current management practices are not entirely supported by scientific evidence as the presence of broadleaf species in conifer stands can improve site fertility and overall quality, which in turn increases the capacity of ecosystems to recover, renew and reorganize after disturbance and hence enhances the overall ecosystem resilience (Turk et al., 2008; Sabau et al., 2010; Seybold, Herrick, & Brejda, 1999). In addition, bigleaf maple may positively influence the surrounding soils and vegetation, which may in turn

influence the economic potential of crop species via yield and quality (Turk et al., 2008). Recent studies suggest that bigleaf maple can modestly improve soil fertility within conifer forests (Fried et al., 1990; Turk et al., 2008). Turk (2006) showed that bigleaf maple canopies have greater litterfall, containing higher elemental concentrations of almost all macronutrients as well as the micronutrients Mn, B, Zn, and Cu compared to Douglas-fir, western hemlock, and western redcedar.

Current and predicted future abundance of bigleaf maple may qualify it for an ecological role greater than what has been perceived by forest managers. Hence, it is important to understand its effects on ecosystem processes such as nutrient cycling and hydrology in order to predict how forests may respond to an ever-changing environment and to make sound management decisions.

Research Objectives

Though there have been several studies examining litter quality and decomposition of bigleaf maple and other broadleaf species in coastal mixed forests of British Columbia (Ogden & Schmidt, 1997; Prescott et al., 2000; Prescott et al., 2004a; Prescott et al., 2004b; Tashe & Schmidt, 2001; Turk et al., 2008), there are relatively few studies of throughfall and stemflow volumes and the nutrient inputs associated with different tree species and/or the extent of its spatial influence on the surrounding forest floor. The impact of bigleaf maple on nutrient inputs via throughfall and stemflow in a conifer forest has not yet been assessed. Furthermore, little is known about the degree and spatial extent of the impact of bigleaf maple on the surrounding forest floor. This thesis thus investigates whether the predicted increase in abundance and distribution of bigleaf maple could influence forest hydrology and nutrient inputs because of species-specific effects on incident rainfall distribution and soil fertility in a coastal Douglas-fir forest. The study consisted of two main parts as shown in table 1.1. The first one focused on examining throughfall and stemflow fluxes, while the second focused on examining forest floor properties.

The specific objectives and hypotheses of this study were:

Objective (1): to compare the spatio-temporal heterogeneity of the water flux to the forest soil under a bigleaf maple canopy with that under Douglas-fir.

Objective (2): to examine the effect of seasonal changes in canopy cover and phenology of bigleaf maple on throughfall chemical properties and compare those with Douglas-fir.

Objectives (1) and (2) are addressed in Chapter 2. The hypotheses tested were that spatial and temporal variations of throughfall and stemflow associated with bigleaf maple would be smaller than those of Douglas-fir, and that bigleaf maple nutrient input via throughfall would be greater than that of Douglas-fir in all phenological stages. This study thus investigated the influence of bigleaf maple on nutrient input in a coastal Douglas-fir forest through an examination of throughfall, stemflow properties in paired plots with and without bigleaf maple present. The objectives of this study were addressed by assessing the spatial and temporal variations of chemical properties of throughfall, and stemflow over three phenological stages of the bigleaf maple life cycle: leafed, leaf senescence, and unleafed.

Objective (3): to assess the quantity and quality of total nutrient input via throughfall and stemflow.

Objective (4): to assess site fertility in the under-canopy forest floor and near trunk forest floor in the vicinity of bigleaf maple.

Objectives (3) and (4) are addressed in Chapter 3. The hypotheses tested were that total nutrient input via throughfall and stemflow of bigleaf maple is greater than that of Douglas-fir, and that the forest floor associated with bigleaf maple is more fertile than that associated with Douglas-fir. The study thus investigates the influence of bigleaf maple on site fertility in a coastal Douglas-fir forest through an examination of throughfall, stemflow, under-canopy (distal to stem) and near trunk (proximal to stem) forest floor properties in paired plots with and without bigleaf maple present. The objectives of this study were addressed by assessing the chemical properties of: throughfall, stemflow, under-canopy forest floor and near trunk forest floor.

Objective (5): characterize the spatial structure of forest floor properties at multiple scales associated with bigleaf maple and western hemlock.

Objective (5) is addressed in Chapter 4. The study used four analytical techniques, namely, Krig mapping, Local Indicators of Spatial Association (LISA), polynomial Redundancy Analysis variance partitioning (polynomial RDA), and Principal Coordinates of Neighbour Matrices Redundancy Analysis (PCNM RDA) were used to explore and compare the effect of tree species on forest floor pH, NO_3 and NH_4 spatial distribution at multiple scales. It segregated the spatial patterns into broad and fine sub-models and related each sub-model to various environmental variables.

Objective (6): to describe the spatial variability, using geostatistics, of forest floor pH and forest floor ammonium (NH_4) concentration associated with bigleaf maple in a mixed conifer forest of southwest British Columbia.

Objective (7): to determine the sample sizes needed to estimate population means for forest floor pH and NH_4, with specified degrees of accuracy.

Objective (8): to optimize a sampling design for mapping the spatial structure of forest floor pH and NH_4 associated with bigleaf maple.

Objectives (6), (7), and (8) are addressed in Chapter 5. The hypotheses tested were that forest floor pH would require fewer samples for a certain degree of accuracy as compared to forest floor NH_4, and a random sampling design would be more accurate than a systematic-cluster design for detecting the spatial structure of forest floor variables associated with bigleaf maple. The study thus investigates the influence of sampling design on spatial patterns of forest floor pH and NH_4 associated with bigleaf maple in a mixed conifer stand.

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Table 1.1. A Summary outline of the study.

Examined variable	Plot level		within plot
	Chapter 2		
Throughfall and stemflow	Spatio-temporal variation of throughfall and stemflow volumes and temporal variation of throughfall chemical fluxes.	Chapter 3 The influence of bigleaf maple on chemical properties of throughfall, stemflow and forest floor.	
	Chapter 4		Chapter 5
Forest floor	Analytical techniques for characterizing the spatial structure of forest floor pH, nitrate, and ammonium associated with bigleaf maple and western hemlock at multiple scales.		Sampling design to detect spatial structure of forest floor chemical properties associated with individual deciduous trees growing among conifers.

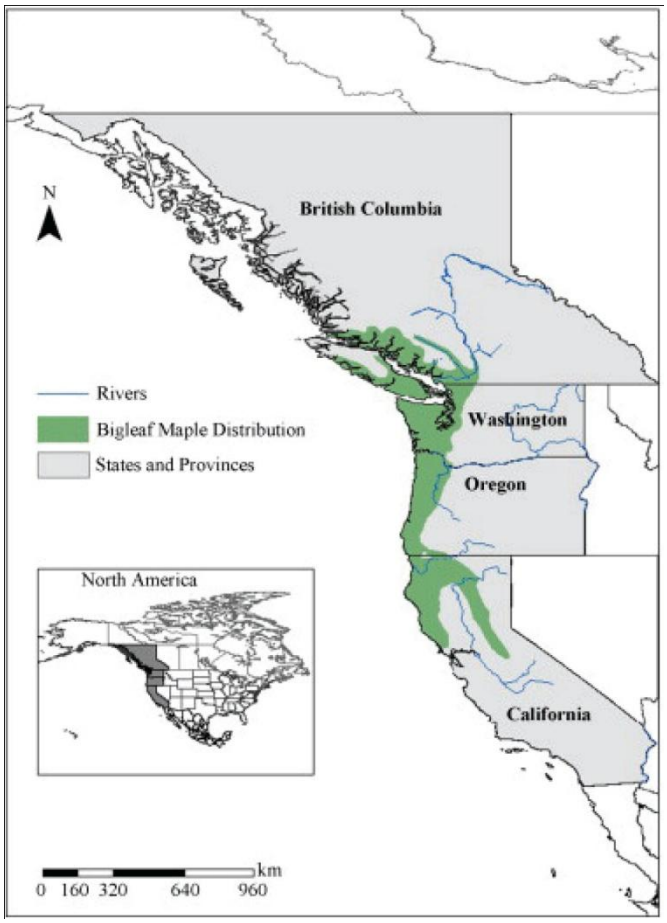

Figure 1.1. Distribution of bigleaf maple (modified from Haeussler et al., 1990 and USDAFS, 2004).

Chapter 2.[1]

Spatio-Temporal Variation in Throughfall and Stemflow Volumes and Temporal Variation of Throughfall Chemical Fluxes beneath Bigleaf Maple and Douglas-fir in a Coniferous Forest in the Pacific Northwest

Abstract

Bigleaf maple (*Acer macrophyllum* Pursh) is a large deciduous tree that is abundant in western North America. Its native range extends from northern Vancouver Island, south into California. This study examined the spatio-temporal variation of bigleaf maple throughfall and stemflow volumes and the temporal variation in throughfall chemical fluxes, in relation to canopy cover and tree phenology (leafed, senescence, and leafless), and compared them to Douglas-fir. Incident rainfall, throughfall and stemflow volumes were measured and samples were collected over ten time periods. The variability in throughfall was lower for bigleaf maple during both leafed and leafless periods compared to Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco). In bigleaf maple plots, the throughfall enrichment ratio of major chemicals was highest for NO_3 during the leafed period and for P, K, Ca, and Mg during the leaf senescence period. The fluxes of DOC, total-N, DON, P, K, Ca, Mg, S, SO_4, Zn, Fe, Cu, and Mn in throughfall were higher in the leafless period than during the leafed period. Bigleaf maple throughfall had a higher deposition and enrichment ratio of P and K during the entire

[1] The following chapter will be submitted to a peer reviewed journal for publication under the co-authorship of Margaret Schmidt and Ilja van Meerveld.

study period compared to that of Douglas-fir. The results of this study suggest that the leafless period is of ecological importance because its high throughfall chemical flux coincides with high rainfall amounts. This may potentially lead to elevated rates of nitrification and mineralization due to the synergistic effect of both N and water addition during this period.

Introduction

Species-specific effects on nutrient cycling in forest ecosystems have been investigated extensively over the last century (Gast, 1937; Zinke, 1962; Turk, Schmidt, & Roberts, 2008; Sabau, Schmidt, & Krzic, 2010). Though several studies have shown that nutrient cycling and availability are higher under deciduous trees than conifers (Ovington, 1954; Schmidt et al., 1998; Tashe & Schmidt, 2001; Tashe & Schmidt, 2003); evidence does not consistently support the idea that nutrient availability is better under deciduous trees and the impact of forest composition on soil chemical properties remains unclear (Binkley, 1995; Prescott, 2002).

An understanding of the nutrient dynamics of deciduous species within Pacific Northwest forests is important because of the potential influence of deciduous species on commercially valuable conifer stands. As these forests are generally nutrient-limited (Meidinger & Pojar, 1991), understanding the impact of deciduous species on nutrient cycling and site fertility of conifer forests is beneficial. Some studies have shown that deciduous trees in the Pacific Northwest may enhance nutrient cycling and site fertility by supplying the forest floor with nutrient-rich leaf litter (Ogden & Schmidt, 1997; Prescott, Zabek, Staley, & Kabzems, 2000; Tashe & Schmidt, 2001; Prescott, Blevins, & Staley, 2004a; Prescott, Vesterdal, Preston, & Simard, 2004b; Turk et al., 2008). In addition, trees alter hydrological conditions by redirecting precipitation, and altering the chemical composition of precipitation (Prescott, 2002). As rain passes through the relatively nutrient-rich foliage and branches of the canopy of deciduous trees and moves towards the forest floor, there is a change in the concentrations of essential nutrients, such as N, P, K and Ca (Sollins et al., 1980, Lovett & Lindberg, 1993; Neary & Gizyn, 1994; Staelnes et al., 2006).

The alteration of the chemical properties of water as it passes through the canopy is well known (Neary & Gizyn, 1994; Staelens, Schrijver, & Verheyen, 2007). Deciduous trees are characterized by considerable temporal variation in canopy cover and physiological activity throughout the year. This leads to a temporal variation in throughfall chemical fluxes. Nevertheless, throughfall fluxes in deciduous forests have mostly been measured during the leafed season; few studies have examined throughfall chemical properties during leaf senescence and leafless seasons (Staelens et al., 2007).

Variation in canopy architecture, leaf area, bark texture, and epiphyte cover affect incident rainfall interception and distribution, which in turn influence soil moisture of the forest floor and mineral soil, understory microclimate, nutrient inputs, and soil leaching (Levia & Frost, 2003). The alteration of hydrological conditions by the forest canopy is influenced by many factors, including species composition, meteorological conditions, season and canopy structure (Levia & Frost al., 2006). Consequently, throughfall is quite variable spatially and temporally. Spatio-temporal variations in throughfall can affect the heterogeneity of hydrological, biogeochemical, and ecological processes in the forest floor and the mineral soil (Staelens et al., 2006). Though there have been several studies examining litter quality and decomposition of bigleaf maple and other deciduous species in coastal mixed forest of British Columbia (Ogden & Schmidt, 1997; Tashe & Schmidt, 2001; Prescott et al., 2000; Prescott et al., 2004a; Prescott et al., 2004b; Turk et al., 2008), there are few studies of throughfall and stemflow and nutrient deposition associated with different tree species. Moreover, few studies have looked at the spatio-temporal patterns of throughfall and/or temporal patterns of throughfall chemical fluxes in relation to canopy cover and phenology. Some studies in the Pacific Northwest have suggested that throughfall and stemflow influence forest floor and mineral soil properties surrounding individual trees but without actually measuring or quantifying them (Crampton, 1982; Crampton, 1984; Chandler, 2006).

This study thus investigates the spatio-temporal variability of bigleaf maple throughfall and stemflow and the influence of bigleaf maple on site fertility in a coastal Douglas-fir forest through an examination of throughfall and stemflow volumes and throughfall chemical fluxes. The objectives of this study were to: (1) quantify the spatio-temporal heterogeneity of the water flux to the forest soil under bigleaf maple canopy as compared to Douglas-fir, and (2) examine the effects of seasonal changes in canopy

cover and phenology on throughfall chemical properties under bigleaf maple and compare them to those of Douglas-fir.

Materials and Methods

Study Area and Sampling Design

The study area is located within the University of British Columbia's Malcolm Knapp Research Forest, Maple Ridge, British Columbia (Fig. 2.1). The dominant trees in the forest are Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco), western redcedar (*Thuja plicata* Donn), and western hemlock (*Tsuga heterophylla* (Raf.) Sarg.). Several deciduous species including bigleaf maple, black cottonwood (*Populus balsamifera* L.) and red alder (*Alnus rubra* Bong) are also common. Understory vegetation includes vine maple (*Acer circinatum* Pursh), western sword fern (*Polystichum munitum* (Kaulfuss) K. Presl), salal (*Gaultheria shallon* Pursh), and trailing blackberry (*Rubus ursinus* Cham. & Schlecht.) (Pojar & Mackinnon, 1994). The study area is located within the Dry Maritime Coastal Western Hemlock biogeoclimatic subzone (CWHdm) (Green and Klinka, 1994). The CWHdm subzone experiences mean annual incident rainfall of 1827 mm and a mean annual temperature of 9.8 °C (Pojar et al., 1991). The soils within the study area were derived from morainal and colluvial parent materials and are sandy loam Gleyed Dystric Brunisols (Agriculture Canada Expert Committee on Soil Survey, 1998).

Two conifer-dominated stands that include some bigleaf maple trees were selected for this study. The two stands are 140 and 125 years old and regenerated naturally following fires that occurred in 1868 and 1881 respectively. Throughfall and stemflow volumes were compared between vegetation types (bigleaf maple and conifer plots) using a paired-plot methodology. Four sets of paired plots were selected within each stand, yielding a total of eight pairs (16 plots). Each bigleaf maple plot had one bigleaf maple tree at the plot centre and was surrounded by conifers. Conifer plots had a Douglas-fir tree at the plot centre. Each plot had an area of 20 m X 20 m. Pair selection was based upon the following criteria: (1) similarity in slope, elevation, and aspect in order to reduce incident rainfall and site variation, (2) similarity in canopy density and gap size to reduce sampling error, and minimize site variation, (3) similarity in tree

diameter at breast height (DBH) to reduce error and variation in stemflow dynamics, and (4) similar tree stand density as a means of controlling for evaporative loss.

All of the selected trees were assessed for the following characteristics: DBH, canopy density, canopy width, canopy area, canopy volume, bark roughness and epiphyte cover percentage (detailed data collection methodology and results are presented in Chapter 3).

Throughfall and Stemflow Sampling and Analysis

One wedge-type rain gauge (0.06 m X 0.065 m) and one rainfall trough, consisting of a longitudinal slit tube (0.67 m x 0.07 m), placed 0.4 m above the ground with a hose that drained into a four-litre plastic container were randomly placed in four distinct clearings within 0.5 km of the study plots. The average of these measurements provided the incident rainfall for the study. Each plot was outfitted with two throughfall troughs (similar to the rainfall troughs) that were positioned randomly under the canopy within 1 to 8 m of each tree trunk. Stemflow collars consisted of 2.0 cm diameter rubber hose that was slit longitudinally and fixed in a slightly downward angle to the trunk with nails. The nail holes and the cracks between the tubing and the tree were sealed with a silicon sealant. The flexible tubing collar was secured to each tree at breast height, and was coiled 1.5 times around the perimeter of the trunk. The tubing drained into a tight fitting four-litre plastic container to collect stemflow. Collars were tested for leaks using deionised water on a monthly basis. Leaks along the collar were resealed with silicone sealant.

The throughfall and rainfall collecting apparatus occasionally malfunctioned for various reasons such as extreme weather pushing the trough upside down, debris falling on the device, or destruction by a black bear. Missing values of throughfall and stemflow represented 10% of the total data and were estimated by a simple linear regression method. Throughfall trough data was used as regressor when only one throughfall trough malfunctioned in a certain plot, while average rainfall was used as regressor when the two throughfall troughs or the stemflow collar malfunctioned in a certain plot.

The total amount of incident rainfall, throughfall, and stemflow were measured during ten periods (P1 to P10) between May and November 2009 (Table 2.1). Based on

field observations, bigleaf maple trees had no leaves during P1, P8, P9, and P10. These periods represented the leafless period. Bigleaf maple trees had green leaves during P2, P3, P4, and P5 and yellowish-brown leaves during P6, and P7. These periods represented the leafed and leaf senescence periods respectively. At the end of each collection period, the rainfall, and throughfall containers were emptied into a graduated cylinder and the volume of water was recorded (detailed results are presented in Chapter 3). Incident rainfall (a total of eight rainfall samples, one for each rain gauge and one for each rainfall trough), and bigleaf maple and Douglas-fir throughfall samples (16 for each) were stored in 500 ml plastic bottles and brought to the lab for further processing and analysis. Samples were filtered through a 0.45-micron membrane filter and two sets of 70 ml subsamples were stored in the dark at 4^{o}C and -20^{o}C respectively.

The first set of subsamples was used for determining rainfall and throughfall pH, total dissolved organic carbon (DOC), and sulphate (SO_4) concentrations. The pH was measured by immersing a glass pH meter into the sample. DOC was measured by the high temperature catalytic oxidation method (Sharp et al., 1993) (Shimadzu TOC-V CSH with OCT-1 8 Port Autosampler). SO_4 was measured by ion chromatography (Dionex Corporation).

The two throughfall samples from each plot were then composited into one sample reducing the 32 throughfall samples per collection period into 16 (8 bigleaf maple and 8 Douglas-fir throughfall samples). Rainfall, and throughfall samples collected over the leafed, leaf senescence, and leafless periods were then separately composited on a volume basis into one sample for rainfall, and also for throughfall from each bigleaf maple and Douglas-fir plot for each period yielding a total of 72 composited samples (8 rainfall, 8 bigleaf maple, and 8 Douglas-fir throughfall samples per period). Composited samples were then sent to the Ministry of Forests and Range, Research Branch Laboratory, Victoria, BC and were analyzed for elemental concentrations of P, K, Mg, Ca, S, Zn, B, Cu, Mn, Fe, Al, and Si by an inductively coupled plasma-atomic emission spectrometer (ICP).

Samples stored at $-20\ ^{o}$C were composited as described for the first set yielding a total of 24 (8 rainfall, 8 bigleaf maple, and 8 Douglas-fir throughfall samples) distinct subsamples for leafless, leafed and leaf senescence periods respectively. These subsamples were used to measure nitrate (NO_3-N) and ammonium (NH_4-N)

colorimetrically using an Alpkem Flow System IV analyzer (Bremmer, 1965; Carter, 1993). A sub-sample was then taken and subjected it to an alkaline-persulphate digestion and analyzed colorimetrically to obtain total N concentration. The difference between total N and the sum of NO_3-N and NH_4-N was assumed to be dissolved organic nitrogen (DON).

Data Analysis

Intraspecies and Interspecies Spatio-Temporal Variation in Throughfall Volumes

Incident rainfall, throughfall, and stemflow volumes were recorded for each collection period (P1 to P10) for both bigleaf maple and Douglas-fir. Rainfall, throughfall, and stemflow volumes were expressed in mm day^{-1} in order to allow comparison between periods (Table 2.1). The temporal variation at the seasonal scale (leafed and leafless) was examined by subjecting the average daily throughfall and stemflow amount of bigleaf maple and Douglas-fir to a paired sample t-test. For this analysis, the leafed period represented leafed and leaf senescence periods.

The spatial variability in throughfall for bigleaf maple and Douglas-fir was expressed by means of the coefficient of variation (CV), i.e. the standard deviation as a proportion of the mean. The CV of bigleaf maple and Douglas-fir throughfall was calculated for the collection periods (P1 to P10) and the leafed/leafless periods. Paired sample t-test was used to compare the CV of throughfall between species and between the leafed and leafless season of each species.

Intraspecies and Interspecies Temporal Variation in Throughfall Chemical Fluxes

For each chemical variable, throughfall deposition (concentration multiplied by volume and divided by the collecting area of the throughfall trough) and throughfall enrichment ratio (TER, throughfall deposition divided by incident rainfall deposition) were calculated (Neary & Gizyn, 1994; Michopoulos, Baloutsos, Nakos, & Economou, 2001). For each of the bigleaf maple and Douglas-fir plots, the significance of the differences between leafed, leaf senescence, and leafless periods was determined. For each chemical variable, incident rainfall, throughfall deposition, and TER were compared between leafed, leaf senescence, and leafless periods using a one-way ANOVA. The interspecies temporal variation of throughfall deposition and TER of bigleaf maple and Douglas-fir in each of the leafed, leaf senescence, and leafless periods was examined by subjecting each variable in

each period to a separate paired sample t-test. All data were analysed using SPSS 17 Software, with plots being considered as individual sample units. A significance level of 0.1 was used for all analyses because of the considerable natural heterogeneity within the measured properties. All variables were checked for normality using Q-Q plots.

Results

Intraspecies and Interspecies Spatio-Temporal Variation in Throughfall and Stemflow Volumes

The recorded incident rainfall amounts over the measured leafed (representing leaf and senescence periods) and leafless periods were 280 mm and 379 mm respectively, representing 15% and 21% of the long-term annual mean of the study area. When leafed and leafless periods were analyzed separately, t-test showed a higher throughfall volume and a lower stemflow volume at bigleaf maple plots compared to Douglas-fir plots during the leafless period but not during the leafed period (Table 2.2).

Bigleaf maple throughfall showed a high spatial variability, as expressed by the CV, during the leafed period and lower CVs during senescence and leafless periods with a very low CV in P10 (bigleaf maple unleafed coinciding with the highest rainfall volume). The mean CV of throughfall volume was 26% and 16% for the leafed and leafless periods respectively, lower than for Douglas-fir. For Douglas-fir throughfall, CV was high throughout all of the periods, except for P10, characterized by high rainfall (Table 2.1).

Intraspecies and Interspecies Temporal Variation in Throughfall Chemical Fluxes

The flux of almost all major chemical variables was higher during the leafless period than during the leafed and leaf senescence periods for rainfall and both bigleaf maple and Douglas-fir throughfall (Table 2.2). Bigleaf maple throughfall deposition of DOC, total-N, DON, P, K, Ca, Mg, S, SO_4, Zn, Fe, Cu, and Mn was higher in the leafless period than in the leafed period while throughfall deposition of NO_3, B, Al, and Si was higher in the leafed period than in the leafless period. Throughfall enrichment ratios were higher for bigleaf maple DOC, K, Mg, SO_4, S, Zn, and Mn during the leaf senescence period compared to the leafless and leafed periods (Table 2.3).

Douglas-fir showed a higher TER for total-N, Ca and S during the bigleaf maple leafless period compared to the bigleaf maple leafed period and a higher Mg enrichment during the bigleaf maple leaf senescence period than the leafed or leafless periods (Table 2.4).

Bigleaf maple had a higher deposition and TER of P during leafed, a higher deposition and TER of P, K, S, Zn, Fe, and Si during leaf senescence, and a higher deposition and TER of DON, P, K, and SO_4 during leafless period compared to Douglas-fir.

Discussion

Throughfall and Stemflow Volumes

Species morphological variation such as canopy architecture, leaf area, deciduousness, and foliage density, are factors that affect throughfall (Mina, 1967; Levia & Frost, 2006). It was anticipated that bigleaf maple would have more throughfall during the leafless period of the year compared to Douglas-fir due to the lack of leaves during this period (Comerford & White, 1977). Stemflow volume collected at bigleaf maple plots was significantly lower only during the leafless season. This season coincides with high rainfall. It is likely that small rainfall events are not able to saturate the trunk and hence a large portion of water is absorbed by tree stems or evaporated. However, when large rainfall events occur after dry periods, larger amounts of water would flow along Douglas-fir trunks. This may suggest that Douglas-fir woody tissue has a lower water storage capacity and confirms previous reports about differences in woody tissue water storage capacities (Herwitz, 1985; Liu, 1998). Liu (1998) reported differences in water storage capacity among *Nyssa sylvatica* (Walt.) Sarg. (blackgum), *Taxodium ascendens* Brongn. (cypress), and *Pinus elliottii* Engelm. (slash pine) in a mixed forest in north-central Florida. Similarly, Herwitz (1985) reported differences in water storage capacity among several tropical rainforest species. This is surprising because of the rough bark of Douglas-fir (see Table 3.1). Bark texture is one of the main factors influencing stemflow volume (Mina, 1967; Návar, et al., 1999). Trees with smooth bark such as bigleaf maple are expected to allow faster flow of water along the trunk. Nevertheless, this was not observed in our study. This may indicate that other factors such as epiphyte cover can be more important than bark

texture (see Table 3.1) due to their high storage capacity (Veneklaas, and Van EK, 1990). In addition, this may also indicate that once saturated, bigleaf maple and Douglas-fir morphological characteristics such as branch inclination (Hutchinson & Roberts, 1981; Levia & Herwitz, 2002; Steinbuck, 2002) have little influence on the amount of water flowing along their trunk (Návar et al., 1999; Crockford & Richardson, 2000). However, given the nature of our study, we cannot make strong conclusions about the influence of epiphyte cover and branch inclination angle of bigleaf maple and hence it should be examined in more detailed studies.

It was anticipated that throughfall spatial variability would be lower for bigleaf maple than for Douglas-fir since it is a deciduous species (Raat, Draaijers, Schaap, Tietema, & Verstraten, 2002; Staelens et al., 2006). Indeed we found throughfall spatial variability to be 16 percent greater at Douglas-fir plots. Bigleaf maple and Douglas-fir throughfall average CV were 20 and 36%, respectively. These values are within the reported range for several deciduous and conifer species (Puckett, 1991; Staelens at al., 2006). Bigleaf maple spatial variability, as expressed by CV, was significantly lower during both leafed and leafless periods than the spatial variability of Douglas-fir. This can be attributed to the differences in morphological characteristics between species including, canopy foliage (Herwitz, 1985; Liu, 1998), leaf shape and orientation (Carleton & Kavanagh, 1990; Crockford & Richardson, 2000) and epiphyte cover (Veneklaas & Van, 1990) that can influence the spatial variability of throughfall inputs. For both bigleaf maple and Douglas-fir plots, there was a trend of decreasing spatial variability with increasing incident rainfall. For small rainfall events, differences in canopy interactions are relatively large resulting in a higher degree of spatial throughfall variability (Lin, Hamburg, King, & Hsia, 1997) than for larger rain events, in which the water storage capacity of the canopy is satisfied (Carlyle-Moses, Flores Laureano, & Price, 2004). These findings confirm previous reports on the inverse relation between throughfall variability and event rainfall amount (Staelens et al., 2006). In addition, for bigleaf maple spatial variability was likely greater during the leafed period because the leaves provide additional drip points and retention areas in the canopy (Peterson & Rolfe, 1979), which contribute to throughfall spatial variability (Bellot & Escarre, 1998). However, due to the small number of rain gauges/throughfall troughs that were used in this study, we cannot make strong conclusions without detailed further throughfall studies.

Spatio-temporal variation of several forest floor and soil properties including moisture content, nitrate, and ammonium has been reported in the literature (Manderscheid & Matzner, 1995; Farely & Fitter, 1999; Raat et al., 2002; Bengtson et al., 2007). Farely and Fitter (1999) reported temporal variation of soil NO_3 and NH_4 in a mixed stand dominated by *Quercus petraea* (Mattuschka) Liebl., with some *Q. cerris* L. and *Acer pseudoplatanus* L. in North Yorkshire, UK. Bengtson et al. (2007) reported a strong spatial variation of forest floor and mineral soil moisture content, NO_3 and NH_4 in a coastal forest of British Columbia. Similarly, Raat et al. (2002) reported that nitrate production could vary by a factor of 3 because of spatial variability in moisture content in a Douglas-fir stand assuming a forest floor of uniform thickness. Our results of spatio-temporal variation in throughfall under bigleaf maple and Douglas-fir may suggest a possible relation between throughfall volume and spatio-temporal variations of forest floor and mineral soil chemical properties reported in the literature (Manderscheid & Matzner, 1995; Farely & Fitter, 1999; Raat et al., 2002; Bengtson et al., 2007). For example, Alexander and Arthur (2010) suggested that stemflow water is a controlling factor of N mineralization rates in areas surrounding stems. This idea can be extended to other areas of the forest that receive variable throughfall volumes, especially because patterns of throughfall can be persistent among storms because of the deterministic processes consistently redistributing precipitation (Keim, Skaugsetb, & Weilerc, 2005). Forest floor and mineral soil areas receiving persistent high throughfall volumes are expected to have higher moisture content (Schume et al., 2003). Hence these areas would be expected to have higher nitrification and mineralization rates given similar environmental conditions (Tietema, Warmerdam, Lenting, & Riemer, 1992).

Throughfall Water Quality

Throughfall chemical deposition under bigleaf maple and Douglas-fir was different from incident rainfall during the leafed, leaf senescence, and leafless periods. Other studies have found that both deciduous and conifer canopies modify chemical properties of incident precipitation passing through the canopy. Several studies reported an increase in ion fluxes as water passes through leafed and leafless canopy (Cappellato, Peters, & Ragsdale, 1993; Neary & Gizyn, 1994; Hamburg & Lin, 1998; Houle, Ouimet, Paquin, & Laflamme, 1999; Staelens et al., 2007). Staeleans et al. (2007) reported a TER greater than one for all ions except H^+ under beech in a mixed deciduous forest in north

Belgium during both leafed and leafless seasons. Neary and Gizyn (1994) reported that throughfall deposition of most ions exceeded bulk deposition during the leafless season in conifer and deciduous stands in eastern Ontario, with TER varying from 1.04 to 4.7. Similar findings were reported by Houle et al. (1999), with a TER ranging from 1.3 to 7.5 for a hardwood forest in Canada. In an oak-hickory stand a TER value greater than one was reported for several ions/elements during the leafed and the leafless season (Cappellato et al., 1993; Hamburg & Lin 1998). Cornan and Reiner (1983) reported higher deposition of all major chemicals, except NO_3, during the leaf senescence period compared to growing season in a hardwood forest of New England.

The NO_3 enrichment of bigleaf maple throughfall during the leafed period may be attributed to the dry deposition of NO_x, and HNO_3 (Butcher & Charlson, 1972; Hanson & Lindberg 1991; Duyzer & Fowler 1994; Fenn, Poth, Bytnerowiz, & Riechers, 1995; Gessler, Rienks, & Rennenberg, 2000). The lower TER of NO_3 in the leaf senescence compared to leafed period can indicate that NO_3 was taken up by the tree canopy and confirms previous reports on NO_3 uptake that occurs during leaf senescence (Bowden, Geballe, & Bowden, 1989; Brumme, Leimcke, & Matzner, 1992; Boyce, Friedland, Chamberlain, & Poulson, 1996; Houle et al., 1999; Stachurski & Zimka, 2002). This is probably linked to N resorption by the trees (Houle et al., 1999). In addition, the high NO_3 and low NH_4 TERs during the leafed period could be due to preferential NH_4 uptake by the leafed canopy (Stachurski & Zimka, 2002). This is because NH_4 is taken up not only through stomata but also by moist surfaces foliage (Wesely & Hicks, 2000).

Throughfall of bigleaf maple was enriched with base cations during the leafless period, this indicates leaching and/or washing of dry deposition from twigs and branches (Tukey, 1970; Levia & Herwitz, 2002; Staelens at al., 2007). Bigleaf maple TER of P, K, and Mg were significantly higher during leaf senescence than during the leafed and leafless periods (Table 2.3). This may indicate a high leaching rate and/or dry deposition of these ions during the leaf senescence phase. This is in line with other studies that reported higher enrichment ratios and/or depositions of K and Mg beneath a deciduous canopy during the leafed season (Houle et al., 1999; Michopoulos et al., 2001; Staelens et al., 2007) and during the leaf senescence period (Cornan & Reirens, 1983). During senescence, K had the highest TER compared to other elements. This may indicate a very high K leaching rate during this period. Canopy leaching from deciduous species was

reported to be the main mechanism of K enrichment in throughfall compared to dry deposition (Houle et al., 1999; Staelens et al., 2007). K is highly susceptible to canopy leaching because it is not bound in structural tissues or enzyme complexes (Marschner, 1995). The lack of differences in the Ca enrichment ratio between the leafed and leaf senescence periods and between the leaf senescence and leafless periods can be partially explained by the location of Ca in leaves. Ca occurs in considerable quantities as relatively insoluble pectates in cell walls and is rarely retranslocated from leaves to woody components in autumn (Marschner, 1995). Furthermore, dry deposition contributes almost equally to Ca leaching (Tukey, 1970). The high TER of Mg during leaf senescence could indicate a high Mg leaching during this period. Alternatively, it is possible that this is due to dry deposition, as bigleaf maple has a low foliar level of Mg with a moderate leaching percentage (1-10%) (Parker, 1983; Turk, 2006) and it has been reported that Mg deposition can increase with increased wind speed in maritime forest stands (Parker, 1983).

The senescence period at Douglas-fir plots does not seem to have a large effect on throughfall chemistry; mainly there was a higher TER of Mg. There was an increase in total-N and Ca TER during the leafless period, which indicates a possible increase in leaching that occurs during this period (Table 2.4). This may indicate an export of nitrogen from the canopy, which does not occur during the leafless period in bigleaf maple. Douglas-fir translocates about 41% of foliar N to the trunk before needle abscission (Turner & Olson, 1976) while maple translocates about 73% (Grizzard et al., 1976; Luxmoore et al., 1981).

The leafless period had the highest daily depositions of total-N, DON, P, K, Ca, and Mg for bigleaf maple and of total-N, K, Ca, and Mg for Douglas-fir. The relatively high daily deposition is likely mainly due to the high rainfall during the leafless period. The combination of relatively high water and nutrient inputs during the leafless period suggests that this period may be of high ecological importance. For example, inputs of water and nitrogen in combination with drying and rewetting periods could lead to a priming effect that activates soil microorganisms (Kuzyakov et al., 2000) and enhances nitrification and mineralisation.

Conclusion

Higher throughfall volumes and lower stemflow volumes were measured at bigleaf maple plots than Douglas-fir plots during the leafless period. During the leafed period, bigleaf maple leaves increased the spatial variability in throughfall compared to the leafless period. The chemical enrichment of throughfall beneath bigleaf maple was influenced by foliation and physiological canopy activity. Throughfall enrichment ratios were significantly higher during the leaf senescence period for P, K, Ca, and Mg, and significantly higher during the leafed period for NO_3. Throughfall enrichment during the leafless period indicated that K and Ca were leached from bigleaf maple branches and twigs. Bigleaf maple throughfall fluxes of DOC, total-N, DON, P, K, Ca, Mg, S, SO4, Zn, Fe, Cu, and Mn were higher during the leafless period than the leafed period. Douglas fir had a higher TER of total N during the leafless period, indicating leaching of nitrogen from needles during this period. This did not occur in the leafless bigleaf maple trees. Bigleaf maple throughfall had a higher deposition and TER of P and K during the entire study period as compared to Douglas-fir, indicating that bigleaf maple twigs and branches contributed significantly to the leaching/dry deposition of these elements. The results of this study suggest a possible relation between the spatio-temporal variations in throughfall volumes and those of forest floor and mineral soil chemical properties that are reported in the literature. In addition, this study suggests that the leafless period is of ecological importance because of its high throughfall nutrient flux coinciding with high rainfall amounts. This condition may potentially lead to enhanced rates of nitrification and mineralization due to the synergistic effect of N and water addition during this period.

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Table 2.1. Throughfall and stemflow collection periods and average amount of incident rainfall collected during those periods (n=8)

Period	Date	Days in period	Average rainfall (mm day^{-1})	Bigleaf maple phenology
1	18- 25 May	7	3.1	Leafless
2	26 May- 26 June	31	0.8	Leafed
3	27 June- 12 July	16	1.4	Leafed
4	13 July- 17 August	36	1.7	Leafed
5	18 August- 21 September	35	2.0	Leafed
6	22 September- 19 October	28	2.6	Leaf senescence
7	20 October- 26 October	7	11.4	Leaf senescence
8	27 October- 03 November	8	7.6	Leafless
9	4 November- 09 November	6	11.6	Leafless
10	10 November- 17 November	8	13.9	Leafless

Table 2.2. Bigleaf maple and Douglas-fir mean throughfall amounts mm day^{-1} ± (SD), and coefficient of variations (CV, %) (n=8)

	Bigleaf maple throughfall			Douglas-fir throughfall		
Period	**Mean**		**CV (%)**	**Mean**		**CV (%)**
1	2.40	(0.41)	17	2.08	(0.58)	28
2	0.52	(0.09)	17	0.51	(0.20)	39
3	0.96	(0.22)	23	0.86	(0.44)	52
4	1.62	(0.54)	34	1.34	(0.67)	50
5	1.61	(0.48)	30	1.22	(0.51)	41
6	2.09	(0.33)	15	2.06	(0.53)	26
7	10.58	(2.21)	21	9.15	(3.32)	36
8	6.71	(1.14)	17	5.63	(2.32)	41
9	10.80	(1.65)	15	8.93	(2.57)	29
10	10.62	(1.56)	14	9.62	(1.69)	18
Season						
Leafed	2.89 a (i)	(0.49)	26 a (i)	2.52 a (i)	(0.83)	45 b (i)
Leafless	7.63 a (ii)	(0.52)	16 a (ii)	6.57 b (ii)	(1.55)	28 b (ii)

a and b designate interspecies significant differences (bigleaf maple vs. Douglas-fir) while (i) and (ii) designate intraspecies significant differences (leafed vs. leafless).

Table 2.3. Mean chemical flux from rainfall, bigleaf maple throughfall, and Douglas-fir throughfall during the leafed, leaf senescence (LS) and the leafless periods

	Rainfall flux ($mg.m^{-2}.day^{-1}$)			Bigleaf maple throughfall flux ($mg.m^{-2}.day^{-1}$)			Douglas-fir throughfall flux ($mg.m^{-2}.day^{-1}$)		
	Leafed	**LS**	**Leafless**	**Leafed**	**LS**	**Leafless**	**Leafed**	**LS**	**Leafless**
DOC	503 a	671 a	9268 a	1284 a	4451 ab	6091 b	1013 a	6472 a	**21536** b
Total N	173 a	112 ab	394 b	158 a	191 a	761 b	137 a	218 a	1307 b
NO_3-N	18 a	25 a	124 b	38 ab	18 a	63 b	35 a	18 a	158 a
NH_4-N	41 a	7 a	208 b	30 a	12 a	79 a	26 a	9 a	133 a
DON	113 a	78 a	51 a	90 a	159 a	**618** b	76 a	190 a	295 a
P	16 a	166 a	775 b	**29** a	**26** a	**168** b	23 a	6 a	11 a
K	165 a	103 a	586 b	789 a	**1876** a	**5235** b	651 a	738 a	3312 b
Ca	70 a	83 a	202 b	130 a	246 a	766 b	114 a	344 a	1517 b
Mg	13 a	15 a	162 b	36 a	83 a	232 b	32 a	83 a	323 b
S	46 a	47 a	300 b	68 a	**150** a	529 b	57 a	80 a	675 b
SO_4	128 a	102 a	1342 b	267 a	648 a	**1959** b	219 a	614 b	11 c
Zn	2.69 a	5.15 a	60.34 b	2.61 a	12.44 a	56.24 b	2.20 a	9.07 a	47.73 b
B	1.09 a	2.40 a	16.22 b	1.45 a	3.61 a	28.21 b	1.22 a	4.00 a	30.16 b
Mn	0.97 a	0.89 a	45.27 b	1.58 a	7.76 a	25.17 a	1.41 a	**14.79** a	49.56 b
Cu	0.76 a	4.57 a	22.67 b	2.25 a	4.71 a	29.77 b	1.88 a	3.54 a	35.93 b
Fe	0.68 a	14.14 a	123.28b	1.73 a	2.75 a	118.84b	1.45 a	**9.40** a	27.53 b
Al	3.19 a	23.00 b	27.03 b	3.59 a	10.03 a	43.90 b	3.09 a	19.64 a	57.39 b
Si	1.04 a	7.06 ab	26.97 b	4.42 a	19.25ab	31.40 b	3.44 a	13.65 a	40.88 b

a, b, and c designate significant differences (Leafed vs. Leaf senescence vs. Leafless) for rainfall chemical flux, bigleaf maple throughfall chemical flux, and Douglas-fir throughfall flux. Bold values indicate whether deposition ($p < 0.1$) is higher in bigleaf maple or Douglas-fir throughfall during leafed, leaf senescence and leafless periods.

Table 2.4. Bigleaf maple and Douglas-fir throughfall enrichment ratio (TER) during the leafed, leaf senescence (LS) and the leafless periods

	Bigleaf maple TER (Bigleaf Maple Throughfall Flux: Rainfall Flux)			**Douglas-fir TER (Douglas-fir Throughfall Flux: Rainfall Flux)**		
	Leafed	**LS**	**Leafless**	**Leafed**	**LS**	**Leafless**
DOC	2.55 a	6.63 b	0.66 c	2.01 a	9.64 b	**2.32** a
Total N	0.92 a	1.71 a	1.98 a	0.79 a	1.94 ab	3.40 b
NO_3-N	2.09 a	0.71 b	0.51 b	1.92 a	0.72 a	1.27 a
NH_4-N	0.73 a	1.65 a	0.39 a	0.63 a	1.13 a	0.63 a
DON	0.79 a	2.04 a	**12.02** b	0.67 a	2.42 a	5.73 a
P	**1.74** ab	**5.17** a	**1.34** b	1.39 a	1.13 ab	0.08 b
K	4.76 a	**18.08** b	**8.92** a	3.92 a	7.11 a	5.64 a
Ca	1.85 a	2.94ab	3.78 b	1.60 a	4.10 ab	7.48 b
Mg	2.60 a	5.23 b	1.43 c	2.27 a	5.16 b	1.99 a
S	1.50 a	**3.20** b	1.76 a	1.24 a	1.71 ab	2.24 b
SO_4	2.07 a	6.36 b	**1.46** a	1.70 a	6.01 b	0.01 c
Zn	0.97a	2.42b	0.93 a	0.82 a	1.76 b	0.79 a
B	1.33 a	1.51a	1.74 a	1.11 a	1.67 a	1.86 a
Mn	1.63 a	8.75 b	0.56 a	1.45 a	**16.67** b	1.09 a
Cu	2.97a	1.03 b	1.31b	2.48 a	0.77 b	1.59 ab
Fe	2.6 a	0.19 b	0.96 b	2.14 a	**0.67** b	0.22 b
Al	1.13ab	0.43 a	1.62 b	0.97 a	0.85 a	2.12 a
Si	4.24 a	2.73ab	1.17 b	3.30 a	1.93 b	1.52 b

a, b, and c designate significant differences (Leafed vs. Leaf senescence vs. Leafless) for bigleaf maple throughfall enrichment ratio, and Douglas-fir enrichment ratio. Bold values indicate whether TER ($p < 0.1$) is higher in bigleaf maple or Douglas-fir during leafed, leaf senescence and leafless periods.

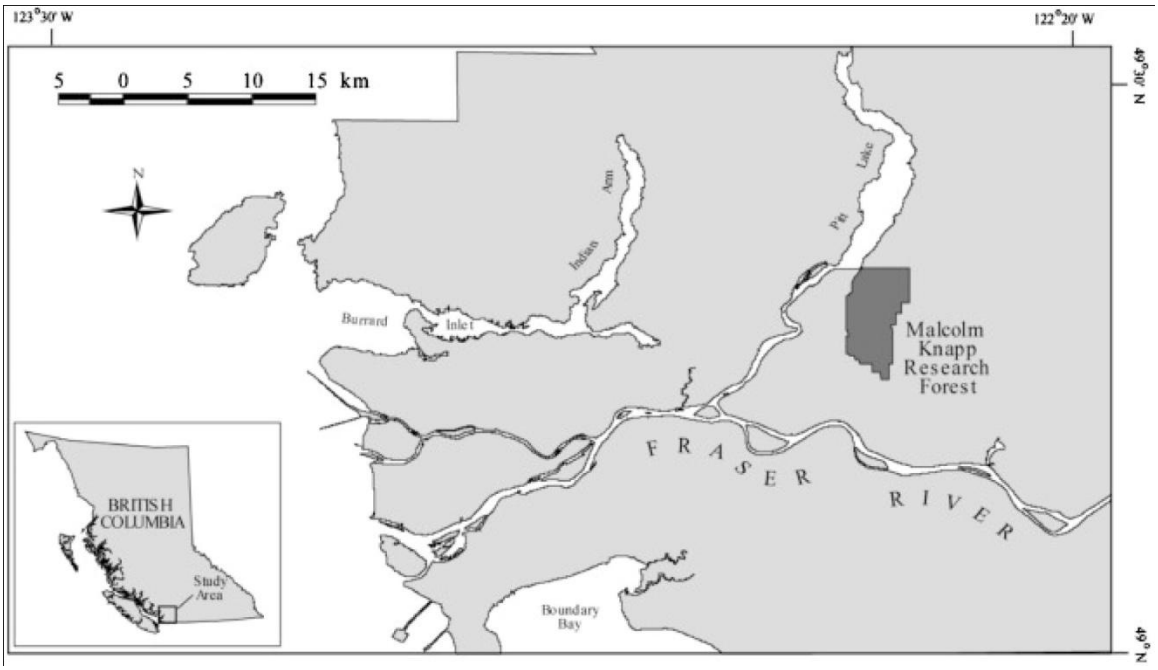

Figure 2.1. Location of the Malcolm Knapp Research Forest in southwest British Columbia.

Chapter 3.[1]

The Influence of Bigleaf Maple on Chemical Properties of Throughfall, Stemflow and Forest Floor in Coniferous Forest in the Pacific Northwest

Abstract

It is predicted that bigleaf maple (*Acer macrophyllum* Pursh) will almost double in frequency, in British Columbia, by 2085 due to climate change. We address whether its frequency increase could influence chemical properties of throughfall, stemflow and forest floor due to species-specific effects. Eight plots with a single bigleaf maple tree in the centre of conifers were paired with eight Douglas-fir plots without bigleaf maple. Compared to conifer plots, bigleaf maple throughfall and stemflow had higher pH, and K concentration. The under-canopy and near trunk forest floor associated with bigleaf maple showed higher pH, total exchangeable bases, CEC and concentrations of exchangeable Ca and Mg. In addition, the near trunk forest floor had higher base saturation and concentrations and contents of NO_3-N and contents of total N, and S. Throughfall and stemflow beneath bigleaf maple appear to contribute to higher pH and N availability in the forest floor. The results suggest that there is a soil microsite around bigleaf maple stems which is influenced by stemflow. These enriched microsites proximal to bigleaf maple trunks would allow bigleaf maple to have legacy effects on soil

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fertility and promote conifer productivity later in succession following bigleaf maple mortality.

Introduction

Climate change is predicted to cause a shift in ecosystem structure including predominant vegetation, age class distribution, and species composition (Gayton, 2008). In forest ecosystems, species-specific effects on forest hydrology and soil fertility have been reported (Alexander & Arthur, 2010; Gast et al., 1937; Levia & Frost, 2003; Sabau et al., 2010; Turk et al., 2008; Zinke, 1962). Species-specific variation in morphological characteristics influences incident rainfall interception and distribution, evaporation, transpiration, understory microclimate, nutrient inputs, and leaching (Levia & Frost, 2003). Species-specific difference in leaf litter quantity and quality influences decomposition rates and nutrient availability (Turk, 2006). Therefore, a shift in forest structure and species composition will lead to a shift in ecosystem function including forest hydrology, decomposition and nutrient cycling, and site fertility and productivity (Gayton, 2008).

In the Pacific Northwest, it is predicted that many naturally occurring deciduous tree species will gain habitat due to climate change (Hamann & Wang, 2006). Bigleaf maple (*Acer macrophyllum* Pursh) is a large deciduous tree that is abundant in western North America. Its native range extends from northern Vancouver Island south into California, and within 300 km of the Pacific Ocean (Peterson E, Peterson N, Comeau, & Thomas, 1999; USDAFS, 2004). Bigleaf maple is one of the most naturally abundant deciduous species in the Coastal Douglas-fir and Coastal Western Hemlock biogeoclimatic zones of British Columbia (Peterson et al., 1999). It is predicted that bigleaf maple will have a frequency increase of 97%, in British Columbia, by 2085 because of climate change, where frequency is a measure of percentage ground cover (Hamann & Wang, 2006).

Forest managers in the Pacific Northwest traditionally view many deciduous trees, including bigleaf maple, as weeds that compete with conifers for resources (Peterson et al., 1999). However, the presence of deciduous species in conifer stands can improve site fertility and overall productivity, which in turn increases the capacity of

ecosystems to recover, renew and reorganize after disturbance and hence enhances the overall ecosystem resilience (Turk et al., 2008; Sabau et al., 2010; Seybold, Herrick, & Brejda, 1999). Recent studies suggest that bigleaf maple can modestly improve soil fertility within conifer forests (Fried, Boyle, Tappeiner, & Cromack., 1990; Turk et al., 2008). The predicted future abundance of bigleaf maple suggests that this species will have an ecological role that is greater than currently perceived by forest managers. Hence, it is important to understand the effects of bigleaf maple on ecosystem processes such as nutrient cycling and hydrology in order to predict how forests will respond to climate change and to make sound management decisions.

Though there have been several studies examining litter quality and decomposition of bigleaf maple and other deciduous species in coastal mixed forest of British Columbia (Ogden & Schmidt, 1997; Prescott, Zabek, Staley, & Kabzems, 2000; Prescott, Blevins, & Staley, 2004a; Prescott, Vesterdal, Preston, & Simard, 2004b; Tashe & Schmidt, 2001; Turk et al., 2008), the impact of bigleaf maple on nutrient inputs via throughfall and stemflow in conifer forest has not yet been assessed. Furthermore, little is known about the degree and spatial extent of the impact of bigleaf maple on the surrounding forest floor. The present study thus investigates whether the predicted frequency increase of bigleaf maple could have species-specific effects on incident rainfall distribution and soil fertility in a coastal Douglas-fir forest. This was addressed by assessing the chemical properties of throughfall, stemflow and under-canopy forest floor and near trunk forest floor in the vicinity of bigleaf maple.

Materials and Methods

Study Area and Sampling Design

The study area is located within University of British Columbia's Malcolm Knapp Research Forest (MKRF), Maple Ridge, British Columbia. Two conifer-dominated stands that include some bigleaf maple trees were located using forest cover maps, local knowledge from MKRF personnel and field data obtained from previous studies (Turk, 2006). Four sets of paired plots were selected within each stand (each pair is composed of a bigleaf maple and a Douglas-fir plot), yielding a total of eight pairs (16 plots). A detailed description of the study area, and selection of the plots is provided in Chapter 2.

All of the selected trees were assessed for the following characteristics: DBH, canopy density, canopy width, canopy area, canopy volume, bark roughness, and epiphyte cover percentage. Canopy and stem observations were taken at 22.5° intervals determined on a rotating dial compass from the tree trunk. Canopy density was visually estimated. Canopy width was estimated by measuring the furthest extent of the canopy observed at ground level. Stem observations included bark roughness and the presence of epiphytes on bark. Bark roughness was measured by finding a representative bark fissure for the interval being measured and inserting a plastic tape measure into the full depth of the bark fissure and measuring outwards to the outer bark surface. The percentage of bark epiphytes was visually estimated in the interval being measured over 100 cm^2 at breast height. Epiphytes included in the analysis were lichen, moss and ferns. Percentages observed were indexed in the same categories outlined by Alexander and Arthur (2010) as follows: 0=<20%, 1 =21%-40%, 2 =41%-60%, 3 = 61%-80%, 4 = 81%-100%. Values for canopy width, bark roughness and epiphyte index were averaged to determine a value for each tree. The average canopy width measurements were then added to trunk radius to determine the full canopy width. Crown height dimensions were estimated using Suunto optical clinometer.

Throughfall and Stemflow Sampling and Analysis

The volumes of incident rainfall, throughfall, and stemflow were measured on ten dates over a 6-month period, from May 18 to November 17, 2009 (Table 3.2). The detailed collection methodology is described in Chapter 2. Samples collected from 22 September to 26 October and from 27 October to 17 November were composited separately on a volume basis into two composite samples reducing the samples collected over the 10 collection dates into seven samples per gauge/trough or stemflow collar (Table 3.2). For each period (P1 to P7 in table 3.2), there was a total of eight rainfall samples (one for each rain gauge and one for each rainfall trough), 16 stemflow samples (8 for bigleaf maple and 8 for Douglas-fir plots), and 32 throughfall samples (16 for bigleaf maple and 16 for Douglas-fir plots).

The set of subsamples stored at 4^oC was used for determining pH, and total dissolved organic carbon (DOC). The pH was measured by immersing a glass electrode pH meter into the sample. DOC was measured by the high temperature catalytic

oxidation method (Sharp, Suzuki, & Munday, 1993) (Shimadzu TOC-V CSH with OCT-1 8 Port Autosampler). The two throughfall samples from each plot were then composited into one sample reducing the 32 throughfall samples per period into 16. Samples representing the seven periods were then composited on a volume basis into one sample for each of rainfall, throughfall and stemflow for each plot for the study period yielding a total of 40 composited samples. Composited samples were then sent to the Ministry of Forests and Range, Research Branch Laboratory, Victoria, BC and were analyzed for elemental concentrations of P, K, Mg, Ca, and S by an inductively coupled plasma-atomic emission spectrometer (ICP-AES).

Samples stored at -20 ^{o}C were composited as described for the first set yielding a total of 40 subsamples. These subsamples were used to measure nitrate (NO_3-N) and ammonium (NH_4-N) colorimetrically using an Alpkem Flow System IV analyzer (Carter, 1993; Bremner, 1965). A sub-sample was then taken and subjected to an alkaline-persulphate digestion and analyzed colorimetrically to obtain total N concentration. The difference between total N and the sum of NO_3-N and NH_4-N was assumed to be dissolved organic nitrogen (DON). Deposition estimates were calculated as content (concentration x volume) divided by the collecting area, which was either the area of the rain guage/trough, throughfall trough or the basal area of the tree. The percentages of throughfall and stemflow of each species were determined by dividing the throughfall and stemflow volume by total rainfall volume respectively (% of stemflow volumes is equivalent to the funnelling ratio that is determined using the equation $SF/(B \times P)$ where, SF is the stemflow volume (l), B the trunk basal area (m^2), and P is the depth equivalent of gross incident precipitation (mm) (Herwitz, 1986).

Forest Floor Sampling and Analysis

At each of the 16 plots, three forest floor samples were collected at the stem (within 1 m from the stem) and six forest floor samples were collected under the canopy but away from the stem (three samples within 1 m from each throughfall trough). The samples were collected by removing a 10 x 10 cm section of the forest floor down to the mineral soil with a trowel, retaining F and H forest floor material and placing it into a labelled sample bag for transport to the Soil Laboratory at Simon Fraser University.

The pH testing was conducted on field moist subsamples and followed standard procedures with a 1:4 soil-to-solution ratio with 0.01 M $CaCl_2$ as the suspension solution and using a glass electrode pH meter (Kalra & Maynard, 1991). The forest floor samples were then air-dried and the three samples per collection point were composited to yield one sample near the stem and two samples under the canopy per plot. Further chemical analysis was conducted at the Ministry of Forests and Range, Research Branch Laboratory, Victoria, BC. Subsamples were oven dried and a correction factor (air dried to oven dried) was used to determine the oven-dried weight of each sample. Total C, N, and S were measured on a Fison NA-1500 Elemental Analyzer. NO_3-N and NH_4-N were measured colorimetrically using An Alpkem Flow System IV analyzer (Carter 1993; Bremner, 1965). Exchangeable K, Mg, and Ca were determined using an ARL 3600 inductively coupled argon plasma (ICAP) spectrometer, using the barium chloride method (Hendershot and Duquette, 1986). The sum of cations (K, Mg, Ca, Na, Fe, Al, Mn) measured by ICAP-spectrometer was used to measure effective cation exchange capacity (CEC) (Carter, 1993; Hendershot & Duquette, 1986). The sum of K, Mg, and Ca was used to calculate total exchangeable bases (TEB). Base saturation was determined by dividing TEB by CEC (Hendershot & Duquette, 1986). Total concentration values were converted to kg ha^{-1} based on the oven-dry weight of the forest floor per unit area.

Statistical Analysis

All data were analysed using SPSS 17 Software, with plots being considered as individual sample units. A significance level of 0.1 was used for all analyses due to considerable natural heterogeneity within measured properties. All variables were checked for normality using Q-Q plots. A one-way ANOVA with Tukey multiple comparison test was used to compare chemical variables of incident rainfall, throughfall and stemflow samples. Standardized volumes of rain gauges and rainfall troughs expressed in mm day^{-1} were used for calculating average rainfall volumes. Incident rainfall volume, pH and DOC concentration, and pH and DOC concentration in incident rainfall, throughfall, and stemflow of bigleaf maple and Douglas-fir were subjected to separate Pearson correlation analysis. In addition, volumes for each collection period, and pH and DOC concentration for each of the seven periods were subjected to separate paired sample t-tests. A paired sample t-test was used to analyse tree characteristics and vegetation (bigleaf maple and conifer) effect on throughfall and

stemflow volumes and nutrient concentrations and contents in the forest floor samples collected from under-canopy and near tree trunk.

Results

Throughfall Volumes and Chemical Properties

Bigleaf maple and Douglas-fir trees exhibited quite different characteristics (Table 3.1). Bigleaf maple trees were shorter in average height than Douglas-fir. The average canopy width, depth, and volume of bigleaf maple trees were greater than those of Douglas-fir. Bigleaf maple had a smoother bark and a greater epiphyte cover as well.

The mean recorded incident rainfall over the study period (May-November 2009) was 659 mm representing 36% of the long-term mean annual rainfall. For the study period, the percentage of incident rainfall falling as throughfall was higher at bigleaf maple plots (85%) than at Douglas-fir plots (76%) (Table 3.2). There was a trend of increasing throughfall volumes at bigleaf maple and Douglas-fir plots with increasing incident rainfall. In addition, a trend of higher throughfall volume was observed at bigleaf maple plots as compared to Douglas-fir plots in all of the collection periods (Table 3.2). Despite this trend, throughfall volume was significantly higher at bigleaf maple plots at only two periods (P9 and P10).

Mean-weighted pH for incident rainfall was not different from pH for throughfall at bigleaf maple plots, but was higher than for throughfall at Douglas-fir plots (Table 3.2). The pH of incident rainfall showed a very strong negative correlation with incident rainfall volume (r= -0.93, P<0.1). The pH in throughfall of bigleaf maple and Douglas-fir showed a strong and a moderate positive correlation respectively with rainfall pH (r= 0.95 and 0.56 respectively with P<0.1). T-tests showed significant differences between pH in throughfall of bigleaf maple and Douglas-fir during all periods (Table 3.2).

Mean-weighted DOC concentration in throughfall of bigleaf maple was significantly lower than that of Douglas-fir but greater than incident rainfall (Table 3.2). DOC concentration of incident rainfall did not correlate with incident rainfall volume. Similarly, DOC concentration in throughfall of bigleaf maple and Douglas-fir did not

correlate with DOC concentration of incident rainfall (all *r* values were below 0.3 with P>0.1). T-tests showed a significantly lower DOC concentration in throughfall of bigleaf maple in all periods except for P5 as compared to Douglas-fir (Table 3.2).

Concentrations of K, Mg, and S, and depositions of Ca, K, and S were significantly higher when associated with bigleaf maple as compared to incident rainfall. Similarly, concentrations of total N, NO_3-N, DON, Ca and depositions of Ca, and K were significantly higher when associated with Douglas-fir as compared to incident rainfall (Table 3.3).

In comparison to Douglas-fir throughfall, bigleaf maple throughfall had higher volume per unit area per day, pH and higher concentrations of P and K as well as higher deposition of, and P, K, and S while bigleaf maple throughfall had lower concentrations of DOC and Ca.

Stemflow Volume and Chemical Properties

Stemflow collected from bigleaf maple as a percentage of incident rainfall (7%) was lower than Douglas-fir stemflow (13%) (Table 3.2). There was a trend of increasing stemflow volumes at bigleaf maple and Douglas-fir plots with increasing incident rainfall. In addition, a trend of lower stemflow volume was observed at bigleaf maple plots as compared to Douglas-fir plots in all of the collection periods (Table 3.2). T-tests showed significant differences between stemflow volume of bigleaf maple and Douglas-fir during one period (P8).

Mean-weighted pH of the incident rainfall was higher than the pH for Douglas-fir stemflow, but did not differ from the pH for bigleaf maple stemflow. The pH in stemflow of bigleaf maple and Douglas-fir showed a strong positive correlation with rainfall pH (r= 0.73 and 0.72 respectively with P<0.1). T-tests showed significant differences between pH in stemflow of bigleaf maple and Douglas-fir during all periods except for period P5 (Table 3.2).

Mean-weighted DOC concentration and deposition in stemflow of bigleaf maple was significantly lower than that of Douglas-fir (Table 3.2). DOC concentration in stemflow of bigleaf maple and Douglas-fir did not correlate with DOC concentration of

incident rainfall (all *r* values were below 0.3 with P>0.1). T-tests showed a significantly lower DOC concentration in stemflow for bigleaf maple in periods P5, P6, and P7.

Concentrations and depositions of P and concentrations of DON, Ca, K, Mg, and S were significantly higher for stemflow of either bigleaf maple or Douglas-fir trees as compared to incident rainfall (Table 3.3). As compared to Douglas-fir stemflow, bigleaf maple stemflow had higher pH, and higher K concentration. Bigleaf maple stemflow DOC, concentrations and depositions, were significantly lower as compared to Douglas-fir stemflow.

Forest Floor Chemical Properties

For under-canopy samples, forest floor mass per unit area, forest floor pH, exchangeable Ca, exchangeable Mg, TEB, and CEC were significantly higher for bigleaf maple plots, when compared to conifer plots (Table 3.4).

For near-trunk samples, forest floor mass per unit area, forest floor pH, total N content, NO_3-N concentration and content, exchangeable Ca, and exchangeable Mg, total S content, TEB, BS, and CEC were significantly higher for bigleaf maple plots, when compared to conifer plots (Table 3.5). Total C concentration and content, and C:N ratio were significantly higher at conifer plots.

Discussion

Throughfall and Stemflow

Our research indicates a potential positive impact of throughfall and stemflow associated with bigleaf maple on site fertility of conifer forest. Though we measured a positive impact of bigleaf maple on throughfall and stemflow chemistry, the degree of difference between bigleaf maple and Douglas-fir was less than originally expected. We found 9 and 5 of 22 measured properties to be significantly different between bigleaf maple and Douglas-fir throughfall and stemflow respectively. These differences suggest a modest improvement in the stemflow and throughfall inputs to site fertility beneath bigleaf maple. The temporal data revealed that the potential positive impact can get

enlarged with predicted incident rainfall increase in the autumn and winter due to climate change in the Pacific Northwest (Gayton, 2008).

Species morphological variation such as canopy architecture, leaf area, deciduousness, and foliage density, are some of the factors that affect throughfall (Levia & Frost, 2003; Mina, 1967). It was anticipated that bigleaf maple would have a greater throughfall volume than Douglas-fir since it is a deciduous species with larger crown surface area to intercept rainfall (Comerford & White, 1977). Despite the trend of more throughfall at bigleaf maple plots, differences were only significant in the two periods that were characterized by the highest recorded daily mean rainfall. This may indicate that a certain rainfall threshold value must be attained before a significant difference is established between the species. Furthermore, we had expected that bigleaf maple would have greater stemflow due to its relatively smooth bark as compared to the rough bark of Douglas-fir, but surprisingly we found 46 percent less stemflow for bigleaf maple than for Douglas-fir. Possible reasons for the lower stemflow volume for bigleaf maple are: the greater epiphyte cover found on bigleaf maple which can lead to great water absorption; and the moderate branch angle inclination of Douglas-fir which directs water flow toward the stem (Hutchinson & Roberts, 1981; Levia & Herwitz, 2002; Steinbuck, 2002).

It was expected that throughfall of bigleaf maple would have a lower DOC concentration because it is a deciduous species (Liu & Sheu, 2003) and because of the smaller C concentration in bigleaf maple foliage as compared to Douglas-fir (Cross & Perakis, 2010). Bigleaf maple throughfall and rainfall mean-weighted DOC concentration were significantly lower than that of Douglas-fir. The lack of correlation between incident rainfall DOC concentration and rainfall volume, or DOC concentration in throughfall and stemflow, and the lower DOC concentration in bigleaf maple throughfall throughout the study periods could be due to the small atmospheric contribution of DOC in pristine sites in the Pacific Northwest (Edmonds, Thomas, & Blew, 1995) that would enlarge the relative percentage contribution of DOC in the throughfall and stemflow of individual species due to DOC washing and leaching from tree foliage.

The concentration and deposition of P were significantly higher for bigleaf maple throughfall than for Douglas-fir. This can possibly be explained by the higher P content of bigleaf maple leaves as compared to Douglas-fir needles (Cross & Perakis, 2010). In

addition, a higher leachability of P from bigleaf maple foliage could contribute to the higher P concentrations (Parker, 1983). Henderson et al. (1977) reported a higher P concentration in oak throughfall as compared to pine throughfall. Similarly, Comerford and White (1977) reported a higher P concentration in birch throughfall as compared to red pine.

The base-rich leaves of bigleaf maple (Cross & Perakis, 2010) were expected to produce throughfall enriched with K, Ca, and Mg. As expected, K concentrations were greater in throughfall of bigleaf maple plots as compared to conifer plots, however, Ca concentrations were lower and Mg concentrations were not significantly different. These variable results likely relate to the different leachability rates of the different bases in each species (Eaton et al., 1973; Henderson et al., 1977).

Bigleaf maple stemflow K concentration was significantly higher than that of Douglas-fir. This can be partially explained by the thick, fissured bark of Douglas-fir that would provide greater potential for the removal of K by ion exchange, thus limiting the enrichment of K in stemflow (André et al., 2008). In addition, the data presented show a much greater enrichment of stemflow than throughfall which suggests either a channelling of leaf leachate to the stems or considerable leaching from the bark (Thomas, 1969).

The pH for bigleaf maple throughfall was significantly higher than that of Douglas-fir throughfall. This may be due to the lower DOC concentration of bigleaf maple throughfall. DOC is composed of several compounds, ranging from short-chain acids to large molecules such as fulvic and humic acids and thus, may influence water acidity (Dalva & Moore, 1991). In addition, the higher base-content of bigleaf maple foliage could have contributed to the higher pH in throughfall as well (Cross & Perakis, 2010). The significant correlation between rainfall pH and rainfall volume in our study could be due to the fact that the first 5-10 mm of rainfall in the coastal forests of British Columbia reflects oceanic effect. However, when rainfall exceeds 10 mm then rainfall chemistry reflects the atmospheric components in the local area. The study area is in close proximity to an urban area with acid forming factors and hence there is a decrease in rainfall acidity (O. Hertzman (personal communication 2011)). The trend of increased pH value as water passed through bigleaf maple canopy and along its trunk irrespective

of rainfall volume, indicates a certain acid buffering capacity of bigleaf maple that is not likely hindered by current and predicted future rainfall volumes.

Forest Floor

Differences in forest floor properties were greater in the near trunk area than away from the trunk with 16 and 6 of 23 measured properties being significantly different between bigleaf maple and Douglas-fir plots in the near trunk and under-canopy areas respectively. These results indicate improved soil fertility under the canopy of bigleaf maple with the best conditions near the tree stems. Reasons for the improved conditions beneath bigleaf maple include: inputs of nutrient-rich litterfall from bigleaf maple (Turk, 2006), and inputs of relatively nutrient-enriched throughfall. In addition, in the vicinity of the bigleaf maple stems there is an input of stemflow with relatively high pH.

Near trunk forest floors at bigleaf maple plots showed a significantly lower C concentration and content than at Douglas-fir plots. Possible reasons for the lower C concentrations and contents beneath bigleaf maple include: higher total carbon concentrations of Douglas-fir litter as compared to bigleaf maple litter (Turk, 2006; Valachovic et al., 2004); lower DOC concentration and deposition in stemflow at bigleaf maple plots (Table 6); and differences in litter quality (C:N) ratio that lead to differences in type and activity of soil organisms and soil respiration beneath bigleaf maple and Douglas-fir (Raich & Tufekcioglu, 2000). It is possible that near bigleaf maple stems, there is a greater degree of mixing of forest floor and mineral soil horizons by soil organisms resulting in lower C concentrations in forest floors. In addition, there could be a higher soil respiration rate associated with bigleaf maple as deciduous trees were reported to be associated with soil of a higher CO_2 efflux (Raich & Tufekcioglu, 2000).

Total N content, as well as NO_3-N concentration and content were higher in the near trunk forest floor samples at the bigleaf maple sites. Possible reasons for the enhanced N status near bigleaf maple stems are: greater N concentrations in bigleaf maple litter as compared to Douglas-fir litter (Turk et al., 2008); and higher pH near stems from litterfall and stemflow inputs that can enhance microbial activity and mineralization and nitrification rates (Boerner & Koslowsky, 1989; Chang & Matzner, 2000). This study supports the idea of Alexander and Arthur (2010) that leaf litter and

stemflow are controlling factors of species N mineralization rates in areas surrounding stems.

The results suggest that throughfall and stemflow make a minimal contribution to forest floor exchangeable bases. It seems that the base-rich bigleaf maple litterfall and decomposition (Turk, 2006; Valachovic et al., 2004) and the chemical weathering of the parent materials dominate the influence of throughfall and stemflow. In addition, the higher leachability of K likely causes it to move to the lower mineral soil horizons.

The pH values in the under-canopy and near trunk forest floor at bigleaf maple plots were significantly higher as compared to conifer plots. Factors responsible for the higher pH beneath bigleaf maple include: more basic litter and throughfall for bigleaf maple; more basic stemflow received by the forest floor near trunk at bigleaf maple plots; higher total C in Douglas-fir litter and forest floor releasing H^+ making the soil solution more acidic; and higher CEC and BS for forest floor beneath bigleaf maple resulting in higher pH (Fisher & Binkley, 2000) CEC of both under-canopy and near trunk forest floors at bigleaf maple sites were significantly higher as compared to Douglas-fir sites which may be due to greater concentrations of organic colloids in the forest floor beneath bigleaf maple (Turk et al., 2008).

Management implications

Bigleaf maple, like other hardwoods, is managed to minimize its competitive influence in conifer forests (Turk et al., 2008). Conventionally, the presence of bigleaf maple has been deemed competitive and even detrimental to conifer survival (Haeussler et al., 1990). Recent studies suggest that bigleaf maple may enhance nutrient availability (Fried et al., 1990; Turk et al., 2008). In coastal forests of British Columbia, bigleaf maple has low to moderate shade intolerance and it is an early to middle successional species (Peterson et al., 1999). Our findings of enriched microsites proximal to bigleaf maple trunks suggest that bigleaf maple has a potential legacy effect on soil fertility and hence, may promote conifer productivity later in succession following bigleaf maple mortality. Biological legacies are central for sustainable forest management. The establishment and/or retaining of biological legacies aid in maintaining crucial structural elements as components of managed stands thereby sustaining many organisms and ecological

processes dependent upon these structures (Franklin et al., 2002). This would allow the ecosystem to restore its structural and functional integrity and enhance its resilience in our ever-changing environment (Seybold et al., 1999). In this context, bigleaf maple may be a desirable species for forest management. Our current findings provide evidence that increased bigleaf maple presence would likely lead to few but important changes in forest hydrology and nutrient cycling. These changes could act as additional mechanisms by which bigleaf maple creates conditions of improved site fertility that potentially foster the proliferation of conifer species at later stages of succession.

Conclusion

The results suggest that bigleaf maple growing within conifer forests has the potential to modestly improve site conditions under its canopy and to a greater extent in the vicinity of its trunk. The greater degree of soil fertility improvement near bigleaf maple trunks is likely due to these areas being influenced by stem-related processes such as stemflow, in addition to canopy related processes such as litterfall and throughfall. We found higher pH and greater K inputs for both throughfall and stemflow, as well as greater P and S inputs in throughfall at bigleaf maple plots compared to conifer plots. Furthermore, areas that are near bigleaf maple trunks are more strongly influenced by bigleaf maple, whereas areas beneath the bigleaf maple canopy but further away from the trunk are influence by bigleaf maple as well as the surrounding conifers. The result is a zone around bigleaf maple stems that likely has enhanced microbial activity and increased nutrient availability. Changes in soil properties induced by bigleaf maple may be long-lasting. For example, Mina (1967) found that after stemflow ceases, changes which had taken place earlier in the soil may be preserved for many years. Thus, the enriched microsites proximal to bigleaf maple trunks may form fertile spots for conifer growth at later stages of forest development.

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Table 3.1. Tree characteristics of bigleaf maple and Douglas-fir (n=8)

Tree Characteristic	Bigleaf maple		Douglas-fir		P (t-test)
DBH (cm)	50.7	(11.4)	49.4	(11.4)	0.17
Canopy density (%)	80.0	(1.5)	77.5	(3.7)	0.24
Basal area (cm^2/tree)	2111	(908)	2007	(877)	0.18
Height (m)	33.9	(7.9)	42.0	(8.9)	**0.028**
Canopy width (m)	7.10	(2.39)	4.72	(2.24)	**0.017**
Canopy area (m^2)	173.9	(119.1)	83.7	(58.1)	**0.031**
Canopy depth (m)	21.3	(8.0)	17.9	(8.4)	0.87
Canopy volume (m^3)	3521	(3034)	1769	(1328)	**0.031**
Bark roughness(mm)	4.8	(2.1)	14.8	(5.7)	**0.001**
Bark epiphyte index	2.71	(0.95)	1.09	(1.09)	**0.012**

Values in parentheses represent standard deviations. Double underlined values indicate a significant difference at $P < 0.05$.

Table 3.2. Incident rainfall, and bigleaf maple and Douglas-fir throughfall and stemflow average volumes (mm day^{-1}), pH, and dissolved organic carbon concentration (mg l^{-1}) (n=8)

Variable	Period	Date	Days	Rainfall		Throughfall				Stemflow			
						Bigleaf maple		Douglas-fir		Bigleaf maple		Douglas-fir	
				Mean		Mean		Mean		Mean		Mean	
Volume (mm day^{-1})	1	18- 25 May	7	3.13 **ad**	(0.47)	2.41**b**	(0.41)	2.08 **b**	(0.58)	0.09**e**	(0.09)	0.25 **e**	(0.26)
	2	26 May-26 Jun	31	0.79 **ad**	(0.13)	0.52 **b**	(0.09)	0.52**b**	(0.20)	0.02 **e**	(0.02)	0.03 **e**	(0.02)
	3	27 Jun-12 Jul	16	1.44 **ad**	(0.21)	0.96 **b**	(0.23)	0.86 **b**	(0.45)	0.04**e**	(0.03)	0.06**e**	(0.06)
	4	13 Jul-17 Aug	36	1.78 **ad**	(0.36)	1.62 **a**	(0.54)	1.35**a**	(0.68)	0.10**e**	(0.08)	0.15**e**	(0.10)
	5	18 Aug-21 Sep	35	2.01 **ad**	(0.28)	1.61 **ab**	(0.48)	1.22 **b**	(0.51)	0.07**e**	(0.04)	0.16**e**	(0.14)
	6	22 Sep-19 Oct	28	2.68 **ad**	(0.45)	2.09 **b**	(0.33)	2.06 **b**	(0.53)	0.13**e**	(0.07)	0.28**e**	(0.22)
	7	20 Oct-26 Oct	7	11.46 **ad**	(1.92)	10.53**a**	(2.21)	9.16**a**	(3.32)	1.15**e**	(0.81)	2.00**e**	(0.87)
	8	27 Oct-03 Nov	8	7.62 **ad**	(0.40)	6.71 **ab**	(1.15)	5.64**b**	(2.32)	0.67**e**	(0.33)	1.67 **f**	(0.70)
	9	4 Nov-09 Nov	6	11.62 **ad**	(1.51)	10.80 **a**	(1.65)	8.94**b**	(1.57)	1.03**e**	(0.56)	0.93**e**	(0.52)
	10	10 Nov-17 Nov	8	13.99 **ad**	(1.83)	10.63**b**	(1.56)	8.63**c**	(1.70)	1.35 **e**	(0.87)	1.96**e**	(1.12)
pH	1	18- 25 May	7	4.80 **ad**	(0.33)	5.82**b**	(0.20)	4.97 **a**	(0.15)	5.62 **e**	(0.19)	4.63 **d**	(0.48)
	2	26 May-26 Jun	31	5.58 **ade**	(0.90)	5.97 **a**	(0.32)	4.98 **b**	(0.12)	6.42 **d**	(1.40)	4.71 **e**	(0.71)
	3	27 Jun-12 Jul	16	5.60 **abd**	(0.18)	6.02 **a**	(0.21)	4.76 **b**	(1.27)	7.31 **e**	(0.41)	5.77 **d**	(1.09)
	4	13 Jul-17 Aug	36	5.26 **ad**	(0.33)	5.67 **a**	(0.24)	3.58 **b**	(1.26)	6.21 **e**	(1.24)	4.33 **f**	(0.45)
	5	18 Aug-21 Sep	35	5.84 **ad**	(0.65)	6.32 **a**	(0.44)	4.17 **b**	(1.50)	7.95 **e**	(2.04)	6.36 **de**	(1.25)

Variable	Period	Date	Days	Rainfall		Throughfall				Stemflow			
						Bigleaf maple		Douglas-fir		Bigleaf maple		Douglas-fir	
				Mean		Mean		Mean		Mean		Mean	
	6	22 Sep-26 Oct	35	4.88 **abd**	(0.41)	5.64 **a**	(0.32)	4.15 **b**	(1.22)	6.58 **e**	(2.13)	4.07 **d**	(0.69)
	7	27 Oct-17 Nov	22	4.15 **abd**	(0.46)	4.96 **a**	(1.04)	3.28 **b**	(1.31)	5.55 **e**	(0.30)	3.92 **d**	(0.40)
DOC (mg l^{-1})	1	18- 25 May	7	1.63 **ad**	(0.26)	6.36 **b**	(1.19)	7.76 **c**	(1.36)	11.43 **e**	(7.65)	15.58 **e**	(11.01)
	2	26 May-26 Jun	31	4.59 **ad**	(5.36)	10.04 **b**	(1.60)	14.46 **c**	(1.70)	16.56 **d**	(9.93)	44.04 **d**	(43.49)
	3	27 Jun-12 Jul	16	4.02 **ad**	(1.87)	14.05 **a**	(2.86)	31.40 **b**	(14.59)	44.57 **e**	(6.95)	45.93 **e**	(32.88)
	4	13 Jul-17 Aug	36	2.64**ad**	(0.72)	8.18 **b**	(3.33)	12.73**c**	(2.86)	16.56 **e**	(8.09)	39.90**e**	(33.13)
	5	18 Aug-21 Sep	35	2.66 **ad**	(0.58)	9.82 **b**	(3.88)	13.03 **b**	(2.50)	26.63 **e**	(7.70)	55.60 **f**	(19.26)
	6	22 Sep-26 Oct	35	1.52 **ad**	(0.50)	11.72 **b**	(1.98)	21.07 **c**	(7.50)	36.24 **d**	(14.56)	136.4**e**	(51.56)
	7	27 Oct-17 Nov	22	1.21 **ad**	(0.21)	6.22 **b**	(2.17)	8.39 **c**	(2.00)	21.43 **d**	(7.45)	64.63 **e**	(44.37)

Values in parentheses represent standard deviations. a, b, and c designate significant differences (rainfall vs. bigleaf maple throughfall vs. Douglas-fir throughfall) while d, e, and f designate significant differences (rainfall vs. bigleaf maple stemflow vs. Douglas-fir stemflow) at P<0.1.

Table 3.3. Rainfall , throughfall, and stemflow chemical properties for bigleaf maple and Douglas-fir plots (n=8)

	Rainfall		Throughfall				stemflow			
			Bigleaf maple		Douglas-fir		Bigleaf maple		Douglas-fir	
Volume (mm day^{-1})	3.45 **ad**	(0.49)	2.86 **ab**	(0.58)	2.49 **b**	(0.83)	0.24 **e**	(0.15)	0.44 **f**	(0.26)
pH	5.41 **ad**	(0.39)	5.47 **a**	(0.38)	3.87 **b**	(0.97)	5.71 **d**	(0.36)	4.02 **e**	(0.63)
Concentration, mg l^{-1}										
DOC	2.60 **ad**	(1.30)	7.91 **b**	(1.24)	13.39 **c**	(3.88)	25.85**e**	(9.64)	82.67 **f**	(34.17)
Total N	0.54 **ad**	(0.37)	0.76 **ab**	(0.19)	1.34 **b**	(1.15)	5.05**d**	(7.30)	3.24 **d**	(1.53)
NH_4-N	0.16**ad**	(0.19)	0.10 **a**	(0.06)	0.14**a**	(0.24)	3.54 **d**	(7.15)	1.22 **d**	(1.17)
NO_3-N	0.09 **ad**	(0.02)	0.12 **ab**	(0.05)	0.47 **b**	(0.24)	0.20 **d**	(0.24)	0.28 **d**	(0.41)
DON	0.29 **ad**	(0.18)	0.54 **ab**	(0.13)	0.72 **b**	(0.36)	0.74 **e**	(0.37)	1.09 **e**	(0.57)
P	0.07 **abd**	(0.07)	0.14 **b**	(0.11)	0.04 **a**	(0.02)	0.62 **d**	(0.82)	0.09 **d**	(0.05)
Ca	0.24 **ad**	(0.05)	0.73**a**	(0.08)	1.30 **b**	(0.74)	5.90 **e**	(4.26)	3.44 **de**	(1.54)
K	0.60 **ad**	(0.26)	4.91 **b**	(0.91)	2.76 **c**	(1.34)	13.25**e**	(7.54)	5.86 **d**	(2.11)
Mg	0.08 **ad**	(0.02)	0.22 **b**	(0.04)	0.29 **b**	(0.14)	0.98 **e**	(0.67)	0.64 **e**	(0.18)
S	0.21 **ad**	(0.05)	0.44 **b**	(0.09)	0.38**b**	(0.13)	1.57 **e**	(1.13)	0.91 **de**	(0.35)
Deposition, kg ha^{-1}										
DOC	25.64 **ad**	(24.80)	39.85 **ab**	(10.14)	58.81 **b**	(25.97)	11.09 **d**	(7.50)	61.24 **e**	(38.67)
Total N	3.32 **ad**	(2.40)	3.61 **a**	(0.77)	4.60 **a**	(5.87)	3.69 **d**	(6.60)	1.97 **d**	(1.04)
NO_3-N	0.55 **ad**	(0.16)	0.58 **a**	(0.22)	1.72 **a**	(2.88)	0.14 **e**	(0.22)	0.12 **e**	(0.14)
NH_4-N	1.01 **ad**	(1.27)	0.48 **a**	(0.21)	0.58 **a**	(1.19)	2.80 **d**	(6.34)	0.70 **d**	(0.76)
DON	1.77 **ad**	(1.16)	2.55 **a**	(0.63)	2.31 **a**	(1.92)	0.75 **e**	(0.36)	1.15 **de**	(0.64)
P	0.49 **abd**	(0.46)	0.71 **a**	(0.54)	0.19 **b**	(0.11)	0.28 **de**	(0.37)	0.07 **e**	(0.04)
K	3.62 **ad**	(1.59)	24.22 **b**	(3.58)	10.86 **c**	(2.81)	5.53 **d**	(3.72)	3.95 **d**	(2.09)
Ca	1.51 **ad**	(0.40)	3.64 **b**	(0.34)	5.34 **b**	(2.86)	2.53 **d**	(2.17)	2.53 **d**	(1.67)
Mg	0.40 **ad**	(0.28)	0.58 **a**	(0.50)	0.76 **a**	(0.74)	0.43 **d**	(0.38)	0.46 **d**	(0.25)
S	1.30 **ad**	(0.38)	2.21 **b**	(0.42)	1.58 **a**	(0.34)	0.66 **e**	(0.51)	0.63 **e**	(0.40)

Values in parentheses represent standard deviations. a, b, and c designate significant differences (rainfall vs. bigleaf maple throughfall vs. Douglas-fir throughfall) while d, e, and f designate significant differences (rainfall vs. bigleaf maple stemflow vs. Douglas-fir stemflow) at P<0.1.

Table 3.4. Forest floor (under-canopy) chemical properties for bigleaf maple and Douglas-fir plots (n=8)

	Bigleaf maple plots		Douglas-fir plots		P (t-test)
Forest floor (kg ha^{-1})	6322	(1527)	4806	(996)	**0.031**
pH (1:4 CaCl2)	4.00	(0.48)	3.59	(0.42)	**0.058**
C:N ratio	23.89	(2.52)	33.65	(20.83)	**0.245**
Concentration					
Total C (g kg^{-1})	302.98	(82.42)	407.21	(202.90)	**0.236**
Total N (g kg^{-1})	12.74	(3.71)	13.38	(3.90)	**0.728**
NO_3-N (mg kg^{-1})	45.60	(41.28)	24.02	(26.31)	**0.165**
NH_4-N (mg kg^{-1})	118.87	(69.20)	143.88	(164.51)	**0.671**
Total S (g kg^{-1})	1.47	(0.34)	1.55	(0.39)	**0.669**
Exch K (cmol kg^{-1})	1.01	(0.16)	0.81	(0.41)	**0.238**
Exch Ca (cmol kg^{-1})	34.89	(12.39)	22.59	(8.78)	**0.006**
Exch Mg (cmol kg^{-1})	4.68	(1.52)	2.45	(0.86)	**0.013**
TEB (cmol kg^{-1})	40.69	(12.56)	25.99	(9.23)	**0.006**
CEC (Ba) (cmol kg^{-1})	43.27	(13.03)	28.81	(8.47)	**0.005**
BS (%)	94.03	(6.14)	90.21	(7.91)	**0.238**
Content					
Total C (kg ha^{-1})	1930.18	(817.93)	2019.77	(1097.21)	**0.829**
Total N (kg ha^{-1})	81.05	(36.21)	64.93	(26.95)	**0.295**
NO_3-N (kg ha^{-1})	0.30	(0.27)	0.13	(0.14)	**0.165**
NH_4- (kg ha^{-1})	0.73	(0.43)	0.63	(0.66)	**0.671**
Total S (kg ha^{-1})	9.27	(3.38)	7.51	(2.70)	**0.588**

Values in parentheses represent standard deviations. Single and double underlined values indicate a significant difference at P <0.1 and P <0.05.

Table 3.5. Forest floor (near trunk) chemical properties for bigleaf maple and Douglas-fir plots (n=8)

	Bigleaf maple plots		Douglas-fir plots		P (t-test)
Forest floor (kg ha^{-1})	5323	(1213)	3629	(1174)	**0.044**
pH (1:4 CaCl2)	4.78	(0.65)	3.47	(0.49)	**0.002**
C:N ratio	18.56	(8.89)	34.48	(9.75)	**0.004**
Concentration					
Total C (g kg^{-1})	264.94	(145.87)	474.13	(103.21)	**0.016**
Total N (g kg^{-1})	15.58	(8.35)	14.04	(1.77)	**0.651**
NO_3-N (mg kg^{-1})	70.89	(62.30)	18.90	(20.87)	**0.030**
NH_4-N (mg kg^{-1})	97.99	(67.70)	134.10	(92.09)	**0.362**
Total S (g kg^{-1})	1.63	(0.79)	1.63	(0.28)	**0.996**
Exch K (cmol kg^{-1})	1.13	(0.60)	0.88	(0.16)	**0.267**
Exch Ca (cmol kg^{-1})	54.62	(30.09)	25.58	(9.75)	**0.050**
Exch Mg (cmol kg^{-1})	7.05	(4.31)	2.60	(0.47)	**0.019**
TEB (cmol kg^{-1})	62.93	30.74	29.22	9.96	**0.045**
CEC (Ba) (cmol kg^{-1})	64.22	(34.07)	32.32	(9.04)	**0.052**
BS (%)	97.99	(5.37)	90.40	(6.53)	**0.05**
Content					
Total C (kg ha^{-1})	1321.30	(576.90)	1705.70	(622.76)	**0.017**
Total N (kg ha^{-1})	80.70	(39.30)	49.95	(12.49)	**0.041**
NO_3-N (kg ha^{-1})	0.43	(0.45)	0.05	(0.06)	**0.030**
NH_4-N (kg ha^{-1})	0.49	(0.32)	0.55	(0.48)	**0.362**
Total S (kg ha^{-1})	8.45	(3.67)	5.79	(1.55)	**0.064**

Values in parentheses represent standard deviations. Single and double underlined values indicate a significant difference at P <0.1 and P <0.05.

Table 3.6 Bigleaf maple plot properties as compared to Douglas-fir plots (n=8, P <0.1)

	Throughfall	Under-canopy Forest Floor	Stemflow	Near-trunk Forest Floor
Volume or weight/area	↑	↑	↓	↑
pH	↑	↑	↑	↑
DOC (concentration)	↓	NA	↓	NA
DOC (deposition)	----	NA	↓	NA
Total C (concentration)	NA	↓	NA	↓
Total C (content)	NA	↓	NA	↓
Total N (concentration)	----	----	----	----
Total N (deposition/content)	----	----	----	↑
NO_3-N (concentration)	----	----	----	↑
NO3-N (deposition/content)	----	----	----	↑
C/N	NA	----	NA	↓
P (concentration)	↑	NA	----	NA
P (deposition)	↑	NA	----	NA
Ca (concentration)	↓	↑	----	↑
K (concentration)	↑	----	↑	----
Mg (concentration)	----	↑	----	↑

NA: not applicable, ----: no difference, ↑: significantly higher, ↓: significantly lower.

Chapter 4.[1]

Analytical Techniques for Characterizing the Spatial Structure of Forest Floor pH, Nitrate, and Ammonium Associated with Bigleaf Maple and Western Hemlock at Multiple Scales

Abstract

Novel analytical techniques are needed to enhance our understanding of species-specific influence on soil properties. Four analytical techniques were used to detect the spatial structure of forest floor properties associated with bigleaf maple (*Acer macrophyllum* Pursh), at multiple scales, within a conifer forest. Two 140 yr-old and two 75 yr-old bigleaf maple and western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) 20 x 20 m plots, centered on individual dominant stems, were sampled at 100 systematic locations and tested for forest floor pH, nitrate, and ammonium. Kriged maps showed that forest floor pH was higher and lower in locations adjacent to bigleaf maple and western hemlock stems respectively. Local indicators of spatial association analysis showed the presence of positive clusters and negative clusters of pH associated with bigleaf maple and western hemlock stems respectively, up to a distance of 3 m from the stems. Polynomial RDA variance partitioning revealed that the spatial component has a higher contribution to overall variability on bigleaf maple plots and PCNM RDA analysis revealed that broad (large) and fine (small) scale spatial patterns of forest floor pH, NO_3, and NH_4 are related to topography, canopy cover, canopy density and moisture content.

[1] A version of this chapter is under review for publication in the Canadian Journal of Soil Science under the co-authorship of Margaret Schmidt.

This study provides an understanding of the multi-scale spatial patterns of forest floor properties due to species-specific impacts on soil properties.

Introduction

Spatial analyses of species-specific impacts on soil properties have not been extensively studied. The early work of Zinke (1962) suggested that there is a general predictable pattern surrounding individual trees. Zinke described this pattern as a set of rings influenced by an inner ring of bark litter, an outer ring of leaf and twig litter, and the adjacent marginal effect of an opening or the corresponding influence ring of a nearby tree. The inner and outer rings are modified by throughfall, canopy drip, and stemflow. These ideas were validated in ecosystems with different forest cover (conifer vs. broadleaf trees) or topography (Crampton, 1982; Crampton, 1984; Escudero, Hernandez, & Arco, 1991; Rhoades & Binkley, 1992), and evolved the "single-tree influence circles" concept (Boettcher & Kalisz, 1990) and the “tree influence potential” concept (Saetre, 1999). The "tree influence potential” concept assumes that the influence of a tree is symmetrical in space and is proportional to the diameter at breast height (DBH) (Saetre, 1999; Saetre & Bååth, 2000; Bengtson et al., 2006).

In the last three decades, the importance of the scale component in ecological datasets has been well established (Dungan et al., 2002; Borcard & Legendre, 2002). Now it is widely recognized that ecological patterns result from the interaction of several ecological processes acting at various scales (Wagner & Fortin, 2005). Hence, appropriate sampling designs and powerful analytical methods can aid in identifying the patterns at various scales and relating the patterns to the appropriate processes generating them (Borcard et al., 2011). Fortunately, statistical methodology rapidly developed to assist in exploring and quantifying spatial patterns at multiple scales (Borcard et al., 1992; Borcard & Legendre, 2002; Dungan et al., 2002). The “scale” term has been used with various definitions in different disciplines (Dungan et al., 2002; Schneider, 2001). In spatial analysis of patterns at multiple scales, the “scale” is used to refer to the separation distance (lag, sampling interval, sampling step) between measurements (Schneider, 2001). Borcard and Legendre (2002) introduced a new spatial analysis technique, namely Principal Coordinates of Neighbour Matrices (PCNM),

to dissect the spatial structure of ecological data to broad (large or global) and fine (small or local) scales and to quantify the variance explained by each of the scales. This method detects the spatial structures at scales ranging from the broadest (the whole sampled area), to the finest (sizes are of the order of magnitude of the sampling interval). The PCNM approach has proven to be a powerful technique for analysing ecological data (Borcard et al., 2004) and hydrological data (Lacey et al, 2007; Ali et al., 2010), however, to the best of our knowledge, PCNM has not been applied to soil data.

Bigleaf maple (*Acer macrophyllum* Pursh) is a large deciduous tree that is abundant in western North America, and is one of the most naturally abundant deciduous species in the Coastal Douglas-fir and Coastal Western Hemlock biogeoclimatic zones of British Columbia (Peterson et al., 1999). It is predicted that bigleaf maple will have an increase in abundance by 97% by 2085 due to climate change (Hamann & Wang, 2006). Local enriched microsites proximal to bigleaf maple trunks suggest that bigleaf maple has a potential legacy effect on soil fertility and hence, may promote conifer productivity later in succession following bigleaf maple mortality (Hamdan & Schmidt, 2012). The predicted future abundance of bigleaf maple suggests that this species will have an ecological role that is greater than currently perceived by forest managers. Hence, it is important to understand the effects of bigleaf maple on the spatial patterns of soil properties.

Observed patterns of soil properties surrounding individual trees reflect both species-specific processes (including, litterfall, throughfall, and stemflow), and other factors acting at various spatial scales such as climate, and topography (Jenny, 1941; Gourbiere, 1995). Therefore, the nature of soil and its chemical properties in relation to forest composition are scale dependent and hence examining patterns of soil properties associated with different tree species, at multiple scales, can enhance our understanding of species-specific effects on soil properties. Our objective was to characterize spatial patterns of forest floor properties (pH, NO_3, and NH_4) under the influence of individual bigleaf maple trees by using PCNM and other commonly used spatial analysis techniques capable of detecting the spatial structure at a different scales, namely, Kriging, Local Indicators of Spatial Analysis (LISA) and polynomial redundancy (RDA) variance partitioning.

Materials and Methods

Study Area

The study area is located within University of British Columbia's Malcolm Knapp Research Forest, Maple Ridge, British Columbia (Fig. 2.1). A description of the study area is provided in Chapter 2.

Sampling design

Two conifer-dominated stands that include some bigleaf maple trees were located using forest cover maps, local knowledge from MKRF personnel and data obtained from previous studies (Chandler, 2006; Turk, 2006). Stand 1 is a 140-year-old stand while stand 2 is a 75-year-old stand. Within each stand a bigleaf maple plot was selected. Selection was based on three criteria: 1) plots were undisturbed, 2) plots were centred on the bole of a bigleaf maple tree dominant in the canopy and 3) the central bigleaf maple bole was at least 20 m away from any other bigleaf maple stem or other deciduous tree. Plots were centred around trees that were more than 10 m distant from signs of major disturbances such as trails or roads.

Within each stand, the bigleaf maple plot was matched with a western hemlock plot displaying similar site characteristics, such as slope, aspect and elevation. The use of plots with similar site characteristics allows for comparison between plots with and without bigleaf maple. Each plot has an area of 20 x 20 m and has the bole of a tree at plot centre. Bigleaf maple plot 1 is located in the 140-yr-old stand and plot 2 is in the 75-yr-old stand. Conifer plots were located at a distance between 30 and 60 m from their bigleaf maple plot counterpart to limit effects of bigleaf maple on conifer plots. The elevation, slope, aspect, and the diameter at breast height and the canopy extent of all the trees within the four plots were measured and are summarized in Table 4.1. The tree canopy type (bigleaf maple, Douglas-fir, western hemlock, and western redcedar) directly above each sample location was recorded and mapped (Appendix A).

In Summer 2009, forest floor was sampled at 2 m intervals along a 20 x 20 m grid having the bigleaf maple or western hemlock stem at its centre. This provided 100 forest floor samples at each of the four plots. The samples were collected by removing a 10 x 10 cm section of the forest floor down to the mineral soil with a trowel, removing F

and H horizons and placing the forest floor sample into a labelled sample bag for transport to the Soils Laboratory at Simon Fraser University.

Laboratory Analysis

For each forest floor sample the following properties were measured: pH, nitrate (NO_3-N) and ammonium (NH_4-N). The pH testing was conducted on field moist samples, within 16 hours of sample collection, and followed standard procedures with a 1:4 soil-to-solution ratio with 0.01 M $CaCl_2$ as the suspension solution and using a glass pH meter (Kalra & Maynard, 1991). The suspension was stirred every 5 minutes for 30 minutes and left to settle for the following 30 minutes. The pH was measured by immersing a glass pH meter into the supernatant solution. The pH value was recorded after the reading on the pH meter stabilized. The forest floor samples were air-dried and analyzed for NO_3 and NH_4 concentrations colorimetrically using an Alpkem Flow System IV analyzer (Carter, 1993; Bremner, 1965), by the Ministry of Forests and Range, Research Branch Laboratory, Victoria, BC.

Data Analysis

Spatial analysis techniques were used to explore and compare species-specific effects on the spatial distribution of forest floor pH, NO_3 and NH_4. Four spatial analysis techniques were used to characterize the spatial patterns in the data at multiple scales. First, Kriged maps were used to visually explore patterns in the data. Second, LISA was used to detect and locate significant spatial clustering of similar values at the fine scale (Anselin, 1995). Third, polynomial RDA variance partitioning analysis was performed to detect the contribution of the spatial component in explaining the variance over the broad scale of the sampled region. Finally, PCNM partial redundancy analysis (PCNM RDA) was used to detect the spatial pattern at multiple scales and to determine what environmental variables are of significance to the detected spatial pattern at each scale (Lacey et al., 2007). Because PCNM variance partitioning is a relatively new analytical technique and has rarely been used to analyse soil data, we will describe it and polynomial RDA variance partitioning in detail, for the other analytical techniques the reader can refer to Chandler et al. (2008).

Polynomial RDA Variance Partitioning

Variance partitioning was used to examine the sources of variability in the forest floor pH, NO_3 and NH_4 using RDA in CANOCO (terBraak, 1998). The spatial variables that were used were developed from the matrix of two-dimensional geographic co-ordinates, x and y (Borcard et al., 1992), that was completed by adding all terms for a polynomial cubic trend surface regression of the form:

$$Z = b_1 x + b_2 y + b_3 x^2 + b_4 xy + b_5 y^2 + b_6 x^3 + b_7 x^2 y + b_8 xy^2 + b_9 y^3$$

The two groups of response variables used were forest floor pH and forest floor NO_3 and NH_4. All variables were assessed for normality and standardized as required to allow better identification of the relationships among the variables in minimizing the overshadowing effects of certain variables having a wider range than others. The environmental variables were: canopy cover type (four qualitative classes: gaps, bigleaf maple, conifer, bigleaf maple and conifer), canopy cover density (three semi-quantitative classes), microtopography (three qualitative classes: pit, flat, or mound), forest floor moisture content (quantitative), topography (relative elevation at each sampling point, quantitative) (Appendix B) and presence/absence of logs, rocks, stumps, and/or ferns (all qualitative). Relative elevation (cm) was measured with a total station, to a reference point selected at the edge of the plot. A forest floor sub-sample was oven dried at 70 ^{o}C for 24 hours, and gravimetric moisture content was determined as (wet weight – dry weight)/dry weight (gram of water/ g of soil) (Kalra & Maynard, 1991). All the other environmental variables were visually determined in the field.

Principal Coordinates of Neighbour Matrices RDA Variance Partitioning

Principal coordinates of neighbour matrices (PCNM) method belongs to the Moran's eigenvector maps (MEM) family of spatial methods (Borcard & Legendre, 2002; Dray et al., 2006). PCNM constructs spatial variables representing the structure of all relevant scales. PCNM can model structures at scales ranging from broadest (the entire sampling extent) to the finest (as small as the sampling interval) (Borcard & Legendre, 2002; Borcard et al., 2004). Several advantages characterize this method over the polynomial RDA approach. PCNM generates linearly independent spatial variables at multiple scales, and the explained variance can be estimated for each spatial scale

(Borcard & Legendre, 2002; Borcard et al., 2011). The PCNM variables (PCNMs) are obtained by principal coordinate analysis (PCoA) of a truncated pair-wise geographical Euclidian distance matrix among the sampling points. PCNMs are linearly independent and of decreasing periods, and they can be grouped into sub-models corresponding to different scales. Selecting the number of sub-models to use and the scale associated with each one (broad, and fine) is a subjective process, based on the objectives of the analysis and the similarity between the significant PCNM periods (Borcard et al., 2004; Lacey et al., 2007; Ali et al., 2010). The obtained sub-models can be used as explanatory variables in RDA. PCNM analysis fits the grouped PCNM variables to the response variables. Given the orthogonal nature (linearly independent) of the PCNM variables, the variance explained by each PCNM sub-model is unique and additive (Jay Lacey et al., 2007).

The total explained variance can therefore be partitioned among the different PCNM sub-models, or spatial scales. In this study PCNM-RDA was used to characterize at what spatial scales the forest floor pH, NO_3, and NH_4 are structured and to assess how much variance is explained by each category of the spatial scale (broad and fine scales) for the bigleaf maple and western hemlock plots. PCNM analyses were carried out separately on the pH dataset and NO_3, and NH_4 dataset of bigleaf maple and western hemlock, 140-yr old plots, as PCNM was introduced to study variation over space without replication (Legendre & Borcard, 2005). PCNM analysis was carried out using R software. Following Borcard et al. (2011), a threshold truncation distance of 2.00001 m was automatically selected and 69 PCNM variables were generated. Out of the 69 PCNM variables, only 54 modeled positive spatial autocorrelation. A forward selection with the Blanchet et al. (2008) double stopping criterion was then applied to reduce the 54 retained variables to a smaller number of significant PCNM variables. The significant PCNM variables were then categorized into “broad scale”, and “fine scale” PCNMs depending on the size of the patches in the plots (Ali et al., 2010), where the broad spatial category had 8 x 8 m^2<patch area, while the fine spatial category had patch area ≤ 8 x 8 m^2 (examples of broad scale and fine scale PCNMS are presented in Fig. 4.2).

The variance of forest floor variables was partitioned into environment (the same set of environmental variables that was used in the polynomial RDA variance

partitioning), trend, broad scale PCNM sub-model, and fine scale PCNM sub-model. The fitted site scores of the two canonical axes explaining the spatial patterns of each broad and fine scale sub-models were plotted on a map of the sites. These two plots represent the spatially structured variation of the undetrended forest floor pH, NO_3, and NH_4. To examine if this variation is related to any of the environmental variables, the fitted site scores of these two canonical axes were regressed on the environmental data (Borcard et al., 2004; Borcard et al., 2011).

Results

Forest Floor pH

Forest floor pH was interpolated with Kriging and the range in its value was presented in 5 discrete classes (Fig. 4.1). Bigleaf maple plots showed higher concentric values toward plot centres and an overall gradient having low values at the north-east edge of the plot (upslope) and high values at the central-south edge (downslope). Western hemlock plot 1 showed lower values toward plot centres, and a gradient of low values north edge (upslope) and high values towards the south edge of the plot (downslope).

For plot 1 bigleaf maple, significant clusters of high values surrounded by high values for forest floor pH were detected near the stem, and at the central-south edge of the plot, and significant clusters of low values surrounded by low values were detected at the north-east edge of the plot (Fig. 4.4). The distance that a cluster of high values surrounded by high values extended from the stem was about 3 m. Plot 2 bigleaf maple showed a cluster of high values near the stem and a cluster of low values near the north-east side of the plot. Plot 1 western hemlock, showed low values surrounded by low values at the stem and high values surrounded by high values at the north side of the plot. Plot 2 western hemlock did not portrait any significant clusters.

Polynomial RDA variance partitioning indicated that almost 65% of the total variance was explained for each bigleaf maple plot. Spatial variables exerted the strongest influence on the variability of forest floor pH explaining about 41% and 37% for plot 1 and 2 respectively. Compared to bigleaf maple, western hemlock plots showed an inconsistent

and smaller total explained variation of about 65% and 39% for plot 1 and 2 respectively with spatial variables explaining about 25 % and 18 % respectively (Figs.4.7 and 4.8).

PCNM RDA applied on the forest floor pH dataset of bigleaf maple indicated that the spatial structure is varying at different scales. It was significant at the broad scale (PCNMs 1, 2, and 3) and fine scale (PCNMs 4, 9, 11, 12, 13, 22, 25, 26, and 34). The trend component of the variance partitioning represented by the x and y coordinates revealed no significant ($p < 0.05$) linear spatial gradients and did not contribute to the explained variance. In addition, variance partitioning indicated that almost 65% of the total variance was explained for each bigleaf maple plot. Fine scale sub-model exerted the strongest influence on the variability of forest floor pH explaining about 34% followed by broad sub-model explaining about 13% of the explained variance. As compared to bigleaf maple, western hemlock showed a smaller explained variance of 55% with fine scale sub-model explaining 34% followed by the broad sub-model explaining 7% (Fig. 4.9).

For the multivariate analysis of forest floor pH, the ‘‘fitted site scores’’ of each first canonical axis of the broad and fine sub-models were plotted (Appendix E). These maps provide a spatial decomposition of the explained variance for each axis and allow for the perception of spatial patterns within the data. Regressing the RDA first canonical axis on the environmental data showed that for bigleaf maple, the broad sub-model was significantly affected by the main topographic gradient across the plot and to a lesser extent by NO_3 (Table 4.2), while the fine scale sub-model features correspond to canopy cover, canopy density, and moisture content. For western hemlock, the broad sub-model was significantly affected by topography, canopy cover, and canopy density while the fine sub-model was affected by moisture content, and canopy cover.

Forest Floor NO_3 and NH_4

Bigleaf maple plots showed random distribution associated with NO_3. Plot 1 bigleaf maple showed a concentric pattern of high NH_4 values towards plot centre. A similar pattern was apparent in plot 2; however, it was dominated by an overall global gradient. Western hemlock plots did not show spatially structured NO_3 and NH_4 patterns (Figs. 4.2 and 4.3).

Significant clusters of high values surrounded by high values for forest floor NO_3 and NH_4 were detected near the stem of the bigleaf maple plots (Figs. 4.5 and 4.6). The average distance that a cluster of high values surrounded by high values extended from the stem, was about 1.7 m and ranged from 1.2 to 5 m for NO_3 and NH_4 respectively. Outside these clusters located near the stem and beyond tree canopies, forest floor NH_4 showed an area of low values surrounded by low values towards western hemlock trees located within bigleaf maple plots. Both western hemlock plots did not show any significant area associated with stem location. Plot 1 western hemlock, showed an area of low values surrounded by low values of forest floor NO_3 extending from the central tree to another western hemlock tree within the plot.

Polynomial RDA approach for variance partitioning indicated that almost 33% and 41% of the total variance was explained for bigleaf maple plot 1 and 2 respectively. Environmental variables contributed almost equally as the spatial variables in explaining the detected variance at each plot. Similarly, 43% and 37% of the total variance was explained on western hemlock plot 1 and 2 respectively. Contrary to bigleaf maple, environmental variables exerted the strongest influence on the variability of forest floor NO_3 and NH_4 explaining about 29% and 23% on plot 1 and 2 respectively (Figs. 4.7 and 4.8).

PCNM RDA applied on the forest floor NO_3 and NH_4 dataset of bigleaf maple indicated that the spatial structure varies at different scale. It was significant at the broad scale (PCNM 2, and, 3) and fine scale (PCNMs 5, 7, 8, 11, 12, 22, 26, 29, 37, and 45). The trend component of the variance partitioning represented by the x and y coordinates revealed a linear spatial gradient but it had a minimal contribution to the explained variance (0.5%). In addition, variance partitioning indicated that almost 55% of the total variance was explained for forest floor NO_3 and NH_4 in the bigleaf maple plot. The fine scale model exerted the strongest influence on the variability of forest floor pH explaining about 34% of both datasets followed by broad scale PCNM variables explaining about 5% of the explained variance. As for the western hemlock plot, none of the broad and the fine sub-models were significant and hence variance partitioning analysis could not be carried out.

Multivariate analysis of forest floor NO_3 and NH_4 of bigleaf maple was carried out in a similar way to the multivariate analysis of the pH dataset. Regressing the RDA first

canonical axis on the environmental data showed that the broad sub-model relationship was significantly affected by pH, and to a lesser extent by the topographic gradient and moisture content across the plot, while the fine scale sub-model features correspond to pH, and canopy cover (Table 4.2).

Discussion

This study characterized the spatial patterns of forest floor properties associated with bigleaf maple and western hemlock at multiple scales. The results indicate that the patterns surrounding individual trees are partially due to species-specific effects. Canopy cover (deciduous vs. conifer) and canopy density seem to affect the fine scale spatial patterns under both bigleaf maple and western hemlock (Table 4.2). It seems that bigleaf maple has a positive spatial impact on site fertility in the conifer forests. We found higher pH, NO_3, and NH_4 associated with the bigleaf maple trunks. The opposite patterns were detected for western hemlock, where low pH, NO_3, and NH_4 concentrations were associated with western hemlock trunks (some of these patterns were detected in the western hemlock plots and some were detected within bigleaf maple plots). This could be due to the relatively rapidly decomposing litter of bigleaf maple that is more basic in nature and of higher nitrogen content than that of conifers (Turk, 2006), and because of the more basic throughfall and stemflow of bigleaf maple compared to conifers (Hamdan & Schmidt, 2012). We expected the forest floor properties to be high near the bigleaf maple trunks and to decrease towards the canopy and the periphery of the plot. Nevertheless, our results indicate that the pattern due to species-specific effects is more restricted to the area directly surrounding the trunk. The influence of bigleaf maple was restricted to the area within 3 m and 2 m from the truck for pH and NO_3 and NH_4 respectively. In addition, the spatial influence was more pronounced for the older bigleaf maple plot 1 as compared to bigleaf maple plot 2.

Kriging

The species-specific effects were mainly detected, for forest floor pH and to a lesser extent forest floor NH_4, within the vicinity of the trunk and beyond the trunk the influence becomes possibly masked by the influence of other processes. Those processes can be acting at a broad scale such as topography (Kriged maps detected an overall

gradient in the direction that matches plot aspect), or fine scale such as the presence of other trees within the plot. This is in agreement with previous reports of local influences of bigleaf maple and conifers on forest floor pH (Zinke, 1962; Crampton, 1984; Escudero, 1991; Chandler, 2006; Chandler et al, 2008).

Local indicators of Spatial Association

LISA showed that the distances of influence from the bigleaf maple and western hemlock stems extended to an average of about 3 m for forest floor pH for plot 1. The mean canopy extent from the trunk of bigleaf maple and western hemlock in plot 1 was 13 m and 5 m respectively. This suggests that stemflow most likely had a significant influence on the forest floor pH. Furthermore, areas near bigleaf maple trunks are more strongly influenced by bigleaf maple, whereas areas beneath the bigleaf maple canopy but further away from the trunk are influenced by bigleaf maple as well as the surrounding conifers. Both plot 2 bigleaf maple and western hemlock did not show any significant cluster associated with their stem, except NO_3 associated with bigleaf maple that showed a significant cluster extending to about 3 m from the stem. We found that the younger plot 2 bigleaf maple and western hemlock trees (75-yr) in our study have much smaller diameters compared with the older plot-1 bigleaf maple and western hemlock (140 yr) and this may partially account for the lack of influence on forest floor properties.

The LISA results partially support the concept of tree influence potential that assumes that the influence of a tree is symmetrical in space and proportional to the diameter at breast height (DBH). For the examined species, it cannot be assumed that the influence is symmetrical in space; however, the influence is proportional to the DBH (as the 140-yr old tree has a larger DBH than the 75-yr old one, Table 4.1). This is in agreement with previous studies that assessed spatial patterns related to species influence (Saetre, 1999; Saetre, 2000; Gallardo, 2003; Bengtson et al., 2006). Contrary to this, Chandler et al. (2008) reported similar ranges of spatial clustering surrounding the stem of both 140-yr and 75-yr bigleaf maple trees. They suggested that for bigleaf maple one cannot assume that the influence of the tree is symmetrical in space or that it is proportional to the DBH. Our results cannot be compared to Chandler et al. (2008) because they used a different sampling design with intensive sampling surrounding the stem area which could create the intense clustering surrounding tree stems. Nevertheless, our study does not have enough replicates to make strong conclusions about the influence

of DBH and tree size on the extent of the spatial patterns and this should be tested in detailed future studies.

The lack of significant clusters for NO_3 and NH_4 in most of the examined plots, may result from a sampling step that is too large to adequately capture the spatial structure of these properties, i.e, the spatial signal of these variables is simply too weak to produce significant clusters with the given number of samples. Bruckner et al. (1999) suggested that forest floor spatial heterogeneity is highest if the period from leaf fall to complete humification is 2–3 years and spatial scales of soil would become finer with decelerated and accelerated decomposition. We did not measure decomposition rates at our study plots, however, Turk et al. (2008) reported about 40-50 % undecomposed bigleaf maple and conifer litter after 18 months of litterfall. This suggests that the humification in this ecosystem would take beyond 2–3 years, and fine-scale patterning would therefore be high.

Polynomial RDA Variance Partitioning

The spatial component of the variance partitioning analysis would reflect the importance of the presence of bigleaf maple on forest floor properties. Hence, it was expected that the spatial component would have a strong influence at bigleaf maple plots. Our results showed that spatial variables exerted the strongest influence on the variability of forest floor properties. There is a clear relationship between results of the variance partitioning and LISA. The variation in forest floor pH that shows significant clusters is driven primarily by spatial processes (Figs. 4.7, 4.8, and 4.9). Properties that exhibited little or no spatial clusters (NO_3 and NH_4) were less explained by the spatial component, indicating that the distribution of these variables is not strongly affected by space. The unexplained variability was likely due to the influence of unmeasured variables that affect the spatial pattern of pH, NO_3 and NH_4 (Borcard et al., 1992) and indicates that ecological processes may be occurring at scales smaller than the measurement scale (i.e., the step between sampled sites was inadequate for capturing dominant processes) (Borcard et al., 1992; Pelletier et al., 1999; Asselin et al., 2001). Alternatively, processes that created the observed variability may no longer be active, but the soil retains the consequences of these influences (Hammer, 1998). In addition, some key structuring elements could have been overlooked, such as the type and distribution of soil organisms, which will affect the

variability of forest floor properties through rates of litter decomposition and soil turnover (Fisher & Binkley, 2000).

PCNM RDA Variance Partitioning

The explicit quantification of characteristic scales is particularly interesting in the context of species-specific impacts on soil properties and tree influence potential. PCNM RDA indicated that the spatial structure of forest floor pH, NO_3 and NH_4 varies at different scales. The spatial structure was significant at both the broad scale and fine scale. The trend component of the variance partitioning represented by the x and y coordinates either revealed no significant ($p < 0.05$) linear spatial gradients or had a minimal contribution to the explained variance. Trend represents the variation occurring at a scale larger than the broad scale (Borcard et al., 2004; Ali at al., 2010). This indicates that the extent of our sampling design is large enough to capture the spatial structure of the examined forest floor variables. The fine scale PCNMs explained a large proportion of the spatial variation in the examined forest floor properties. This indicates that the ecologically-relevant processes producing coherent forest floor pH, NO_3 and NH_4 patterns occur at a fine scale (patches smaller than 8 x 8 m^2).

The influence of topography on the pattern detected by the broad scale sub-model is in agreement with other studies that used PCNM to assess the influence of environmental variables on the spatial patterns at broad scale (Borcard et al., 2004; Ali et al., 2010). It was surprising to find that moisture content affected the spatial pattern at a fine scale, given that moisture content is greatly impacted by topography (Ali et al., 2010). Hence, it seems that at the plot scale that we examined, moisture content is more influenced by tree related processes such as stemflow and water uptake by roots rather than topography. Canopy cover and density impacted the fine scale patterns as well. This could be related to litterfall type and amount. Chandler et al. (2008) reported that significantly higher amounts of bigleaf maple litter were deposited directly beneath bigleaf maple canopy than outside the canopy. Bigleaf maple litter has different chemical properties compared to conifers (Turk, 2006) and hence could be a major driver of the observed fine scale patterns. As for western hemlock, canopy cover and density possibly acted at a broader scale because the central conifer tree was surrounded by conifers. This enabled the existence of a homogenous broad scale impact of the coniferous litterfall and decomposition on forest floor pH.

Forest floor pH and moisture content had significant impact on the NO_3 and NH_4 broad scale patterns, and canopy cover had an effect on the fine sub-model. pH and moisture content are two factors that control bacterial abundance and activity (Fisher & Binkley, 2000). Soil pH is known to have a considerable effect on the activities of microbial communities and the biogeochemical processes which they mediate. There is also strong evidence that soil pH is an important determinant of bacterial diversity and community structure on a global scale (Fierer & Jackson, 2006), and pH was reported as the most important predictor of the distribution of the microbial communities in many cases (Nicol et al., 2008). Our results show that pH is of importance to microbial communities (as inferred from NO_3 and NH_4 patterns) at all scales (at least all the ones examined in our study).

Conclusion

The application of various analytical techniques to examine species-specific effects at multiple scales revealed that the influence of individual trees is highly localized. The application of the PCNM method enabled us to extract the main influential factors impacting forest floor pH and possibly other soil properties at the plot scale. For forest floor pH, PCNM revealed that topography is mainly acting broadly and canopy cover, canopy density and moisture content are mainly acting at a finer scale. For forest floor NO_3 and NH_4, PCNM indicated that pH is important at all of the examined scales. LISA statistics were effective in locating statistically significant fine patterns of positive and negative spatial association, hence, detecting species-specific impacts on soil properties. For forest floor NO_3, LISA was able to detect significant clusters of high values at the centre of one of the bigleaf maple plots. Though this cluster was not captured by Kriging, however, Kriging was able to visualize the broad and fine scale spatial patterns within the forest floor pH associated with bigleaf maple and to provide helpful insights into the processes affecting the patterns such as topography or canopy cover.

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Table 4.1. Bigleaf maple and western hemlock plot characteristics

	Bigleaf maple plot 1	Bigleaf maple plot 2	Western hemlock plot 1	Western hemlock plot 2
Elevation (m)	150	180	172	180
Slope %	25	26	20	18
Aspect (Deg)	265	160	230	180
DBH (mm)	1018	588	604	668
Basal area (m^2 ha^-):bigleaf maple	20	6	0	0
Basal area (m^2 ha^-):western hemlock	3	8	7	55
Basal area (m^2 ha^-):Douglas-fir	14	0	19	0
Basal area (m^2 ha^-):western redcedar	31	93	37	35
Central tree: Mean canopy extent (m)	13	10	5	8

Table 4.2. Environmental variables regressed on significant canonical axes of the ''fitted site scores'' plotted on the sampling location coordinates: broad and fine PCNM sub-models of bigleaf maple and western hemlock pH and NO_3 and NH_4

Variable	Bigleaf maple				Western hemlock	
	pH		NO_3 and NH_4		pH	
	Broad scale axis	Fine scale axis	Broad scale axis	Fine scale axis	Broad scale axis	Fine scale axis
pH	NA	NA	+++	+++	NA	NA
NO_3	+	---	NA	NA	---	---
NH_4	---	---	NA	NA	---	---
Moisture content	---	++	+	---	---	+
Topography	+++	---	++	---	+	---
Canopy cover	---	++	---	+	+	+
Canopy density	---	++	---	---	+	---
Tree presence	---	---	---	---	---	---
Log presence	---	---	---	---	---	---
Rock presence	---	---	---	---	---	---
Stump presence	---	---	---	---	---	---
Fern presence	---	---	---	---	---	---

+++: significant at P<0.001; ++ significant at P<0.05, +: significant at P< 0.1, ---: not significant, NA: not applicable.

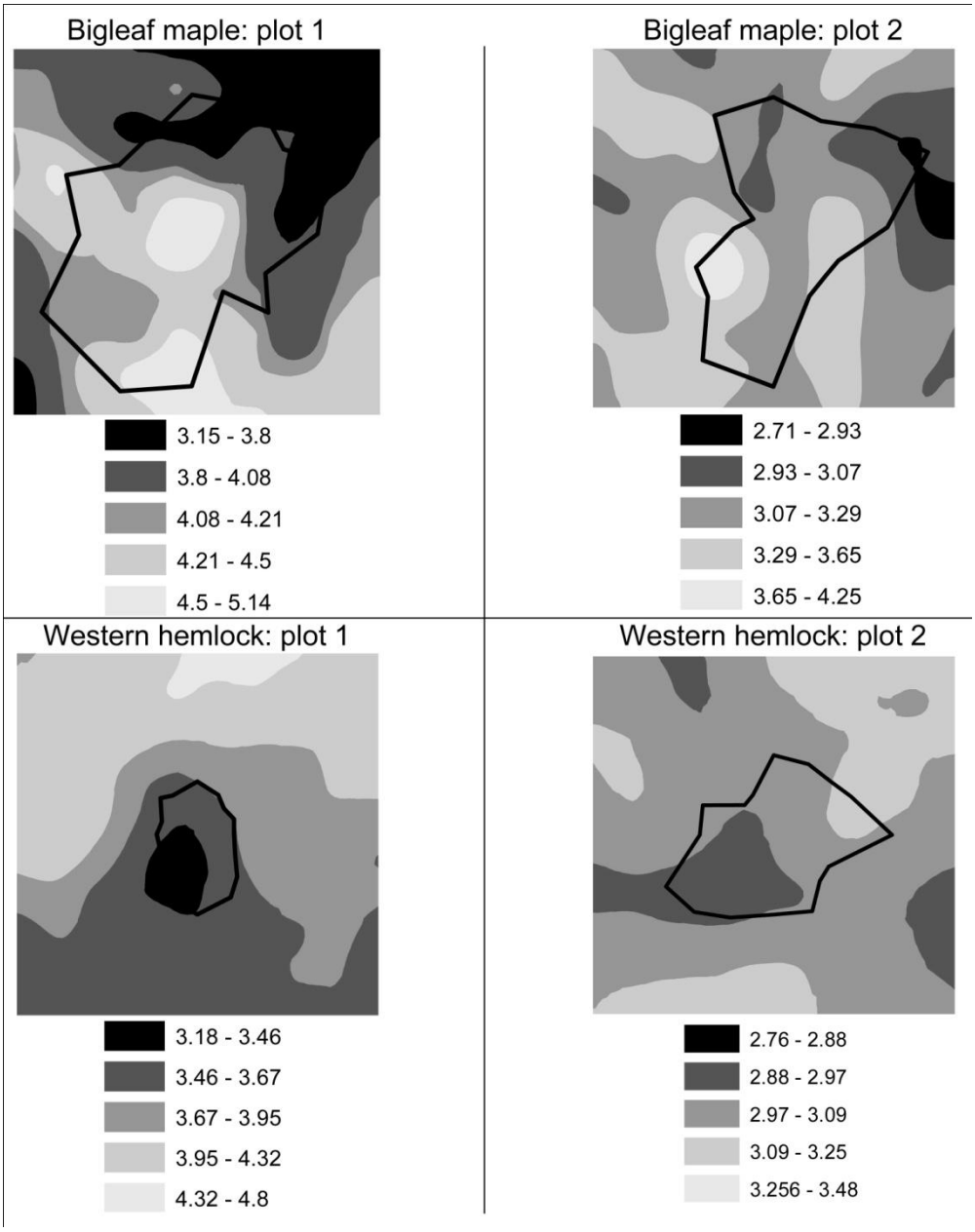


Figure 4.1. ***Forest floor pH interpolated with ordinary Kriging and classified into five classes. Each interpolation map is overlaid with a polyline delineating the canopy extent of the central dominant bigleaf maple or western hemlock tree.***

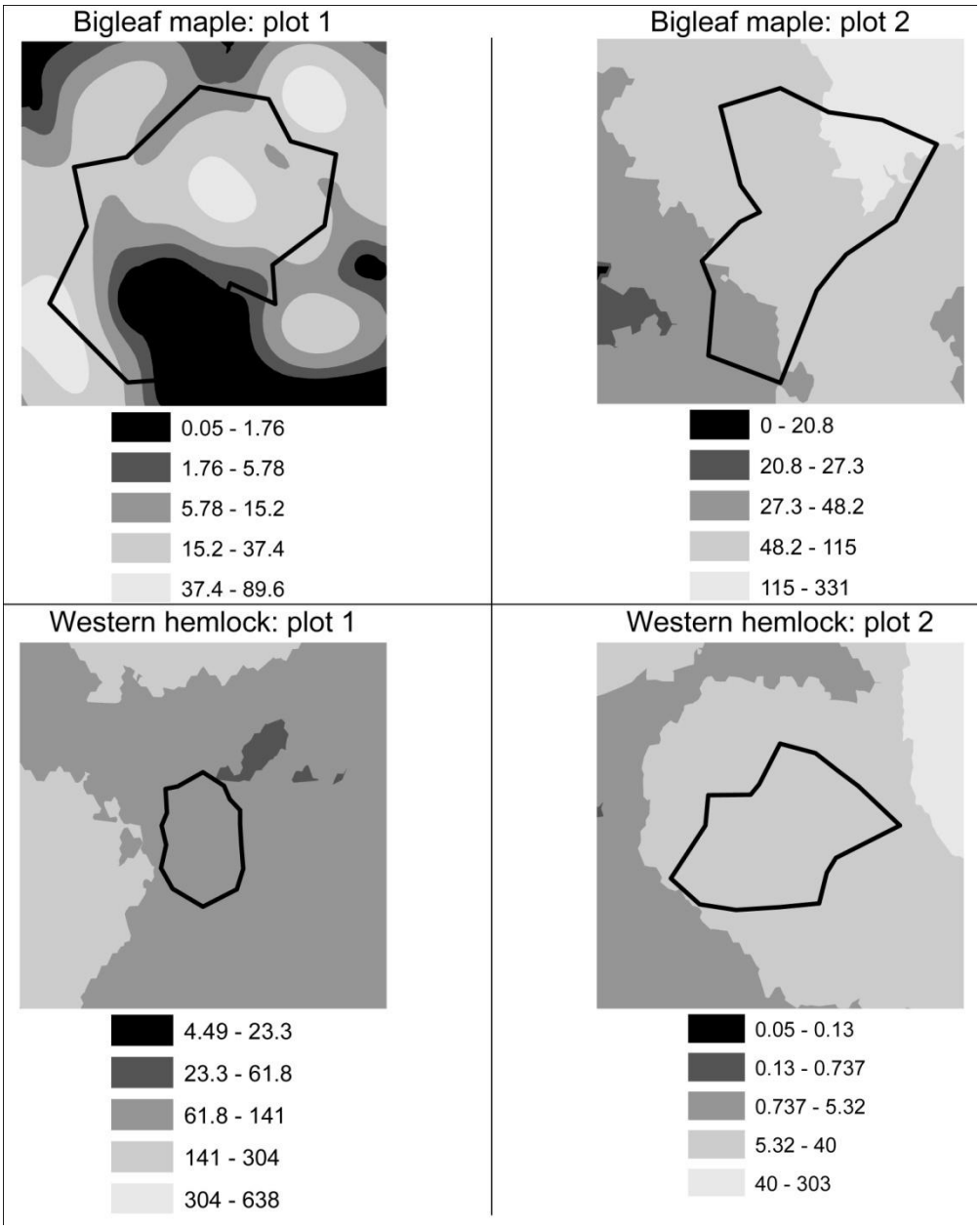


Figure 4.2. ***Forest floor NO_3 with ordinary Kriging classified into five classes. Each interpolation map is overlaid with a polyline delineating the canopy extent of the central dominant bigleaf maple or western hemlock tree.***

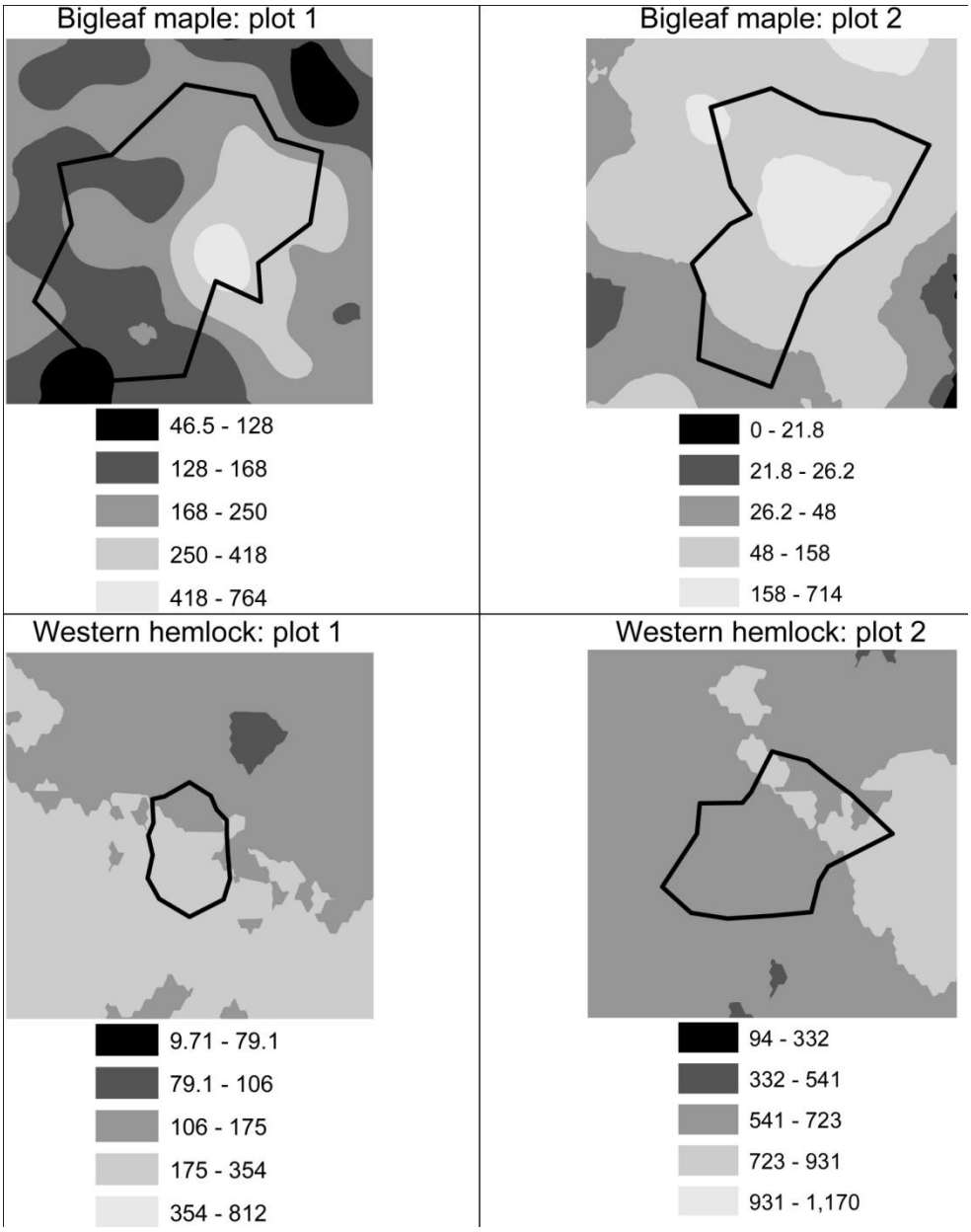


Figure 4.3. ***Forest floor NH_4 with ordinary Kriging classified into five classes. Each interpolation map is overlaid with a polyline delineating the canopy extent of the central dominant bigleaf maple or western hemlock tree.***

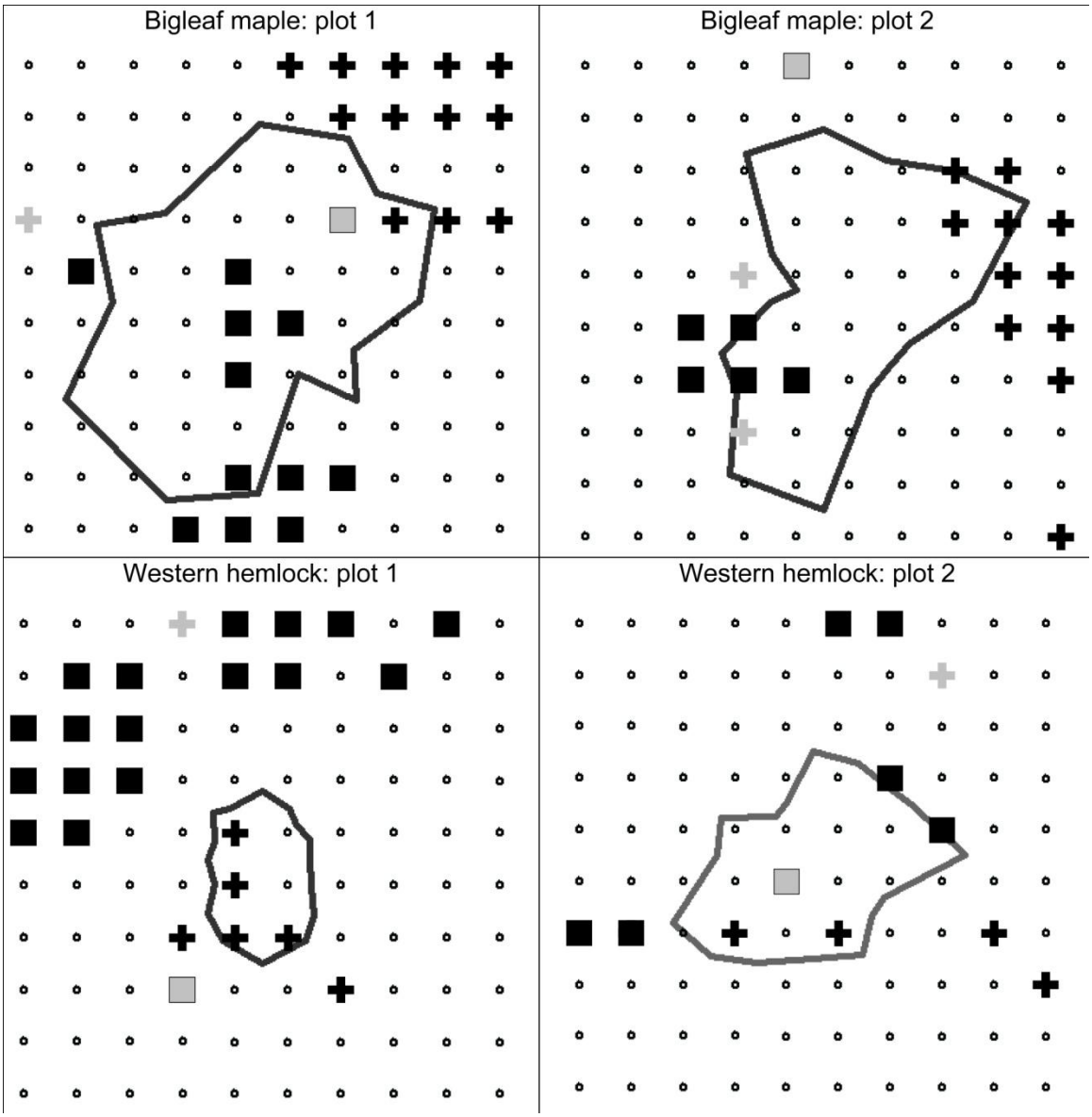


Figure 4.4. ***Forest floor pH LISA maps overlaid on the 20 m x 20 m sample grid. A polygon indicates the central tree canopy extent. Black squares indicate clusters of high values of soil properties surrounded by high values; white squares indicate high values surrounded by low values. Black crosses indicate low values surrounded by low values; white crosses indicate low values surrounded by high values (P< 0.05).***

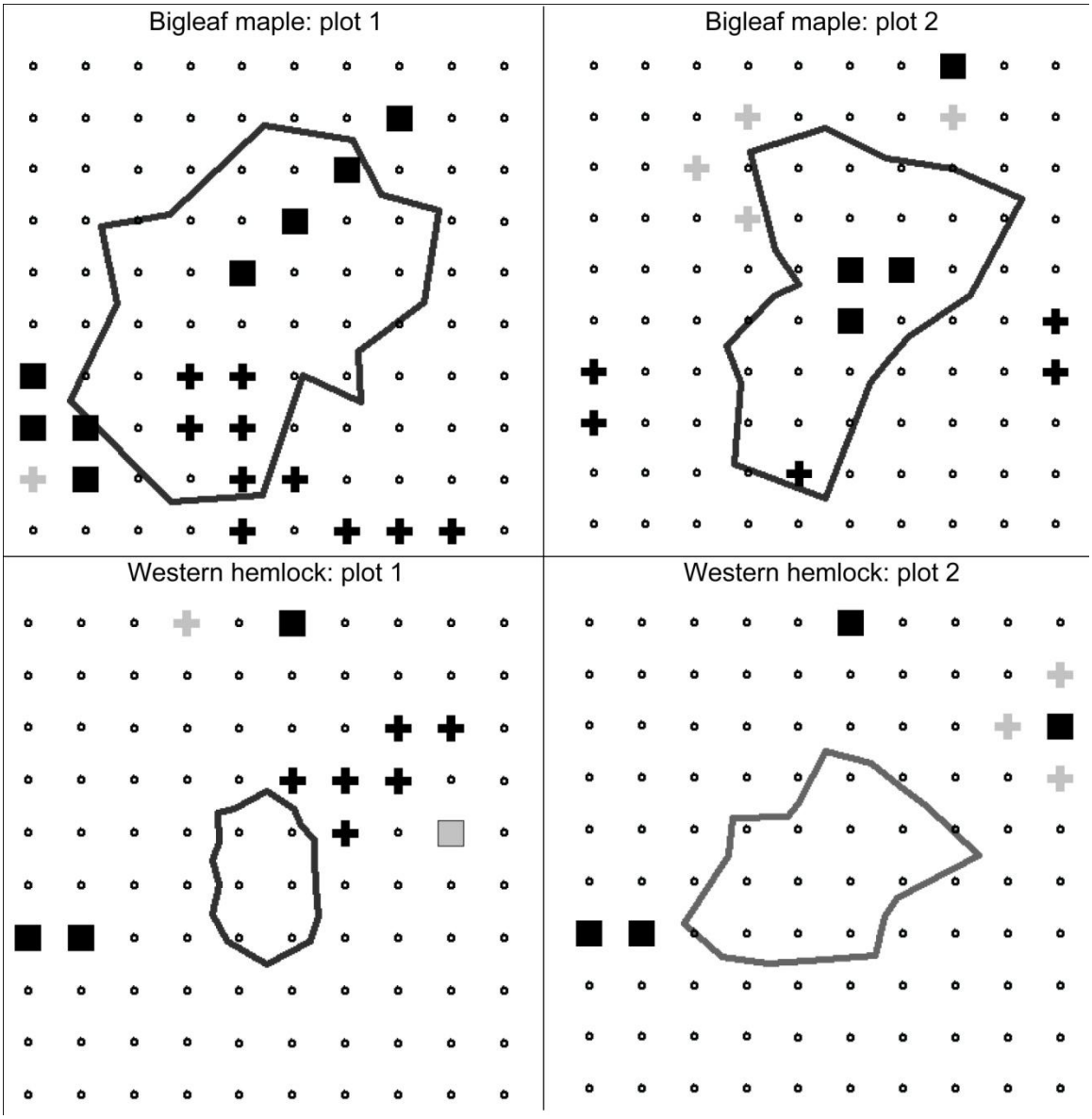


Figure 4.5. ***Forest floor NO_3 LISA maps overlaid on the 20 m x 20 m sample grid. A polygon indicates the central tree canopy extent. Black squares indicate clusters of high values of soil properties surrounded by high values; white squares indicate high values surrounded by low values. Black crosses indicate low values surrounded by low values; white crosses indicate low values surrounded by high values ($P< 0.05$).***

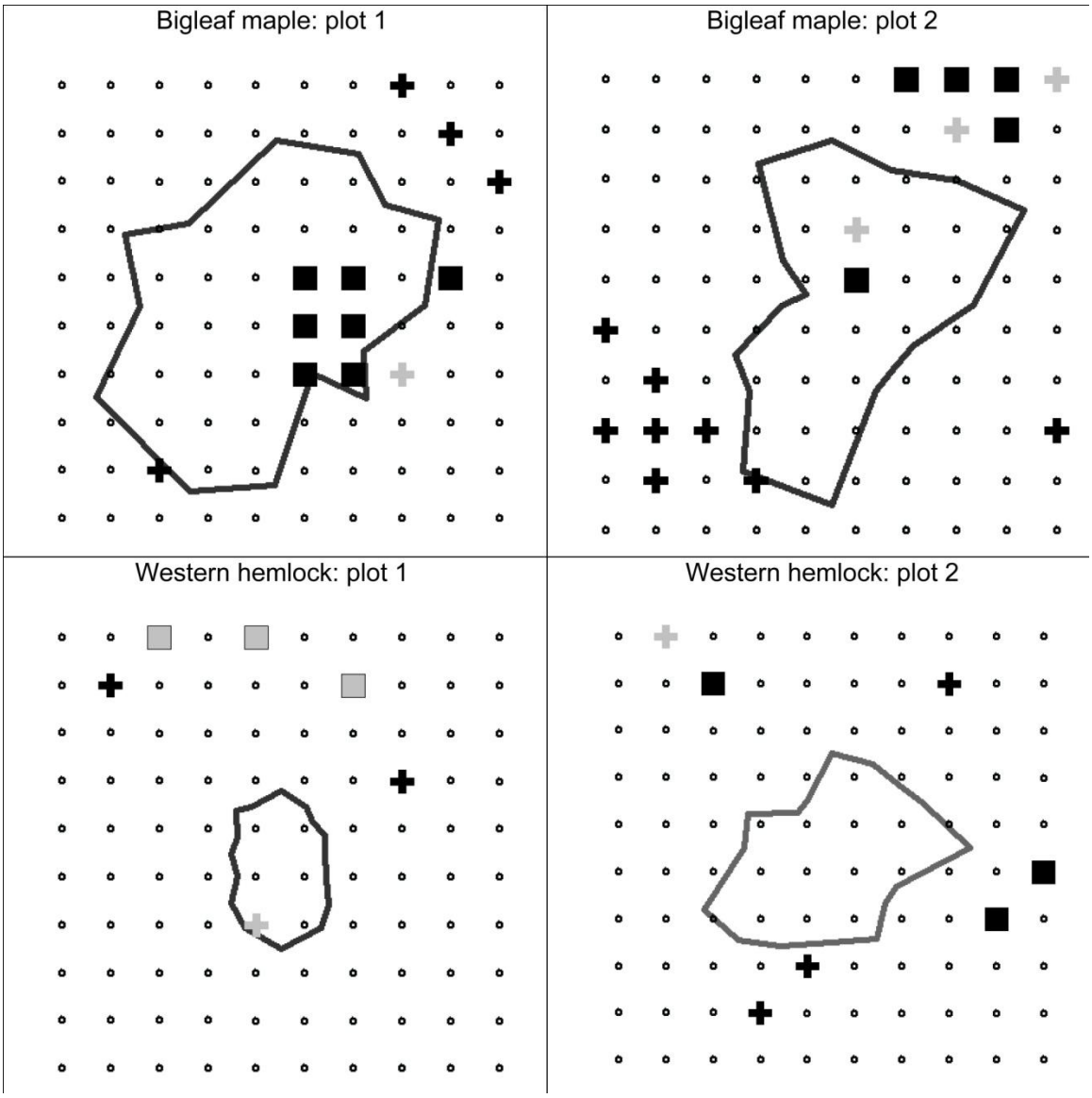


Figure 4.6. ***Forest floor NH_4 LISA maps overlaid on the 20 m x 20 m sample grid. A polygon indicates the central tree canopy extent. Black squares indicate clusters of high values of soil properties surrounded by high values; white squares indicate high values surrounded by low values. Black crosses indicate low values surrounded by low values; white crosses indicate low values surrounded by high values (P< 0.05).***

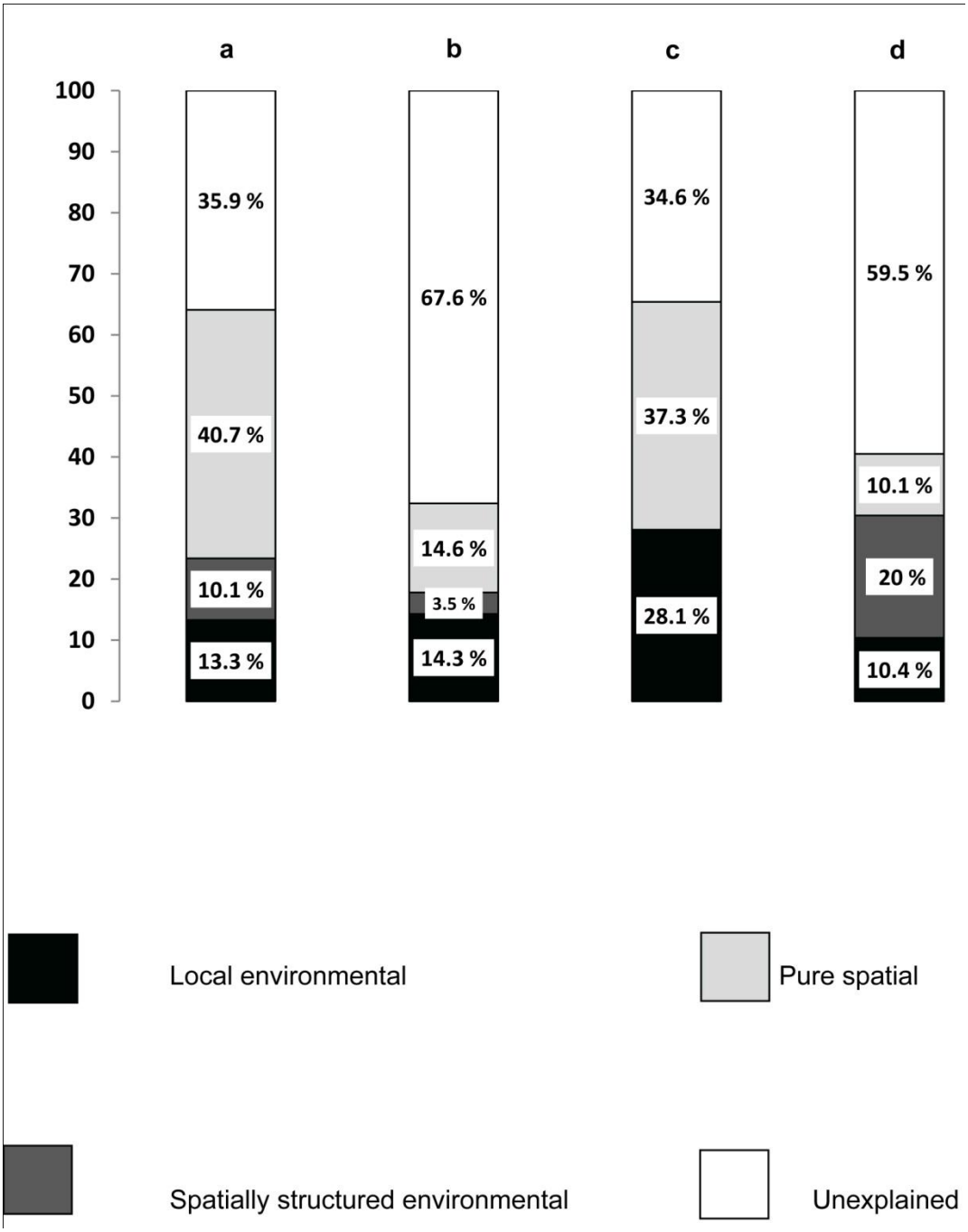


Figure 4.7. ***Variance partitioning analysis of bigleaf maple forest floor using polynomial RDA approach. a: plot 1-pH, b: plot 1-NO_3& NH_4, c: plot 2-pH, d: plot 2-NO_3 & NH_4***

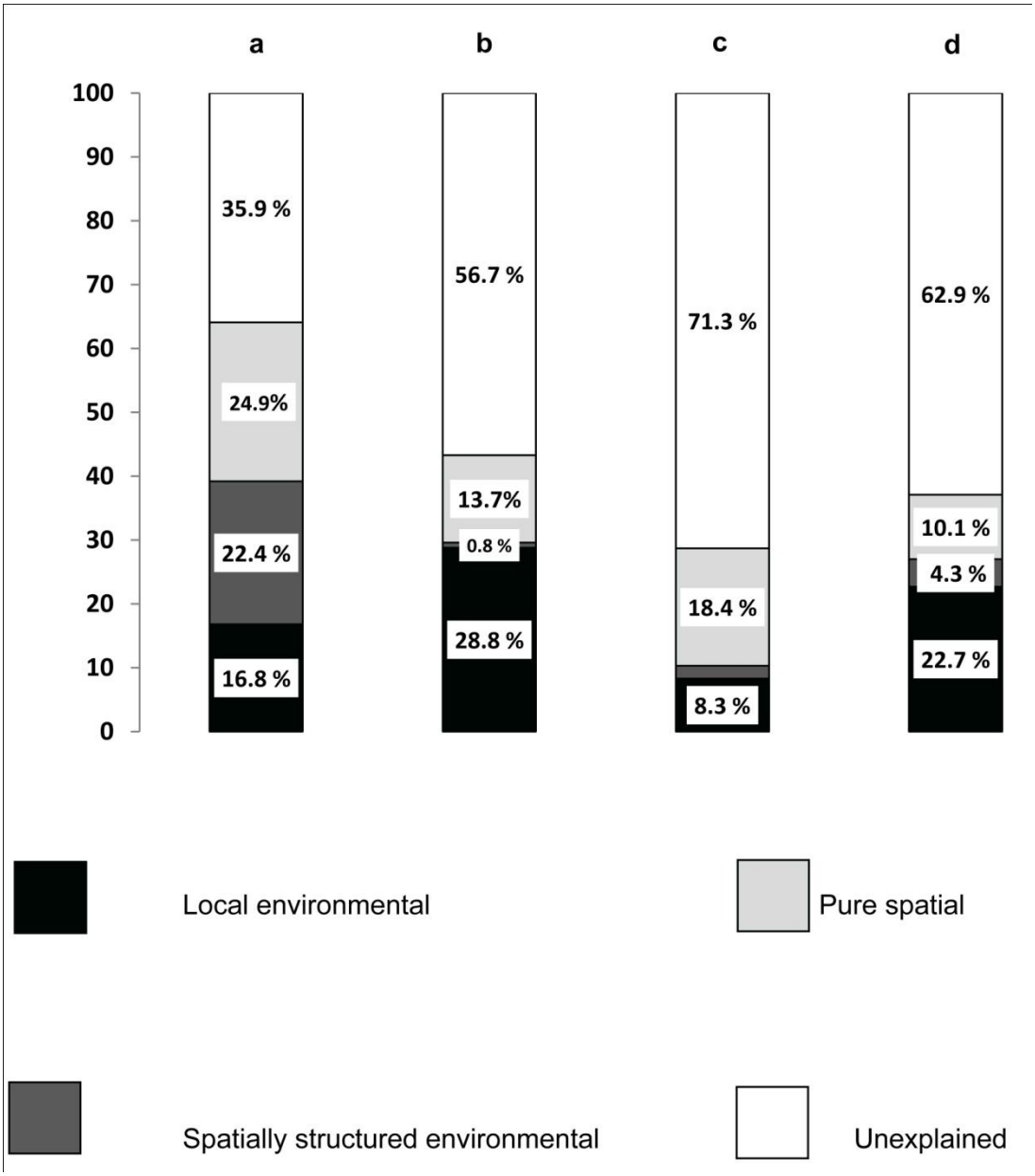
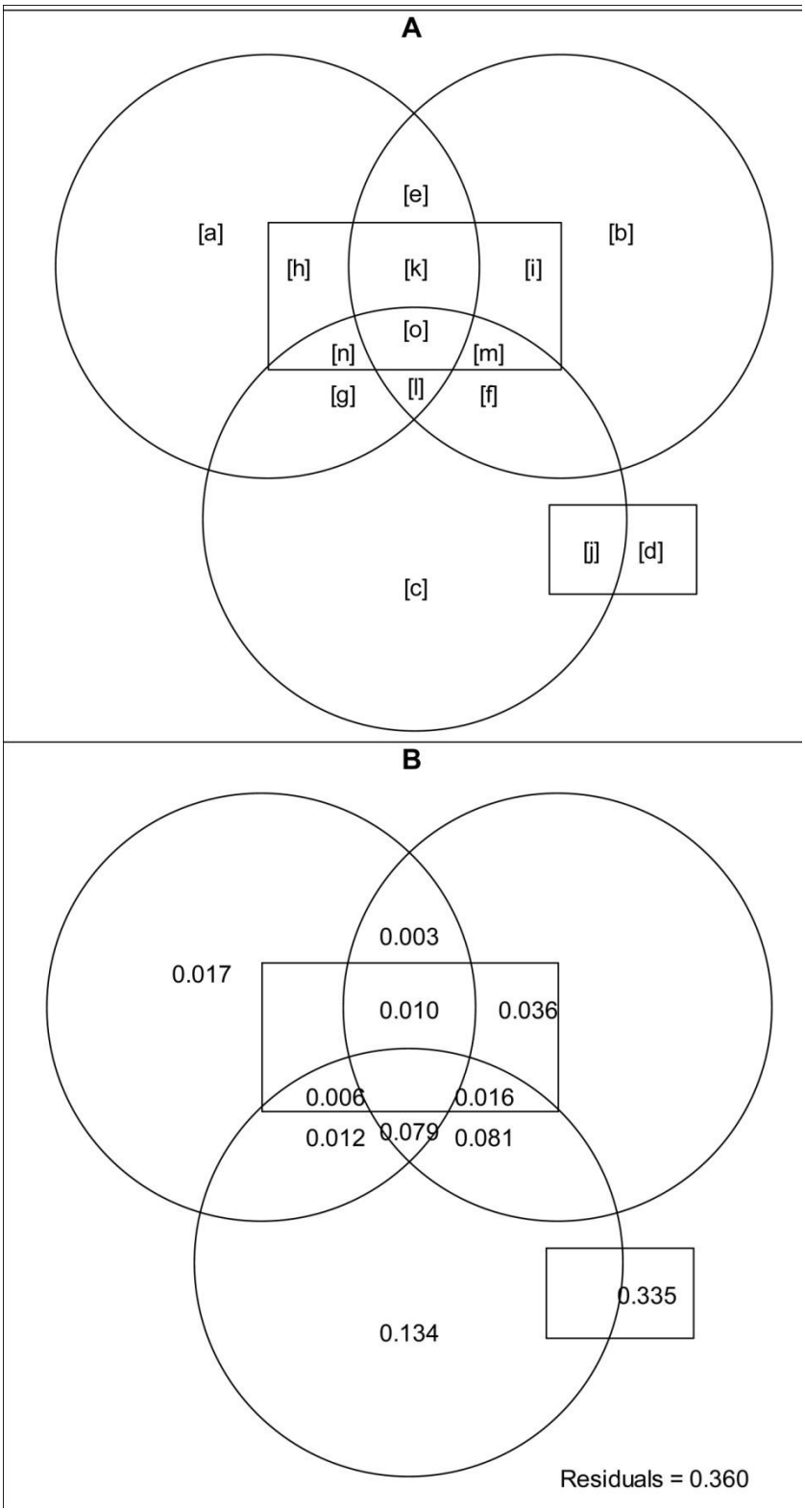
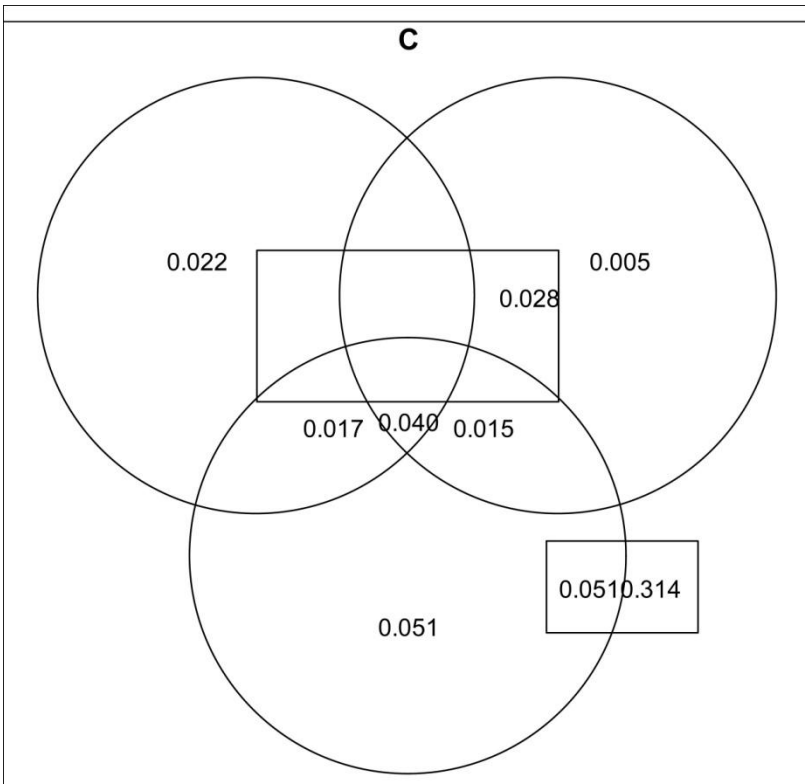


Figure 4.8. ***Variance partitioning analysis of western hemlock forest floor using polynomial RDA approach. a: plot 1-pH, b: plot 1-NO_3& NH_4, c: plot 2-pH, d: plot 2-NO_3 & NH_4***


A
[a]
[b]
[c]
[d]
[e]
[f]
[g]
[h]
[i]
[j]
[k]
[l]
[m]
[n]
[o]
B
0.003
0.017
0.010
0.036
0.006
0.016
0.012
0.079
0.081
0.335
0.134
Residuals = 0.360


C
0.022
0.005
0.028
0.017
0.040
0.015
0.0510.314
0.051

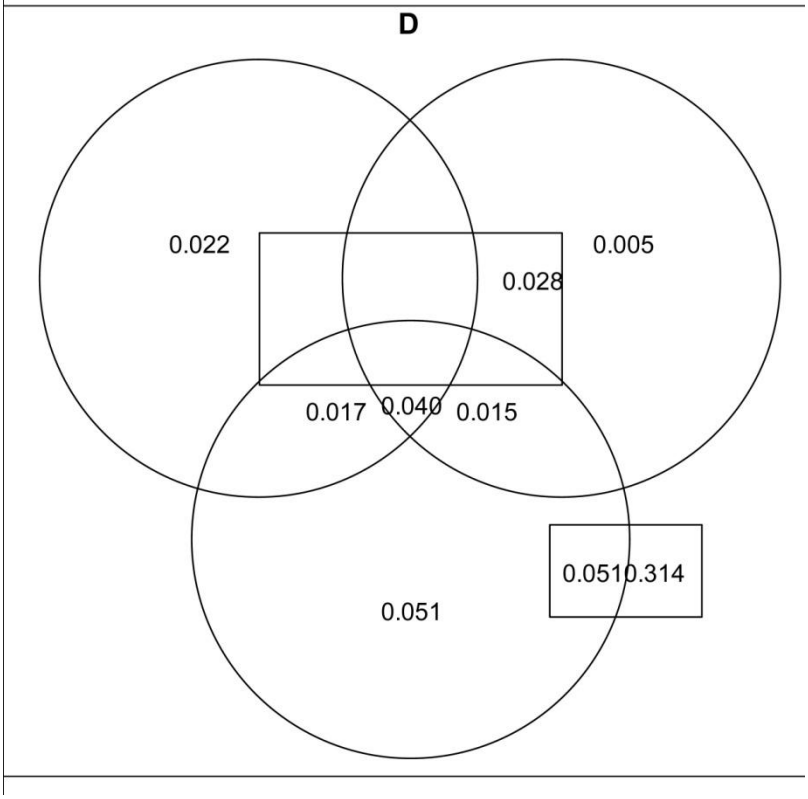

D
0.022
0.005
0.028
0.017
0.040
0.015
0.0510.314
0.051

Figure 4.9. ***Variance partitioning analysis of bigleaf maple and western hemlock forest floor using PCNM approach. A: a generic representation of the various fraction of explained variance (a: pure environmental; b: trend; c: broad sub-model; d: fine sub-model, e: variance explained by both pure environmental and trend, f: variance explained by both trend and broad sub-model, ..., o: variance explained by pure environmental, trend, broad sub-model, and fine sub-model); B: bigleaf maple pH (plot-1), C: bigleaf maple NO_3 and NH_4 (plot-1); D: western hemlock pH (plot-1).***

Chapter 5.[1]

Sampling Design to Detect Spatial Structure of Forest Floor Chemical Properties Associated with Individual Deciduous Trees Growing Among Conifers

Abstract

The aim of this study was to investigate the spatial variability in forest floor pH and NH_4 associated with bigleaf maple in a mixed stand in coastal British Columbia using parametric statistics and geostatistics and to optimize a sampling design for mapping their spatial distributions. A 20 x 20 m plot, centered on a dominant individual 140 year-old bigleaf maple stem, was systematically sampled on two occasions with a sampling interval of 2 m and 1 m respectively, and tested for forest floor pH, and ammonium (NH_4). Coefficient of variation and nugget to sill ratio were used to characterize spatial variability of pH and NH_4 and Least Significant Difference (LSD) test and goodness-of-prediction (G) test were used to quantify the accuracy of Kriged and coKriged maps for sampling design optimization. Forest floor NH_4 had a higher coefficient of variation and nugget to sill ratio compared to forest floor pH, and hence a larger sample size is needed to estimate the population mean of NH_4. Random and stratified random designs showed a higher accuracy in mapping the spatial distribution of forest floor pH and NH_4 compared to a systematic cluster configuration. A sample size of 50 seems to be adequate for mapping the spatial structure of both variables, and

[1] A version of this chapter will be submitted to a peer reviewed journal for publication under the co-authorship of Margaret Schmidt.

coKriging improved the prediction of NH_4 concentration by having pH as its secondary variate. Time stability assessment of forest floor pH indicated that locations directly adjacent to the bigleaf maple trunk consistently showed a higher pH compared to the plot mean. The study provides an approach for reducing sample size and cost associated with assessing the long-term spatial patterns of soil variables, such as mineralizeable N, that are expensive to measure.

Introduction

Species-specific effects of trees can cause substantial differences in forest floor and mineral soil properties (Turner, Sollins, Leuking & Rudd, 1993; Chapter 3; Chapter 4). Considering that deciduous species are abundant in the Pacific Northwest forest ecosystem (Peterson et al., 1999; USDAFS, 2004), an understanding of their effects on the quantity and spatial distribution of soil nutrients is important for maintaining forest productivity in the long term (Turner et al., 1993).

Nitrogen is a very important element for the growth of trees in the Pacific Northwest because nitrogen can limit the productivity in these forests (Turner et al., 1993), and because available nitrogen (in the forms of NO_3 and NH_4) is only about 1.5-3.5% of the total nitrogen (Fisher & Binkley, 2000). Soil pH is also important because it controls the availability of elements both required and toxic to plants and organisms; it plays a role in the weathering of minerals; it is critical to the soil cation exchange complex; and it influences chemical reactions, particularly hydrolysis and redox reactions (Fisher & Binkley, 2000). Although pH, and nitrogen content and availablity are higher under bigleaf maple compared to conifers (Chapter 3), their spatial distribution is quite variable (Chapter 4). The variability in nitrogen availablity is due to the fact that nitrogen mineralization is controlled by microbial processes that are affected by plant litter chemistry, soil moisture potential and soil temperature (Donald & Kurt, 1990). Given that soil properties can be highly patchy in space, and that this variation can occur over very small distances (Chapter 4), a reliable assessment of the variability in soil pH and NH_4 may require a large sample size.

Few field studies have examined species-specific effects on the spatial patterns and/or the time stability of forest floor pH and NH_4 (Turner et al., 2005; Turner et al.,

1993). Conducting a long-term spatial assessment of site productivity could be expensive especially when nitrogen availablity is assessed (Goovaerts & Chiang, 1993). Hence, an optimal sampling design that maximizes sampling efficiency to obtain information with minimized cost is desired (Chen et al., 1995).The importance of spatial sampling strategies as a first step in field experiments has long been recognized. Adequate description of spatial patterns associated with trees such as bigleaf maple is the first step towards understanding its impacts on site productivity. Sampling design plays an important role in detecting the spatial patterns of variables of interest (Fortin & Dale, 2005). Sampling designs have several components, including sample size, sampling configuration, and sampling scale (Fortin & Dale, 2005; Dungan et al., 2002). Reliable estimation of a spatial structure may require 100 or more sampling locations; nevertheless, if a proper sampling design is implemented then sample size could be reduced from 100 to 30 and in exceptional cases, where the spatial structure is very strong, a sample size of 20 may be sufficient to detect the spatial pattern (Fortin & Dale, 2005).

The present study thus investigates the influence of sampling design on spatial patterns of forest floor pH and NH_4 associated with bigleaf maple in a mixed conifer stand. The objectives of this study were (1) to describe the spatial variability in forest floor pH and forest floor NH_4 concentration as expressed by CV and nugget to sill ratio, associated with bigleaf maple in a mixed conifer forest of southwest British Columbia, (2) to determine the sample sizes needed to estimate population means for both variables, assuming no spatial autocorrelation, (3) to optimize a sampling design for mapping the spatial distribution of both variables, and (4) to assess the time stability of forest floor pH associated with bigleaf maple.

Materials and Methods

Study Area

The study area is located within the University of British Columbia's Malcolm Knapp Research Forest, Maple Ridge, British Columbia. The description of the study area is provided in Chapter 2.

Field Sampling

A 140-year-old conifer dominated stand that includes some bigleaf maple trees was located using forest cover maps, local knowledge from MKRF personnel and data obtained from previous studies (Chandler, 2006; Turk, 2006). A bigleaf maple plot was selected based on three criteria described in Chapter 4.

The tree canopy types (bigleaf maple, Douglas-fir, western hemlock, and western redcedar) directly above each sample location were recorded and mapped (Fig. 5.1). The forest floor was sampled in summer 2009 at 2 m intervals along a 20 x 20 m grid. This provided 100 forest floor samples, labelled 1, 2, 3, ..., 100 according to their geographic location surrounding the bigleaf maple trunk (Fig. 5.2). The same plot was revisited in summer 2011 and forest floor was sampled at 1m intervals along a 20 x 20 m grid. This provided 400 forest floor samples. The samples were collected by removing a 10 x 10 cm section of the forest floor down to the mineral soil with a trowel, removing F and H forest floor material and placing it into a labelled sample bag for transport to the Soils Laboratory at Simon Fraser University.

Laboratory Analysis

For each forest floor sample collected in summer 2009 pH, and ammonium (NH_4) were measured. The 400 forest floor samples collected in summer 2011 were tested for pH. The pH testing was conducted at Simon Fraser University and followed standard procedures with a 1:4 soil-to-solution ratio with 0.01 M $CaCl_2$ as the suspension solution (Kalra & Maynard, 1991). The suspension was stirred every 5 minutes for 30 minutes and left to settle for the following 30 minutes. The pH was measured by immersing a glass pH meter into the supernatant solution. The pH value was recorded after the reading on the pH meter stabilized.

The forest floor samples were air-dried and the 100 samples were analyzed for NH_4 concentration colorimetrically using an Alpkem Flow System IV analyzer (Carter, 1993; Bremner, 1965) at the Ministry of Forests and Range, Research Branch Laboratory, Victoria, BC.

Data Analysis

Summer 2009 pH (referred to as pH-100 from now on) and NH_4 data sets (n=100) and summer 2011 pH data set (n = 400; referred to as pH-400 from now on) were first checked for normality using Kolmogrov–Smirnov (KS) test (Sokal & Rohlf, 1981). In addition, descriptive statistics including the mean, standard deviation (SD), coefficient of variation (CV), min., and max. were determined for each of the pH-400, pH-100, and NH_4 data sets. Geostatistical analysis (semi-variance) was then carried out and variogram properties (e.g. nugget/sill) were determined using GS+ software.

Sample Size Estimation for Non-Spatial Purposes

For the summer 2009 data set, the Hald (1960) equation ($n= (t_{n, \alpha/2} s/d)^2$) was applied to estimate the number of samples required if the mean of the n measured values of a sample property is to be within ± *d* units of its population mean, (1−α)% of the time (Shi & Wang, 2000),

where t is student's t distribution (obtained from a t-table), s is the sample standard deviation, and d is the acceptable error (e.g. 10%, 5%, or 1%). Following (Shi & Wang, 2000), in case n is larger than 10% of the population size (N), then sample size was reduced by applying n' = n/ (1+n/N) (Sachs, 1982; Shi & Wang, 2000).

Semi-Variance analysis, Kriged, and coKriged maps

The pH-400, pH-100 and NH_4 (n=100) data sets were used to develop a reference semi-variance analysis and an interpolation Kriged map for each variable. Semi-variance analyses were carried out on both data sets using the GS+ software package, and variogram properties (i.e. nugget and sill variances, nugget/sill, and range), were determined. Ordinary Kriging (Matheron, 1970) was used to interpolate the values of 400 points for the forest floor pH-400 data set and the values of 100 points for forest floor pH-100 and NH_4 data sets. Kriging is an interpolation method that originated from geostatistics (Matheron, 1970). Kriging models the spatial structure of sampled data and enables the prediction of values at unsampled locations. In this study, Kriging was used to visualize the spatial distribution of forest floor pH, and NH_4. An ordinary Kriging model (quadratic drift/search radius of 12 points) was used as it is efficient for small study areas (Burrough & McDonnell, 1998). CoKriging is an interpolation technique

that allows mapping a primary variate from few sampling points. CoKriging needs a cross-variogram of the primary variate and a correlating secondary variate with a larger sample size (Goovaerts, 1997). The values of all the Kriging and coKriging output surfaces were classified and presented in five discrete classes (highest value = white; and lowest value = black). Kriged and coKriged maps were created with ArcMap.

Optimizing Sampling Design for Detecting the Spatial Structure of Forest Floor pH and NH_4

pH-400 data set

The ability of two sub-sampling designs to identify or reconstruct spatial structures correctly using fewer data points was evaluated. The nested systematic sampling and systematic sampling designs were used. The nested sampling design had a sample size of 148, 100 samples were withdrawn at 2 m intervals from the 20 x 20 m grid, and 64 samples were withdrawn at 1 m intervals in a 8 x 8 m grid having the tree trunk at its center. The two grids had 16 samples in common. The systematic sample design had a size of 100 samples withdrawn at intervals of 2 m in the 20 x 20 m grid. The configurations of the two new designs are represented in Fig. 5.3 B and 5.3 C. Forest floor pH data for each of the two sample designs (Fig. 5.3 B to 5.3C), and for the original field-sampling pattern (Fig. 5.3 A), were subjected to Kriging interpolation, and semi-variance analyses.

pH-100 and NH_4 data sets

The ability of nine sub-sampling designs (Fig. 5.5 b to 5.45j) in identifying or reconstructing spatial structures correctly using fewer data points was evaluated. The simple random sampling, stratified random sampling and systematic cluster sampling designs were used. These sampling designs are often favoured because they contain varying sampling steps (Fortin et al., 1989). The systematic cluster design was chosen by hand to fit on the grid. Three sample sizes were able to fit; they are 66, 50, and 36 as shown in figure 5.5-a. The 66 and 36 systematic cluster designs had similar sampling steps. The simple random design of 66, 50, and 36 sampling points was drawn respectively at random from the reference set of 100 sampling points. The stratified random sampling design of 66, and 36 samples were drawn by random selection of alternating seven/six or four/three sampling points from each grid row. Six replicates of

the 50 random sub-sampling design were produced and were labelled as (f-1, f-2, f-3, f-4, f-5, and f-6). Similarly, six replicates of the 50 stratified random sub-sampling design were produced and were labelled as (i-1, i-2, i-3, i-4, i-5, and i-6). Forest floor pH, and NH_4 data for each of the nine sample designs (Fig. 5.5 b to 5.5 j), and for the original field-sampling pattern (Fig. 5.5 a), were subjected to Kriging interpolation, and semi-variance analyses. Forest floor NH_4 of the (f-1, f-2, f-3, f-4, f-5, and f-6; and i-1, i-2, i-3, i-4, i-5, and i-6) were subjected to Kriging interpolation as well. In addition, coKriging was used to enhance the accuracy of sub-sampling designs 5.5 b - 5.5 j in detecting the spatial pattern of forest floor NH_4 by using the pH-100 as a secondary variate. A sample size of 100 was used for the secondary variate because coKriging provides better predictions than Kriging when the correlating secondary variable is oversampled (Yates and Warrick 1987).

Comparing the sub-sampling designs to the reference field designs

The interpolated values for pH at each sampling point, in each of the two sub-sampling designs (Fig. 5.3 B to Fig. 5.3 C); for pH and NH_4 in each of the nine sub-sampling designs (Fig. 5.5 b to Fig. 5.5 j) (Kriged and coKriged maps of NH_4); and for all of (f) and (i) replicates were then extracted and the mean (interpolated) values of these properties in each sampling design were calculated (Shi & Wang, 2000). The mean interpolated values obtained for each new sampling design were then compared with those for the original reference design (either Fig. 5.3 A or Fig. 5.5 a), using a Least Significant Difference (LSD) criterion at 10% probability levels (Gupta et al., 1997). The accuracy of each of the sub-sampling designs was assessed by using the goodness-of-prediction (G) (Agterberg, 1984).

$$G=(1-\{\sum_{(si)}[Z_{(si)}-\hat{Z}_{(si)}]^2/\sum_{(si)}[Z_{(si)}-\bar{Z}]^2\})100\%$$

Where $z_{(si)}$ is the measured value at field sampled location (si), $\hat{Z}_{(si)}$ is the extracted value from the Kriged map, and $\bar{z}_{(si)}$ is the average of the reference data set. A model that gives very accurate predictions relative to reference data set will have large, positive values for G (Gotway, Ferguson, Hergert, & Peterson, 1996).

The (G) of the six 50 random replicates (f-1, f-2, f-3, f-4, f-5, and f-6) and 50 stratified random (i-1, i-2, i-3, i-4, i-5, and i-6) sub-sampling designs were separately

tested with one-sample t-test against the G(%) of the (f) and (i) respectively. In addition, (G) of the six 50 random replicates (f-1, f-2, f-3, f-4, f-5, and f-6) was compared with paired-sample t-test to (G) of the six stratified random replicates (i-1, i-2, i-3, i-4, i-5, and i-6) using SPSS 17.

Temporal Stability of pH Spatial Patterns

Temporal stability of pH spatial patterns was assessed with the time-stability method described by Vachaud et al. (1985), where time stability represents the time invariant association between spatial location and classical statistical parametric values of a given soil property. This method has been applied to soil moisture, water storage and throughfall data, and it can be applied to other spatial data (Gómez-Plaza et al., 2000; Raat et al., 2002). Following Vachaud et al. (1985), the method was used to calculate the temporal average (δ_j) and standard deviation of the relative difference $\delta_{t,j}$ of a variable $S_{t,j}$ *(t = time, j = location):*

$$\delta_j = \frac{1}{m}\sum_{t=1}^{m} \delta_{t,j}$$

$$\delta_{t,j} = (s_{t,j} - \bar{s}_t)/\bar{s}_t$$

$$\bar{s}_t = \frac{1}{n}\sum_{j=1}^{n} S_{t,j}$$

Where, m represents time period, and n represents location, δ_j was ranked from smallest to largest to represent the relative deviation of forest floor pH from the plot mean at the various locations j within a plot (Appendix G). Given that it is hard to represent 100 locations on the same graph, the lowest and highest five δ_j and the ten median δ_j were represented on one graph.

Results

Normality tests indicated that pH-400, pH-100 and NH_4 data sets were normally distributed at the 95% probability level. The CV values for pH-400, pH-100 and NH_4 were 11%, 11% and 57% respectively. In addition, the results of the semi-variance analyses

indicated that forest floor NH_4 had a higher nugget/sill ratio (28%) than forest floor pH-100 (24%) (Table 5.1).

A sample size of 2 and 4 is required to obtain a mean within ±15%, 10% of the true mean of the pH-100, 95% of the time (Table 5.2). The values of n required to provide mean values of pH-100 ±5%, and 1% and NH_4 ±15%, 10%, ±5%, and 1% of the true population means, were greater than 10% of the population size (N). The corresponding corrected sample size was 13 and 43 for pH-100 at ±5%, and 1% respectively, and 28, 47, 78, and 98 for NH_4 at ±15%, 10%, ±5%, and 1% respectively (Table 5.2).

The Kriged maps for forest floor pH-400 showed that both sub-sampling designs (B and C) were able to depict the broad and fine spatial patterns of the reference Kriged map (the overall gradient and the central clustering in the vicinity of the central tree) (Fig. 5.4 A–5.4C). For both pH-100 and NH_4, the 66 random, 50 random, 66 stratified random, 50 stratified random, and 50 systematic cluster sub-sampling designs were able to depict the major spatial patterns of their corresponding reference Kriged map (Fig. 5.6 a- 5.6 j and Fig. 5.7 a- 5.7 j). CoKriged maps of NH_4 showed an improved visual resemblance to the reference Kriged map, compared to their corresponding Kriged maps (Fig, 5.8a-5.8j). The LSD test showed that for both pH-400, pH-100 and NH_4 the interpolated mean value for the new sub-sampling designs (B-C and b-j) were not significantly different at the 90% confidence interval (Tables 5.4 and 5.5). For forest floor pH-400, both B and C designs had a similar value of (G) (66 and 62% respectively). The highest and lowest (G) of 75 and 38% were found for a sample size of 66 for the random design and sample size of 36 for the stratified random design for forest floor pH-100. In addition, Δ (1,i) increased, and the goodness-of-prediction (G) decreased, as sample size decreased, in the random and stratified random designs. A sample size of 50 showed lowest Δ (1,i) and highest (G) for systematic cluster design.

For forest floor NH_4, the highest and lowest (G) were 35 and 5% for a sample size of 66 for random and a sample size of 36 for systematic cluster designs. In addition, values for Δ (1,i) and those for the goodness-of-prediction (G) increased as sample size decreased for both random and stratified random designs. Similarly to forest floor pH, a sample size of 50 showed lowest Δ (1,i) and highest (G) for systematic cluster design. CoKriged maps of forest floor NH_4 showed a higher goodness-of-prediction (G) of all the sub-sampling designs compared to their corresponding Kriged interpolation. The (G)

shifted from, 35 to 60% and 25 to 65% for 66 random and 66 stratified random respectively; and from 31 to 38% and from 21 to 37% for 50 random and 50 stratified random respectively (Table 5.4).

Replications of the 50 random and 50 stratified random sub-sampling designs showed no significant differences between their mean estimated goodness-of-prediction (G). In addition, the mean estimated goodness-of-prediction (G) of the 50 random replicates and 50 stratified random replicates showed no difference in the (G) of (f) and (i) sub-designs respectively (Table 5.5). The temporal stability of the spatial patterns indicated that the locations directly surrounding a bigleaf maple trunk have the highest deviation from the time-average plot mean. Those were locations 45, 46, 55, and 56 (Fig. 5.10).

Discussion

pH-400 data set

The extensive sampling provided a clear picture of the variability of the forest floor pH, but was time-consuming and expensive. When a soil property varies spatially, soil scientists often sample more intensively in areas deemed to be critical (Berry & Baker, 1968). We identified the area around the stem to be critical due to the many nutrient cycling related processes concurrently occurring there (litterfall, barkfall & stemflow) (Chapter 4). Two different subsets of data were extracted from the original complete pH-400 data set and were used to investigate the influence of a nested sampling configuration on Kriging interpolation.

It was expected that the values for Δ (1,i) would increase, and those for the goodness-of-prediction (G) would decrease, as sample size decreased. Surprisingly, the LSD test showed that for forest floor pH, none of the interpolated mean values for designs (B and C) were significantly different from those of the reference design (A) and the difference between the goodness of prediction (G) was less than 5%. This could indicate that the 2 m sampling interval captures the spatial signal associated with the tree trunk and that there is no need to perform intensive nested sampling to detect a tree spatial influence on forest floor pH when this sampling interval is used. Thus, when mapping

forest floor pH, sample size might be reduced from 400 to 100 samples collected systematically without significant loss of spatial information. This could be explained by the fact that the spatial structure of the data set is characterized by a patch at the centre of the plot. Such spatial structure is detected equally by aggregated or systematic sampling (Legendre et al., 2002). Nevertheless, nested sampling would be important when using a large sampling interval that is unable to detect the spatial signal of critically important areas (Berry & Baker, 1968), or when the spatial variation is occurring over fine scale (<1m) such as with mineralizeable N (Goovaerts & Chiang, 1993).

pH-100 and NH_4 data sets

It was expected that forest floor pH and NH_4 would show different spatial variability expressed by differences in CV, nugget and nugget/sill ratio of their variograms (Rothe at al., 2002). The CV value for NH_4 was almost 5 times that for pH, which implies that the within-field variability in forest floor NH_4 was much greater than that in forest floor pH. The results of the semi-variance analyses (Table 5.1) showed that forest floor NH_4 had a higher nugget/sill ratio (28%) than forest floor pH (24%). Cambardella et al. (1994) suggested the presence of a strong spatial dependence if the nugget/sill ratio is less than 25%, a moderate spatial dependence if this ratio is between 25% and 75%, and a weak spatial dependence if the ratio is more than 75%. This indicates the presence of a strong and moderate spatial dependence in forest floor pH and NH_4 respectively. Reasons for higher nugget/sill ratio for NH_4 can possibly be related to the fact that natural phenomena can vary spatially over a range of scales and that variation at microscales smaller than the sampling distances will appear as part of the nugget effect. This suggests that the variability in forest floor NH_4 has a greater short-range component compared to forest floor pH. Hence, the spatial structure of forest floor pH is better detected than forest floor NH_4 with a sampling step of 2 m. This could be due to the fact that the concentrations of elements retained by biological mechanisms such as NH_4 are more variable than elements retained by geochemical mechanisms such as pH (Gallardo, 2007; Bengtson, 2006). Alternatively, forest floor NH_4 can possibly have a much greater random component compared to forest floor pH. Differences in nugget/sill ratio among soil variables was reported by Shi and Wang (2000) which contrasts with the results of McBratney and Pringle (1997) who found the nugget/sill ratios for P and K to be almost identical for a

range of arable soils. This could be related to the fact that natural soils would exhibit more variability compared to agricultural soils.

It is clear from the results in Table 5.2, that the estimated numbers of samples needed to obtain sample means within ±15%, 10%, 5%, and 1% of the true values were between 1/3 to 14 times greater for NH_4 than for pH. This difference in sample size reflects the greater within-field variability in forest floor NH_4 than in forest floor pH. As shown in table 5.2, increasing the accepted error level from ±5% to ±10% would result in a 3 to 2-fold reduction in the required sample size for pH and NH_4 respectively. Our results of sample size in relation to CV are comparable to Goovaerts and Chiang (1993), who reported that a sample size of 37 was needed to estimate averaged mineralizeable N with a precision of 10% for a dataset with a CV of 36%. Furthermore, increasing the accepted error level from ±5% to ±15% would result in a 7 to 3-fold reduction in the sample size needed to estimate mean values for pH and NH_4 respectively and hence would significantly lower the costs and efforts of forest floor sampling and analysis. However, semi-variance analysis, Kriging, and coKriging interpolation require a minimum number of samples of 30 for the production of accurate soil maps (Fortin & Dale, 2005; Shi & Wang, 2000). Therefore, a careful examination of the influence of sample size and sample configuration on the subsequent Kriging interpolation is necessary before making any decision regarding the optimal sample size.

The LSD test showed that for forest floor pH and NH_4, none of the interpolated mean values for designs b, c, d, e, f, g, h, i, j, k, and l was significantly different to that for the reference design (a). It was expected that values for Δ (1,i) would increase, and those for the goodness-of-prediction (G) decrease, as sample size decreased. For both forest floor pH and NH_4, however, the value of Δ (1,i) and G did not show a consistent negative and positive correlation with sample size in the systematic cluster design. The pattern was observed, however, in the random and stratified random designs.

For the systematic cluster design, a sample size of 50 had a higher (G) as compared to a sample size of 66 and 36. This could be due to the fact that the systematic cluster design had various sampling steps that were different between the 66 and 50 sample sizes. The samples were hand-fit and it seems that the 50 points overlapped with some samples capturing the spatial structure within the vicinity of the central bigleaf maple (Fig. 5.3-a) while the 66 sample size had fewer samples within the vicinity of the central

tree (Fig. 5.3-b). This is why the 50 sample size design was better in detecting the spatial structure compared to the 66 and 36 sample size designs. This indicates that when mapping forest floor pH and NH_4, sample size might be reduced from 100 to 50 without significant loss of spatial information as long as there is knowledge about the spatial pattern in the mapped area. In the absence of knowledge about the spatial pattern in the mapped area, a random design is recommended (Fortin et al., 1989). Both random and stratified random designs showed that (G) increases as sample size increases. From visual inspection of the Kriged maps, it seems that a sample size of 50 can adequately produce the spatial patterns of the examined variables. The visual representation of the spatial patterns and the (G) of forest floor NH_4 of the nine sub-sampling designs were improved by coKriging interpolation. This is in agreement with previous reports that coKriging is more precise than Kriging (Zhang et al., 1992). NH_4 is widely used to assess site fertility (Turner et al., 1993), and is associated with high cost (Goovaerts and Chiang, 1993). The results demonstrate that pH can be used as a secondary variate to improve the prediction when NH_4 sample size is reduced.

The results in Table 5.4 confirm that sample configuration, and not just sample size, should be considered when devising sampling designs for mapping forest floor properties. For example, although the sample sizes for designs (b), (e) and (h) were identical (66 samples each), the random and stratified random designs showed a higher (G) for both pH and NH_4 than the systematic cluster design. Random and stratified random designs, therefore, would seem to be more reliable for interpolation of forest floor pH and NH_4 than the systematic cluster design. For the random and stratified random designs, it was expected that interpolation accuracy would increase as sample size increases. Our results confirmed our expectations and showed a better prediction associated with random sampling as compared to stratified random sampling. This could be explained by the fact that stratified random sampling selected a constant number of samples along each row. In the random design, however, there was a variable number of samples along each row. This enabled the random design to withdraw samples along the vicinity of the central tree where the spatial signal would be more pronounced.

Due to the effort, cost and time associated with assessing the efficiency of sub-sampling designs in depicting the spatial patterns, it is acceptable to carry out such assessments without replications (Fortin et al., 1989; Goovaerts & Chiang, 1993, Johnson

et al., 2010; Shi & Wang, 2006), nevertheless, the two proposed 50 sample size (random and stratified random) sub-sampling designs were replicated and tested for significance. Though there was a higher accuracy level associated with the 50 random design as compared to the 50 stratified random, the difference was not significant. Hence, we recommend adopting a stratified random sampling design to ensure a certain minimum number of samples will be selected from the vicinity of the tree (Yfantis et al., 1987; Gotway et al., 1996).

Time-stability graphs (Fig.5.10) have been used to exclude extreme values (at the peripheries of the graph) from future sampling and their corresponding locations have been treated as non-representative of the sampling area (Raat et al., 2002), nevertheless, outliers could indicate the existence of hotspots within the sampled area (Johnson et al., 2010). In this study, locations showing extreme positive deviation from the time-average mean possibly indicate an area of improved site quality (more basic pH). The locations directly surrounding bigleaf maple trunk showed a certain temporal persistence (high values occurred at the same locations) during summer 2009 and summer 2011. This enhances the understanding of the interaction between spatial and temporal scales of forest floor pH in relation to tree influence. Though there are two replicates for time, the examination of time stability indicated that clustering surrounding the trunk is persistent and that a one snapshot in time could reflect the pH of locations in close proximity to the tree trunk (at least for the summer season). Considering that the temporal stability of soil variables does not usually behave equally (Goovaerts & Chiang, 1993), it cannot be generalized to NH_4 and a time stability assessment is needed before making any conclusion about NH_4 temporal persistence within the vicinity of the tree.

Conclusion

The concentration of forest floor NH_4 associated with bigleaf maple in a mixed conifer stand was more variable than forest floor pH. This had a direct implication on the sample size needed to estimate the plot mean within a certain degree of accuracy. A smaller sample is required to estimate the plot mean for pH compared to NH_4. Geostatistical analysis revealed that at a plot scale, a sample size of 50 selected randomly or stratified randomly seems to be adequate for mapping the spatial structure of both

variables, and coKriging improved the prediction of NH_4 concentration by having pH as its secondary variate. Time stability assessment of forest floor pH indicated that locations directly surrounding a bigleaf maple trunk consistently show a higher pH compared to the time-average mean of the plot. This study contributes new knowledge concerning the spatial impact of deciduous species on soil properties in conifer forest and provides an approach for reducing sample size and cost associated with assessing impacts on mineralizeable N. This could allow the initiation of long term assessments of spatial patterns of soil variables that are critical for our understanding of the long term species-specific effects on site productivity.

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Table 5.1. A summary of the conventional statistical and semi-variogram properties for pH, and NH_4 in forest floor samples collected from a bigleaf maple plot using a 20 x 20 m square reference sampling grid (a) and 400 sampling points, systematically sampled in a 20 X 20 m grid (A).

		Conventional statistical properties						Semi-variogram properties				
Soil property	**Sampling design**	**Mean**	**SD**	**CV (%)**	**Min.**	**Max.**	**P**	**Model**	**Nugget variance (Co)**	**Sill variance (C)**	**Nug/Sill (%)**	**Range (m)**
pH	(A)	4.52	0.49	11	3.08	5.64	0.22	Exponential	0.045	0.29	15.15	23.16
pH	(a)	4.05	0.44	11	3.15	5.13	0.46	Spherical	0.07	0.29	24.13	12.33
NH_4	(a)	195.98	111.79	57	46.5	763	0.11	Spherical	96.00	344	27.90	4.92

Table 5.2. Uncorrected and corrected sample sizes needed to obtain mean values for forest floor pH, and NH_4 within ±15%, ±10%, ±5% and ±1% of the true means 95% of the time.

Soil property	Original sample size	±15%		±10%		±5%		±1%	
		Un-C	C	Un-C	C	Un-C	C	Un-C	C
pH	100	2	NA	4	NA	15	13	75	43
NH_4	100	38	28	88	47	>100	78	>100	98

Un-C: uncorrected, and C: corrected, using n' =n/ (1+n/N); NA: not applicable.

Table 5.3. ***Mean forest floor pH (extracted form the Kriged maps) for the sampling designs (A), (B) and (C); the difference (Δ (1,i)) of the mean forest floor pH of the reference data set (A) and the mean pH of the sampling designs (B) and (C); and estimates of the goodness-of-prediction (G) of the two sampling designs (B) and (C).***

Sample size	Sampling design	Forest floor pH		
		Mean	Δ (1,i)	G (%)
400	(A)	4.52	-	-
148	(B)	4.60	0.008	65
100	(C)	4.51	0.010	62

Table 5.4. ***Mean forest floor pH, NH_4 (extracted form the Kriged maps) and Co-NH_4 (extracted from Co-Kriged maps) for the sampling designs (a), (b), (c), (d), (e), (f), (g), (h), (i), and (j); the difference (Δ (1,i)) of the mean forest floor pH and NH_4 of the reference data set (a) and the mean pH and NH_4 of the nine sub-sampling designs; and estimates of the goodness-of-prediction (G) of the nine sub-sampling designs.***

		Mean			Δ (1,i)			G (%)		
Sample size	**Sampling design**	**pH**	**NH_4**	**Co- NH_4**	**pH**	**NH_4**	**Co- NH_4**	**pH**	**NH_4**	**Co- NH_4**
100	(a)	4.05	195.98	195.98	-	-	-	-	-	-
66	(b)	4.03	190.19	192.5	0.02	5.79	3.45	55.80	14.55	19.6
50	(c)	4.06	215.05	215.48	0.01	19.07	19.51	66.42	24.06	28.74
36	(d)	4.04	192.29	197.46	0.01	3.69	1.49	44.85	4.63	7.24
66	(e)	4.04	197.21	207.29	0.01	1.23	11.31	75.08	34.86	60.21
50	(f)	4.03	211.18	200.80	0.02	15.2	4.83	53.88	30.95	38.96
36	(g)	4.11	205.89	212.15	0.06	9.91	16.17	39.80	16.74	19.85
66	(h)	4.07	202.27	191.28	0.02	6.29	4.70	51.76	25.37	64.73
50	(i)	4.11	199.19	217.63	0.06	3.21	21.65	43.47	20.92	37.26
36	(j)	4.07	194.90	212.48	0.02	1.08	16.51	38.82	19.13	24.67

Table 5.5. Conventional statistical comparison (using t-test) of the differences between the estimates of the goodness-of-prediction (G) of forest floor NH_4 for the six replicates of the 50 random and 50 stratified random designs.

Sample size	Sampling design	Mean	SD	min	max	P
50	Random	35.95	21.31	9.34	58.93	
50	Stratified random	34.22	21.46	10.43	62.47	
t-test	Random vs. Stratified random					0.93
t-test	Random vs. (f)					0.671
t-test	Stratified random vs. (i)					0.303

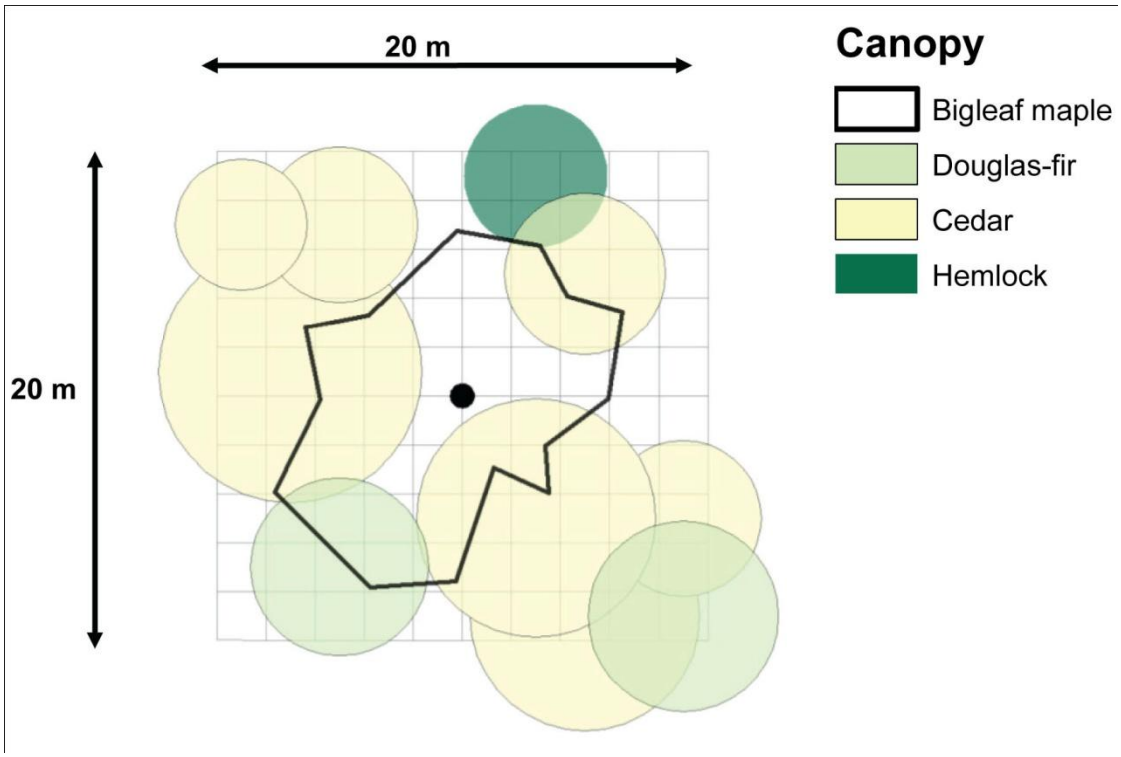

Figure 5.1. ***Canopy extent of trees on bigleaf maple plot. A single central tree is located at the center of the 20 m X 20 m plot (canopy outlined by a solid black line).***

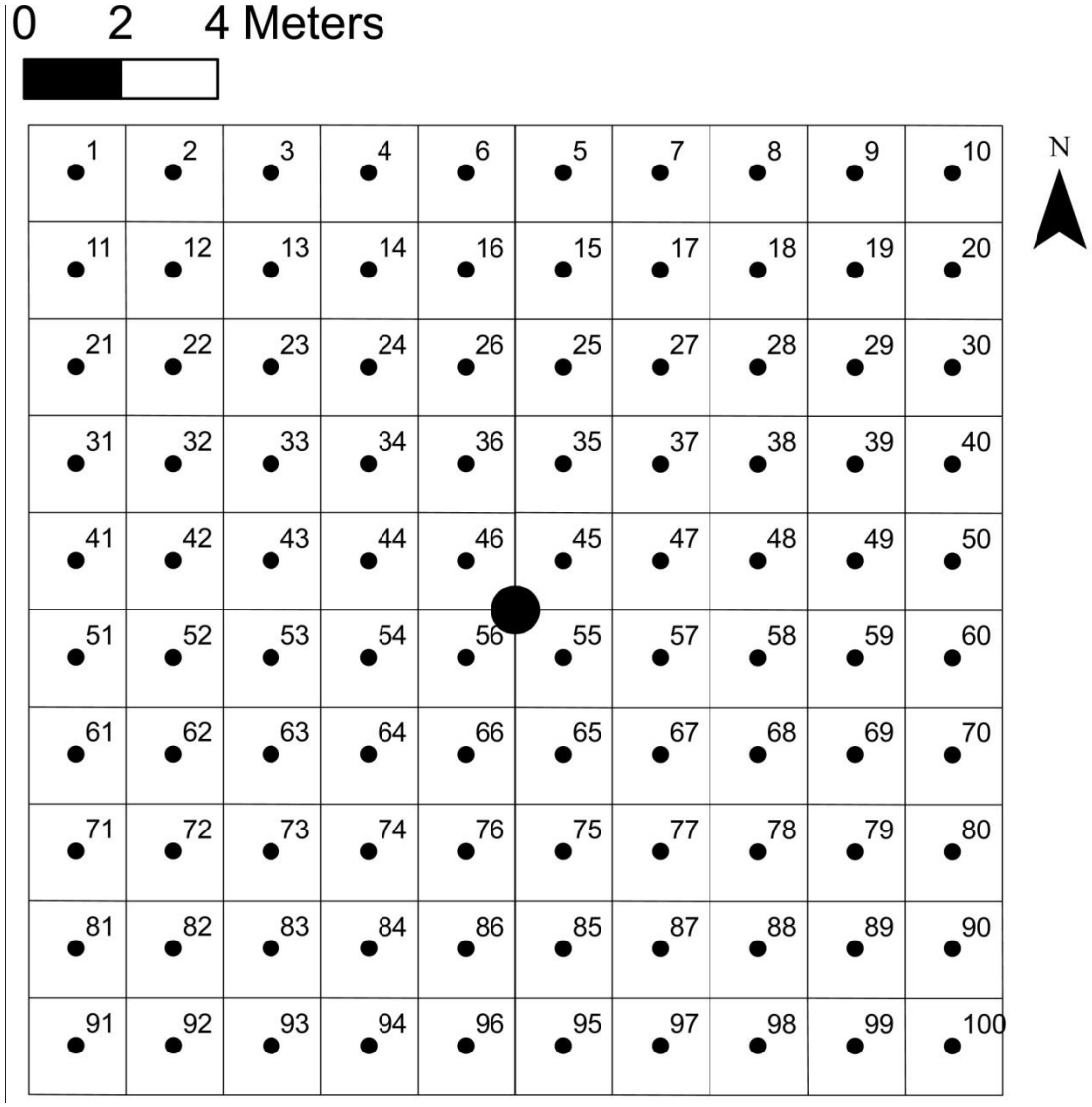

Figure 5.2. ***A 20m X 20 m grid is centered on a central tree where forest floor was sampled every 2 m (n=100). Location 1 is at the north-west corner, location 2 is at the north-east corner, location 91 is at the south-west corner, location 100 is at the south-west corner, and locations 45, 46, 55, and 56 are directly surrounding the central trunk in the centre of the plot.***

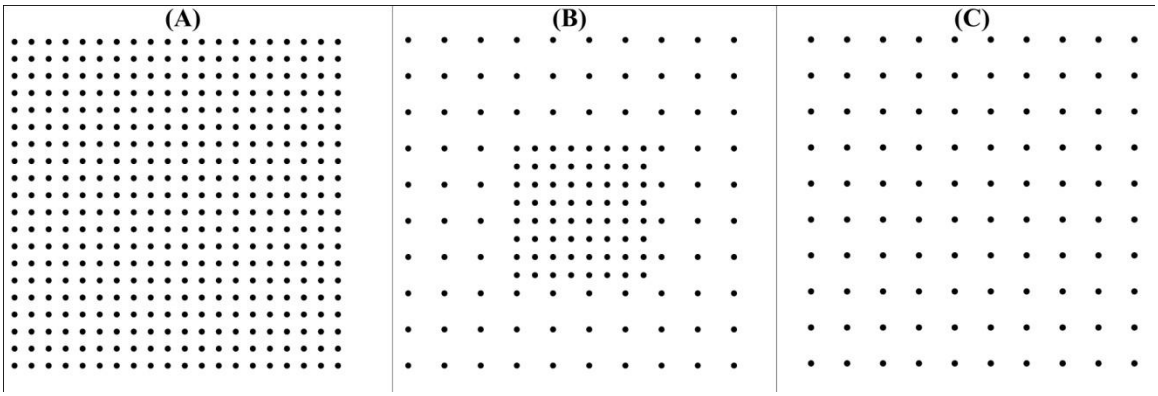

Figure 5.3. Sampling designs: (A) 400 sampling points, systematically sampled in a 20 X 20 m grid; (B) 148 sampling points, systematically sampled in a 20 X 20 m grid, (C), 100 sampling points, sampled in a 20 X 20 m grid.

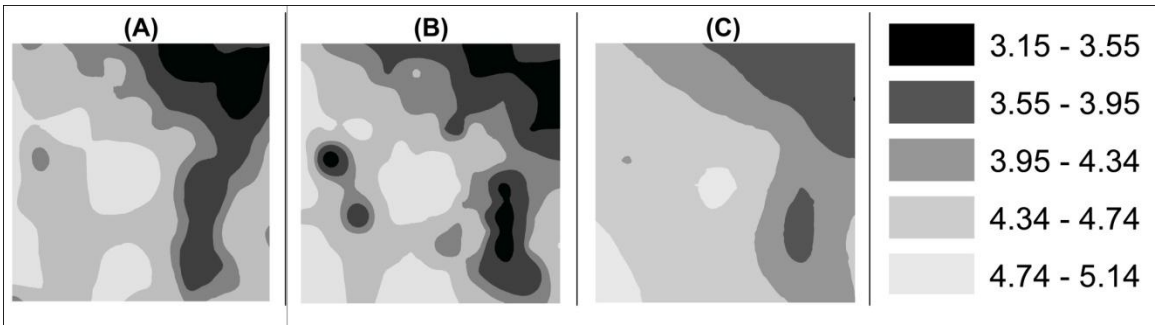

Figure 5.4. ***Krig maps of forest floor pH for each of the three different sampling designs given in Fig. 5.3: (A) 400 sampling points, systematically sampled in a 20 X 20 m grid; (B), 148 sampling points, sampled in a 20 X 20 m grid; (C) 100 sampling points, systematically sampled in a 20 X 20 m grid.***

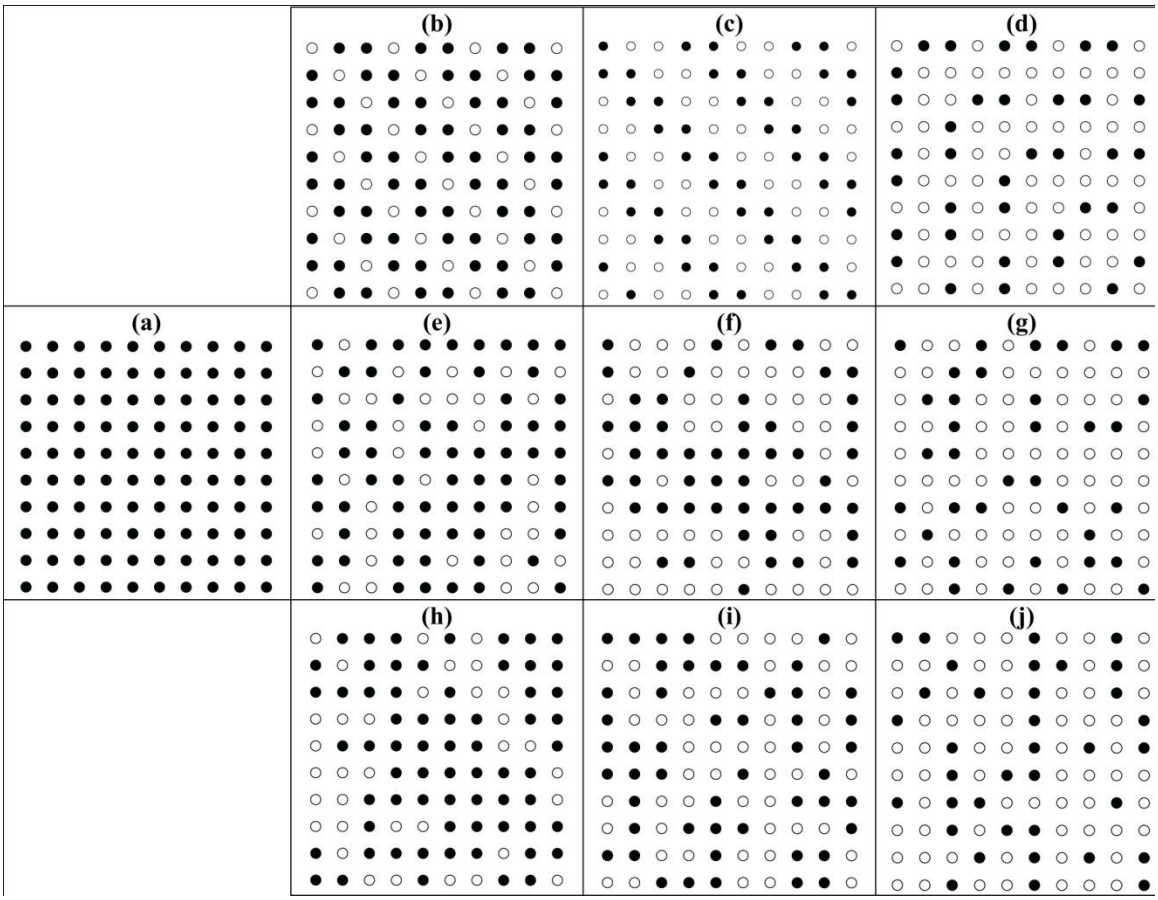

Figure 5.5. ***Sampling designs: (a) 100 sampling points, systematically sampled in a 20 X 20 m grid; (b) 66-point systematic cluster subsample; (c), 50-point systematic cluster subsample; (d) 36-point systematic cluster subsample; (e) 66-point random subsample; (f), 50-point random subsample; (g) 36-point random subsample; (h) 66-point stratified random subsample; (i), 50-point stratified random subsample; (j) 36-point stratified random subsample.***

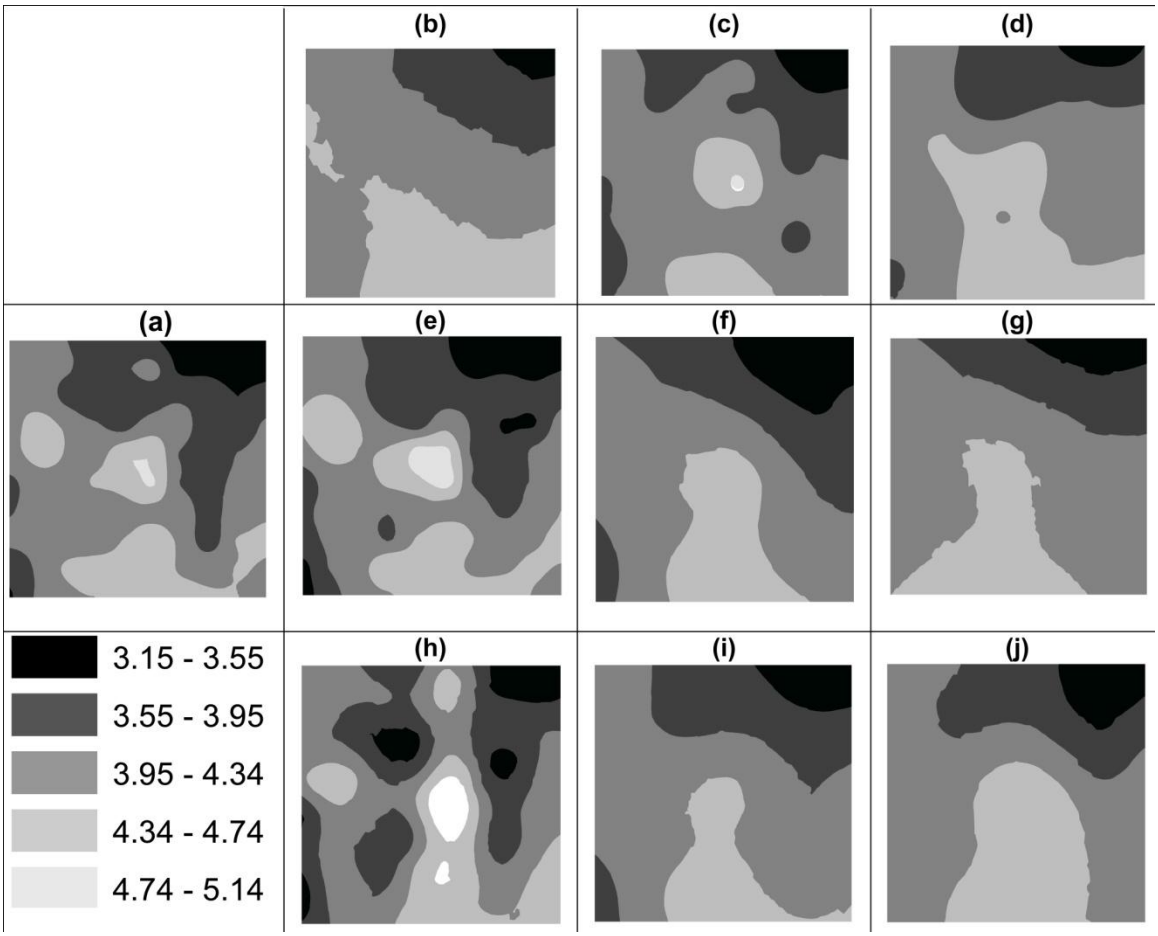

Figure 5.6. ***Krig maps of forest floor pH for each of the ten different sampling designs given in Fig. 5.3: (a) 100 sampling points, systematically sampled in a 20 X 20 m grid; (b) 66-point systematic cluster subsample; (c), 50-point systematic cluster subsample; (d) 36-point systematic cluster subsample; (e) 66-point random subsample; (f), 50-point random subsample; (g) 36-point random subsample; (h) 66-point stratified random subsample; (i), 50-point stratified random subsample; (j) 36-point stratified random subsample.***

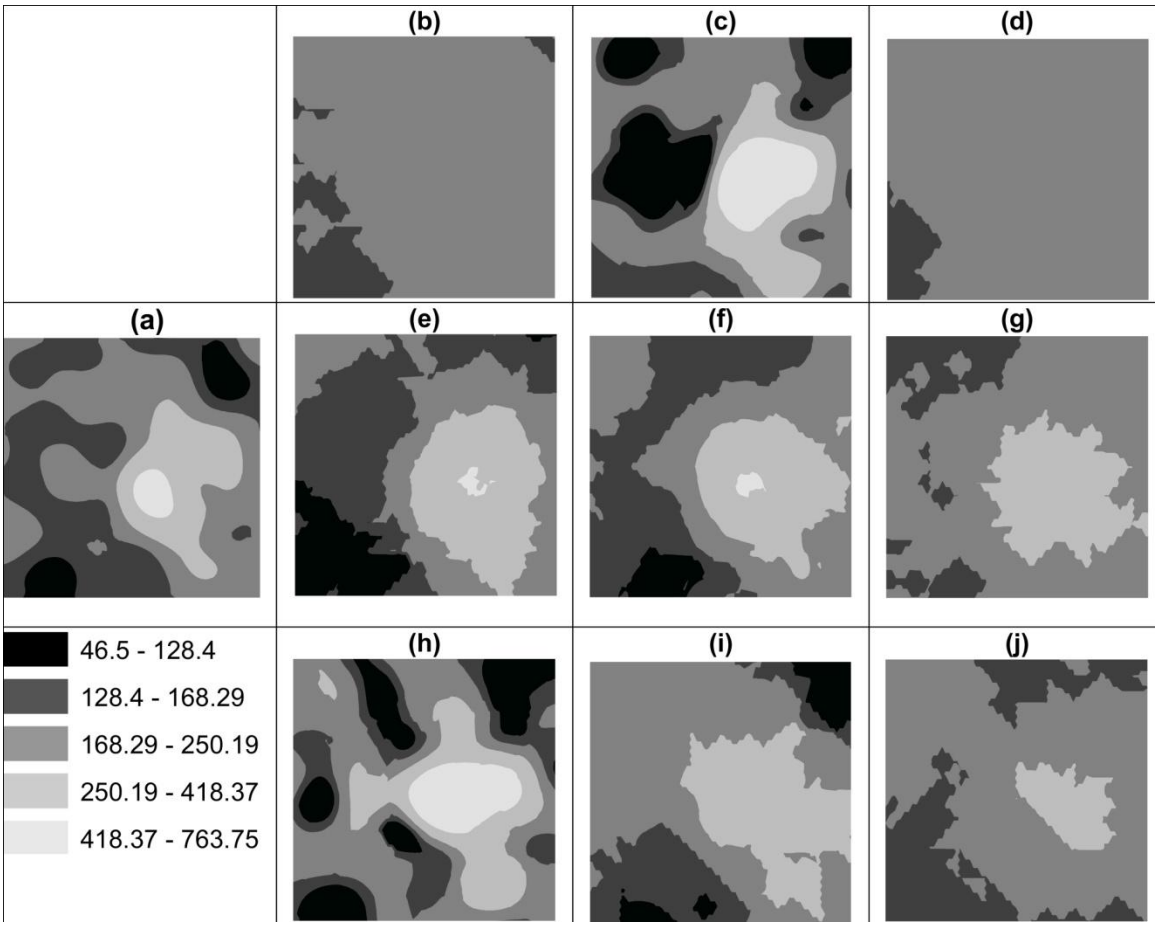

Figure 5.7. ***Kriged maps of forest floor NH_4 for each of the ten different sampling designs given in Fig. 5.3: (a) 100 sampling points, systematically sampled in a 20 X 20 m grid; (b) 66-point systematic cluster subsample; (c), 50-point systematic cluster subsample; (d) 36-point systematic cluster subsample; (e) 66-point random subsample; (f), 50-point random subsample; (g) 36-point random subsample; (h) 66-point stratified random subsample; (i), 50-point stratified random subsample; (j) 36-point stratified random subsample.***

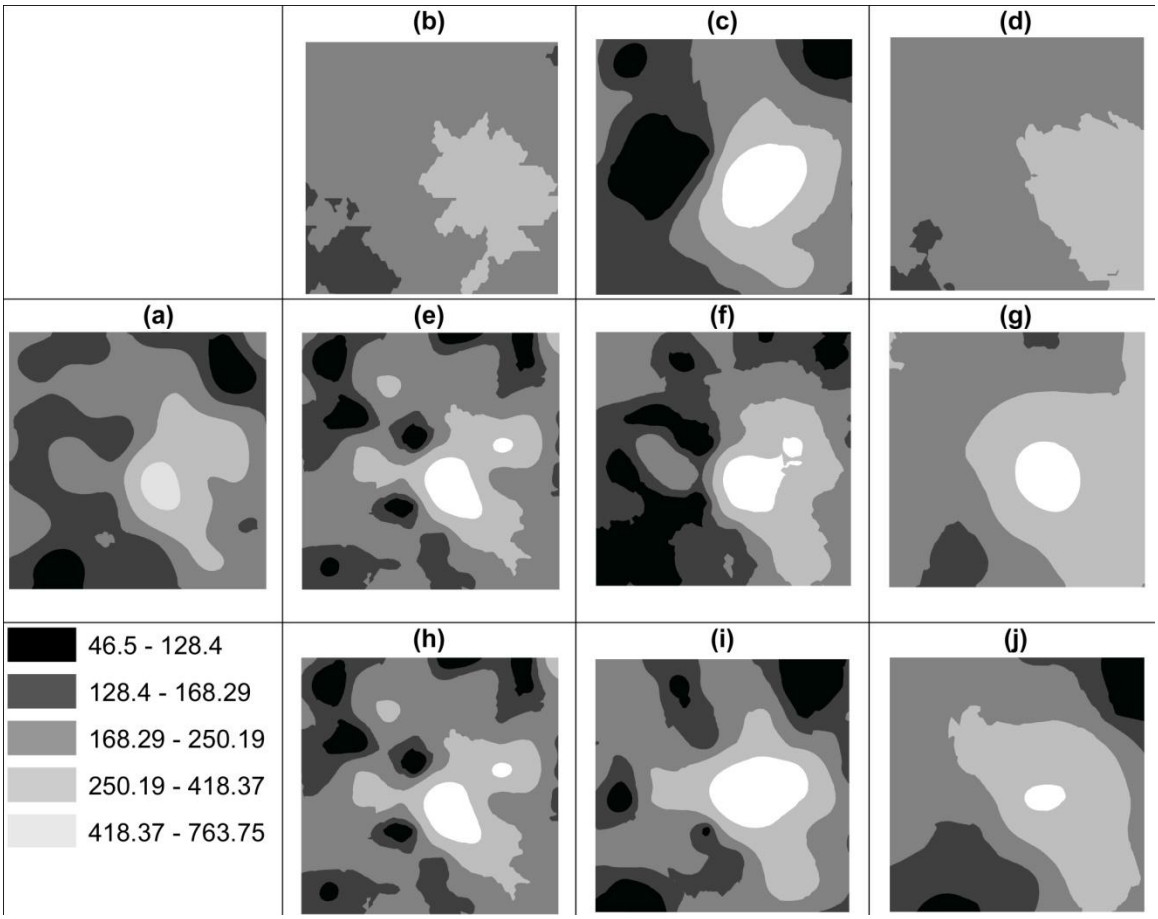

Figure 5.8. ***CoKriged maps of forest floor NH_4 for each of the nine different sampling designs given in Fig. 5.3: (b) 66-point systematic cluster subsample; (c), 50-point systematic cluster subsample; (d) 36-point systematic cluster subsample; (e) 66-point random subsample; (f), 50-point random subsample; (g) 36-point random subsample; (h) 66-point stratified random subsample; (i), 50-point stratified random subsample; (j) 36-point stratified random subsample.***

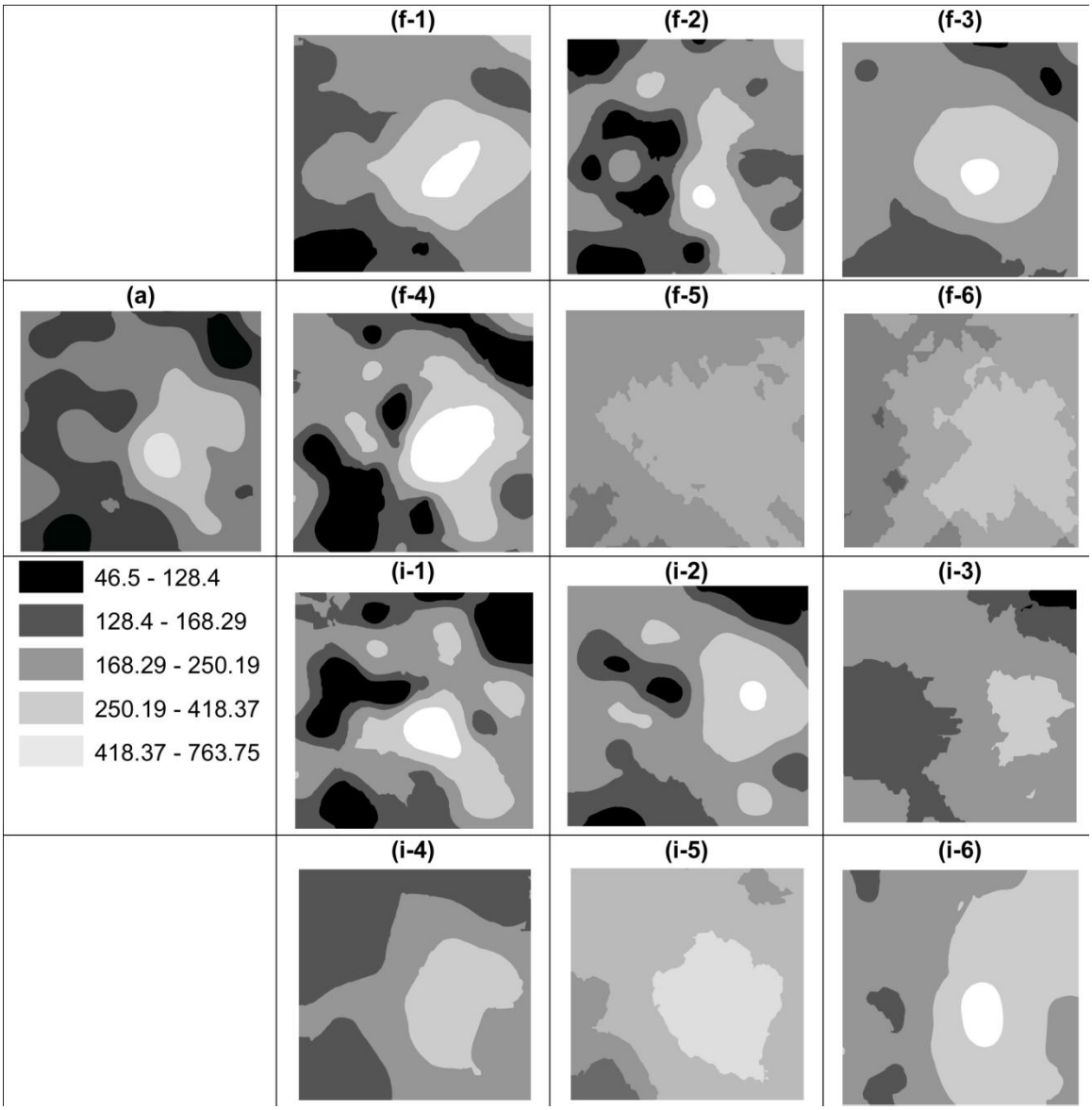

Figure 5.9. Kriged maps of forest floor NH_4 for three replicates of 50-point random subsample (f-1, f-2, f-3, f-4, f-5, and f-6); and three replicates of 50-point stratified random subsample (i-1, i-2, i-3. I-4, i-5, and i-6).

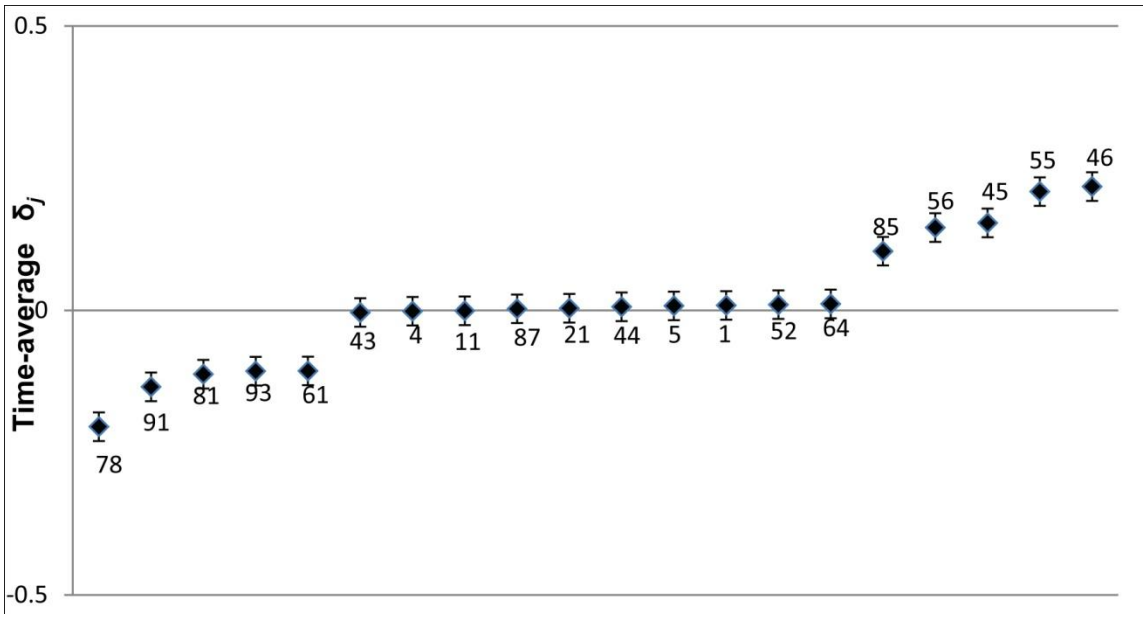

Figure 5.10. Time stability plot for forest floor pH, time-average δ_j of two periods; numbers refer to location number.

Chapter 6. Conclusion

Synthesis of the Results

The research presented in this thesis achieved the overall goal of further understanding the potential implications of climate change on forest hydrology and site fertility due to the expected shift in species composition and species-specific effects in a mixed forest stand. Bigleaf maple and other deciduous trees are expected to increase in frequency in the Pacific Northwest ecosystem in the coming decades (Hamann & Wang, 2006). The findings in chapter 2 of higher throughfall, lower stemflow, and greater chemical enrichment of almost all throughfall fluxes beneath bigleaf maple during leafed and leafless periods indicated the continuous higher nutrient input under bigleaf maple throughout the year. This has led me to investigate the total nutrient input via throughfall and stemflow and to compare forest floor fertility of bigleaf maple and conifers in Chapter 3.

The findings in Chapter 3 suggest that bigleaf maple growing within conifer forests has the potential to modestly improve site conditions under its canopy and to a greater extent in the vicinity of its trunk. I found higher pH and greater K inputs for both throughfall and stemflow, as well as greater P and S inputs in throughfall at bigleaf maple plots compared to conifer plots. The greater degree of soil fertility improvement near bigleaf maple trunks is likely due to these areas being influenced by stem-related processes, such as stemflow, in addition to canopy related processes such as litterfall and throughfall. Furthermore, areas near bigleaf maple trunks are more strongly influenced by bigleaf maple, whereas areas beneath the bigleaf maple canopy but further away from the trunk are influenced by bigleaf maple as well as the surrounding conifers. The result is a zone around bigleaf maple stems that likely has enhanced microbial activity and increased nutrient availability. Changes in soil properties induced by bigleaf maple may be long-lasting. For example, Mina (1967) found that after stemflow input ceases, changes which had taken place earlier in the soil may be preserved for many years. Thus, the enriched

microsites proximal to bigleaf maple trunks may form fertile spots for conifer growth at later stages of forest development. The variation of forest floor properties between the under-canopy and near trunk sites led us to characterize the spatial patterns of forest floor properties at multiple scales in relation to trunk and canopy position in Chapter 4.

In chapter 4, the application of various analytical techniques to study species-specific impacts on soil properties and tree IP indicated that Kriging, LISA, and PCNM can be used as complementary analytical techniques to address various spatial questions. The application of the PCNM method enabled us to extract the main factors impacting forest floor pH and possibly other soil properties at the plot scale. It revealed that topography mainly acts broadly and canopy cover, canopy density and moisture content act at a finer scale.

To achieve the objective of Chapter 4, there was a great effort and time put into sample collection and processing, as well as a high costs. This led me to consider optimizing the sampling design in an attempt to reduce the total number of samples collected without compromising the accuracy of the outputs of the analytical techniques. Chapter 5, showed that a sample size of 50 seems to be able to capture the spatial signal of forest floor pH and NH_4 associated with bigleaf maple. CoKriging improved the prediction of NH_4 concentration by having pH as its secondary variate. It was evident, though, that the optimal sampling strategy related not just to sample size, but to sample configuration as well.

Strengths of the Thesis

My thesis provides theoretical and applied contributions to the discipline of species-specific effects in forest ecosystems. In this thesis, I have made the following original findings and contributions:

Incident rainfall, throughfall, and stemflow volumes, pH, and DOC were measured at a high resolution over a six month period. In addition, incident rainfall, throughfall, and stemflow chemical fluxes were determined in the leafed, leaf senescence and leafless periods. Total nutrient input via throughfall and stemflow and forest floor chemical properties were determined as well. These measurements allowed

the comparison of the spatial and temporal variability of throughfall and stemflow nutrient inputs to the forest floor associated with bigleaf maple and Douglas-fir plots during the growing and dormant seasons. I found that at certain rainfall amounts, bigleaf maple throughfall pH and DOC are significantly altered from those of rainfall and Douglas-fir throughfall. This has a direct implication on our understanding of how the predicted precipitation increase during the fall and winter in British Columbia, due to climate change could alter forest hydrology. In addition, bigleaf maple canopy affected the spatial heterogeneity of chemical fluxes in leafed, leaf senescence and leafless seasons. Most previous studies have focused on the growing season and very few studies reported the nutrient fluxes in the leafless season (Staelens, 2007). This study shows that the leafless period is of ecological importance as well.

Forest floor properties were examined at a high resolution at the plot scale. Parametric tests showed that the bigleaf maple plots are more fertile than Douglas-fir plots and that the near trunk forest floor sites under bigleaf maple are more fertile than the under-canopy sites. This study showed that patterns in forest floor properties were related to individual bigleaf maple stems growing within a conifer forest. In general, the highest pH, and the highest nitrate and ammonium concentrations were found close to the bigleaf maple stems with decreasing concentrations away from the stems. The application of the PCNM method enabled us to extract the main influential factors impacting forest floor pH and possibly other soil properties at the plot scale. It revealed that topography mainly acts broadly and canopy cover, canopy density and moisture content act at a finer scale. The intensive sampling used in this study indicated that distance from tree stems may be an important factor to consider in traditional plot-based field experiments.

The overall findings of this work contribute to forest management practices in British Columbia. Bigleaf maple, like other hardwoods in conifer forests, is managed to minimize its competitive influence (Turk et al., 2008). Conventionally, the presence of bigleaf maple has been deemed competitive and even detrimental to conifer survival (Haeussler et al., 1990). Recent studies suggest that bigleaf maple seems to enhance nutrient availability (Fried et al., 1990; Turk et al., 2008). In coastal forests of British Columbia, bigleaf maple is a shade intolerant tree and an early to middle successional species (Peterson et al., 1999). The findings of enriched microsites proximal to bigleaf maple trunks suggest that bigleaf maple has potential legacy effects on soil fertility and

hence, may promote conifer productivity following bigleaf maple mortality later in succession. Biological legacies are central for sustainable forest management. The establishment and/or retention of biological legacies aid in maintaining crucial structural elements as components of managed stands, thereby sustaining many organisms and ecological processes dependent upon these structures (Franklin et al., 2002). This would allow the ecosystem to restore its structural and functional integrity and enhance its resilience in an ever-changing environment (Seybold et al., 1999). In this context, bigleaf maple may be a desirable species for forest management. The findings of this study provide evidence that increased bigleaf maple presence would likely lead to a few but important changes in forest hydrology and nutrient cycling at the plot scale. These changes could act as additional mechanisms by which bigleaf maple creates conditions of improved site fertility that potentially foster the proliferation of conifer species at later stages of succession.

Limitations of the Thesis

Precipitation in forms other than incident rainfall was not examined, i.e. the influence of snowfall on nutrient inputs and leaching from trees was not investigated. Levia and Herwitz (2000) reported that nutrient leaching is greater during mixed winter precipitation (rain-snow) events than during spring rainfall events. They suggested that this is possibly due to air temperature fluctuations around the freezing point that increase the kinematic viscosity and surface tension of the intercepted precipitation, increasing the contact time of melted water with the bark tissue, and because snow sits on the branches much longer than incident rainfall.

Forest floor fertility in relation to distance from trunk and forest floor spatial patterns was examined but their temporal persistence was only investigated for forest floor pH. The temporal variation in throughfall and stemflow input could have a considerable effect on the temporal variation of forest floor moisture content, which in-turn could greatly affect bacterial processes such as nitrification and mineralization leading to priming effects. Priming effects are strong short-term changes in the turnover of soil organic matter caused by comparatively moderate treatments of the soil including

the input of organic or mineral fertilizer, exudation of organic substances by roots, mere mechanical treatment of soil, or it's drying and rewetting (Kuzyakov et al., 2000).

PCNM method was able to dissect the spatial component at multiple scales. Nevertheless, it was not tested on an irregular sampling design such as the sampling schemes obtained in Chapter 5. The main limitation of the PCNM method is the dependence of the PCNM variables on the uniformity of the sampling grid. In irregular sampling schemes, the PCNMs will not still be orthogonal to properly describe the sampling space (Borcard et al., 2004).

Future Research

Studies on throughfall and stemflow volume and chemical fluxes of deciduous species have often focused on the leafed period of the tree life cycle. Future research can focus on the incident rainfall redistribution and throughfall enrichment during the leafless period. This may include correlating nutrient input with incident rainfall. Woody components such as twigs and branches appear to contribute to throughfall enrichment; hence controlled experiments would be useful to assess ion leaching from leafless branches.

The impact of heterogeneous nutrient and volume input via throughfall and stemflow is understudied for deciduous species. More research is needed to assess the influence and ecological consequences of time persistent throughfall fluxes on forest floor and soil moisture content and microbial processes such as nitrification and mineralization. This could be studied by examining the temporal variation of forest floor N availability during different seasons.

Investigating the spatial patterns at multiple scales on the irregular sampling schemes obtained in Chapter 5, by applying PCNM approach. In recent years, researchers have increased their awareness of the fact that ecological processes occur at defined scales, and that their perception depends upon a proper matching of the sampling strategy to the size, grain and extent of the study, and the statistical tools used to analyse the data. Understanding how PCNM will behave under irregular sampling intervals will help us design future studies. Borcard et al. (2004) provided an approach

for irregular sampling designs that is based on filling the voids, then after obtaining PCNM variables, the supplementary objects were removed from the matrix of PCNM variables. This approach could be attempted on some of the schemes obtained in Chapter 5 and results could be compared with PCNM findings in Chapter 4.

Sampling design optimization was examined for one bigleaf maple plot. The results are only relevant to the plot under investigation. Before any generalizations can be made, i.e. as regards optimal sampling strategies for detecting the influence of a single tree on soil properties in a mixed stand, similar investigations would be needed on more tree species. Nevertheless, the information presented in the present study should provide a reasonable indication of the intensity and the pattern of sampling that would be necessary to encompass the spatial variability of the forest floor. Cokriging showed that the accuracy of forest floor NH_4 mapping could be improved by using pH as a secondary covariate. Future studies could assess coKriging accuracy with a smaller sample size of forest floor pH. In addition, the temporal stability of forest floor variables such as NH_4 could be examined.

This detailed examination of nutrient input through various tree processes and their spatial and temporal variation in bigleaf maple and coniferous plots would enable researchers to better predict and understand changes at the stand scale. Previous studies reported a potential positive role of several commonly occurring deciduous trees, including vine maple, and black cottonwood, in the Pacific Northwest (Rhoades & Binkley, 1992; Prescott, et al., 2000; Turk et al., 2008; Sabau et al., 2010). In addition, the abundance, ground cover, and/or gross volume of each species are documented (Peterson et al., 1999). A stand scale model can be developed to compute total nutrient input from deciduous trees in a mixed stand of a coastal forest in British Columbia.

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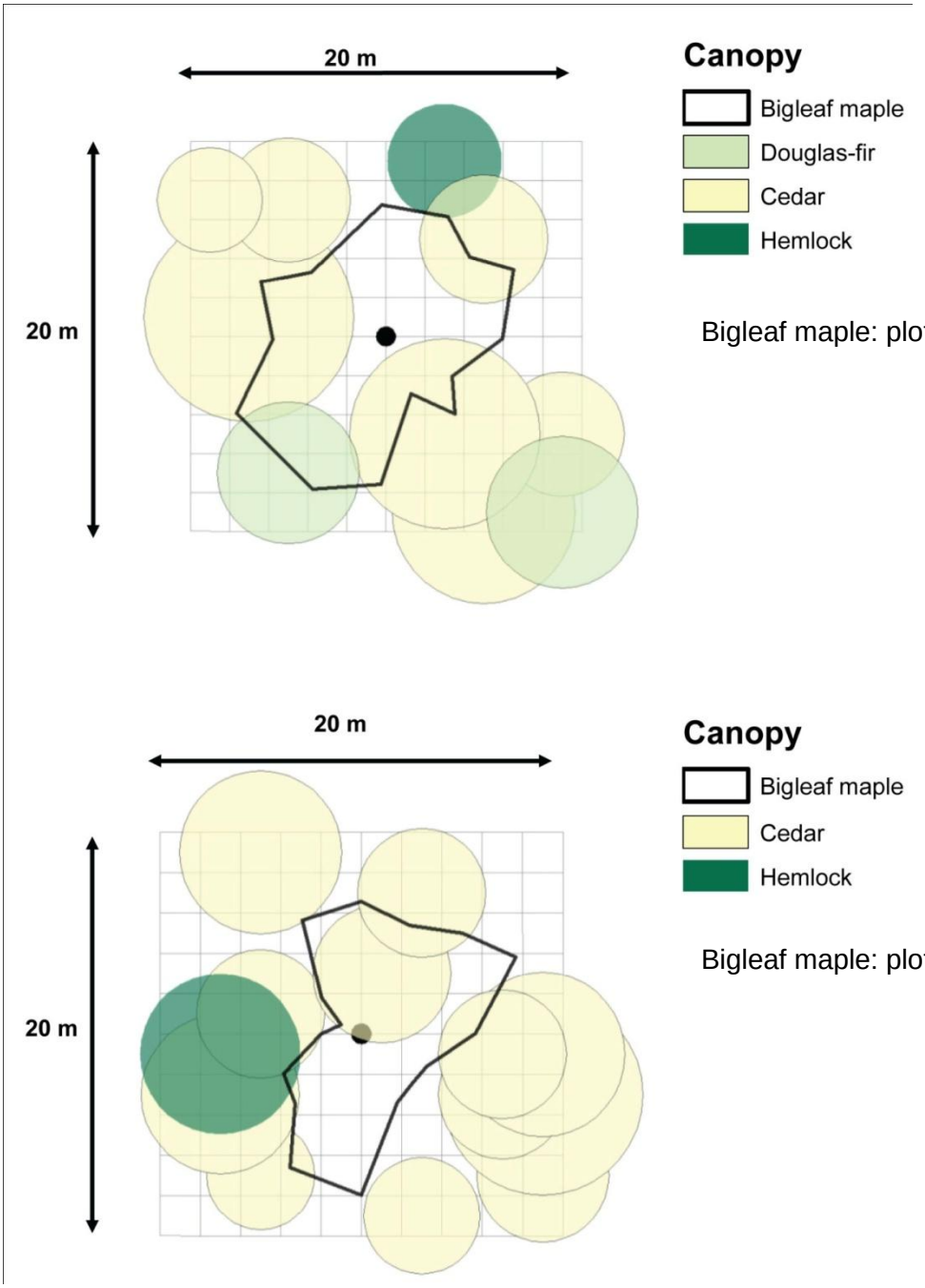
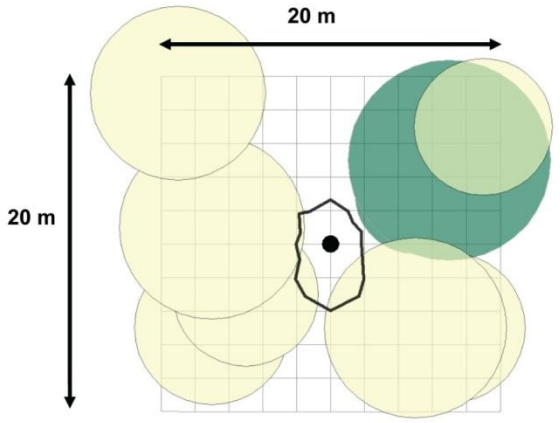
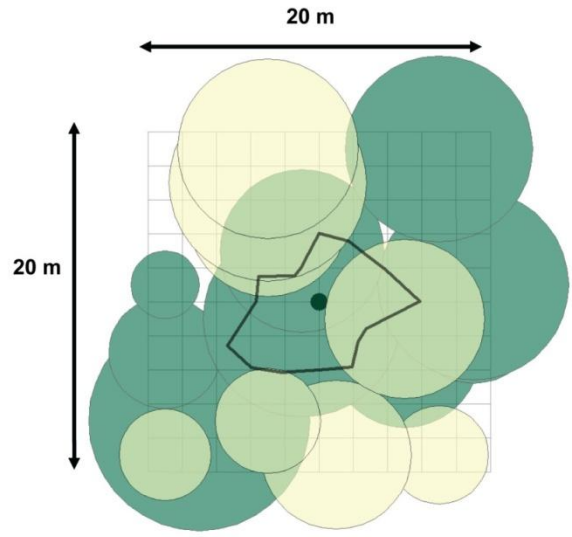
Appendices

Appendix A. Canopy extent of trees on bigleaf maple, and western hemlock plots. A single central tree is located at the center of each 20 m X 20 m plot (canopy outlined by a solid black line).



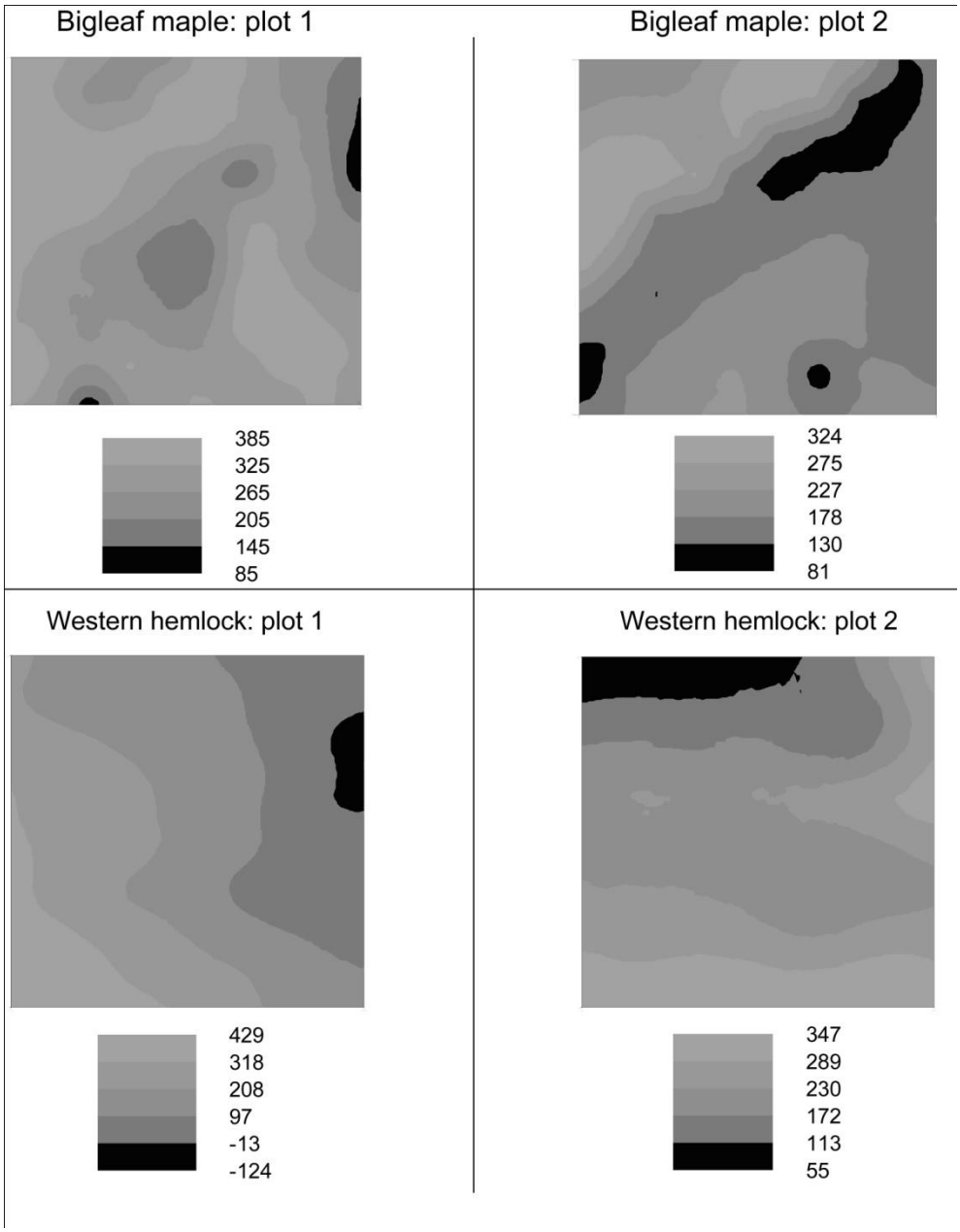


Western hemlock: plot 1

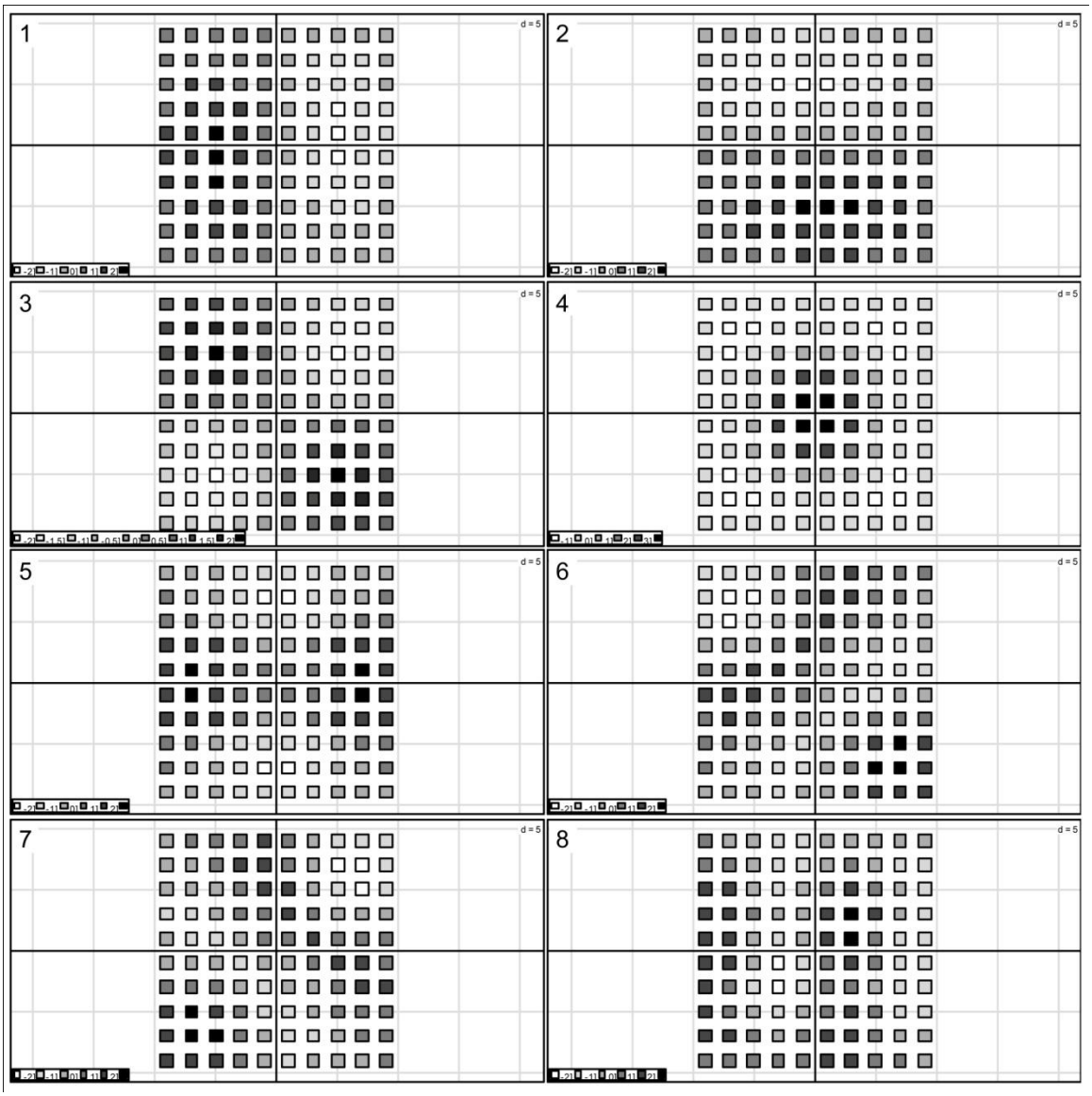


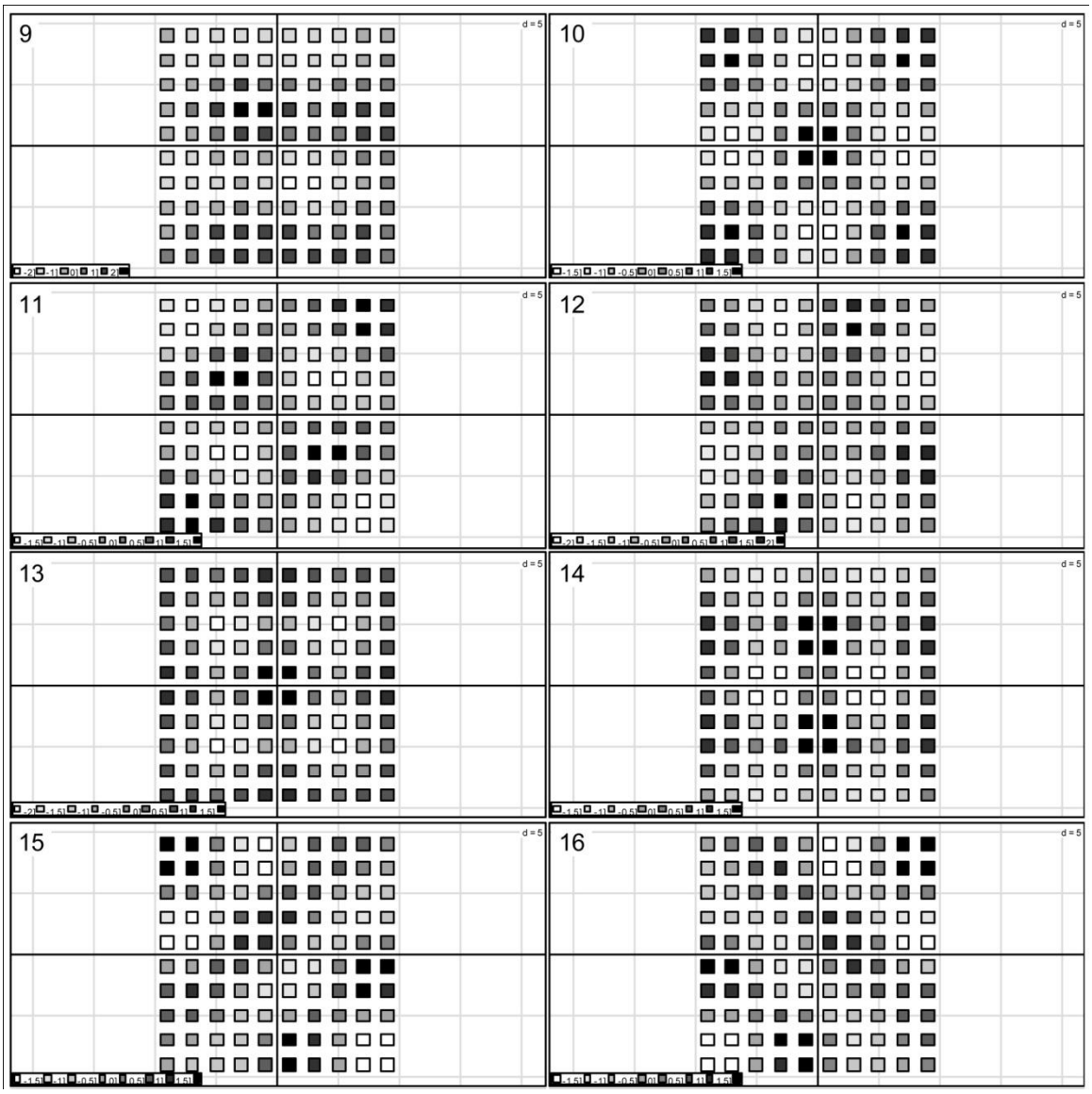
Western hemlock: plot 2

Appendix B. Topographic maps of bigleaf maple and western hemlock plots. The maps are based on the relative elevation (cm) at each sampling point measured to a reference point selected at the edge of the plot.



Appendix C. Multi-scale PCNM variables with positive eignvalues built from a 20 x 20 grid sampling at a 2 m sampling interval. The colour relates to the associated value with black representing highest positive value and white representing lowest negative value.

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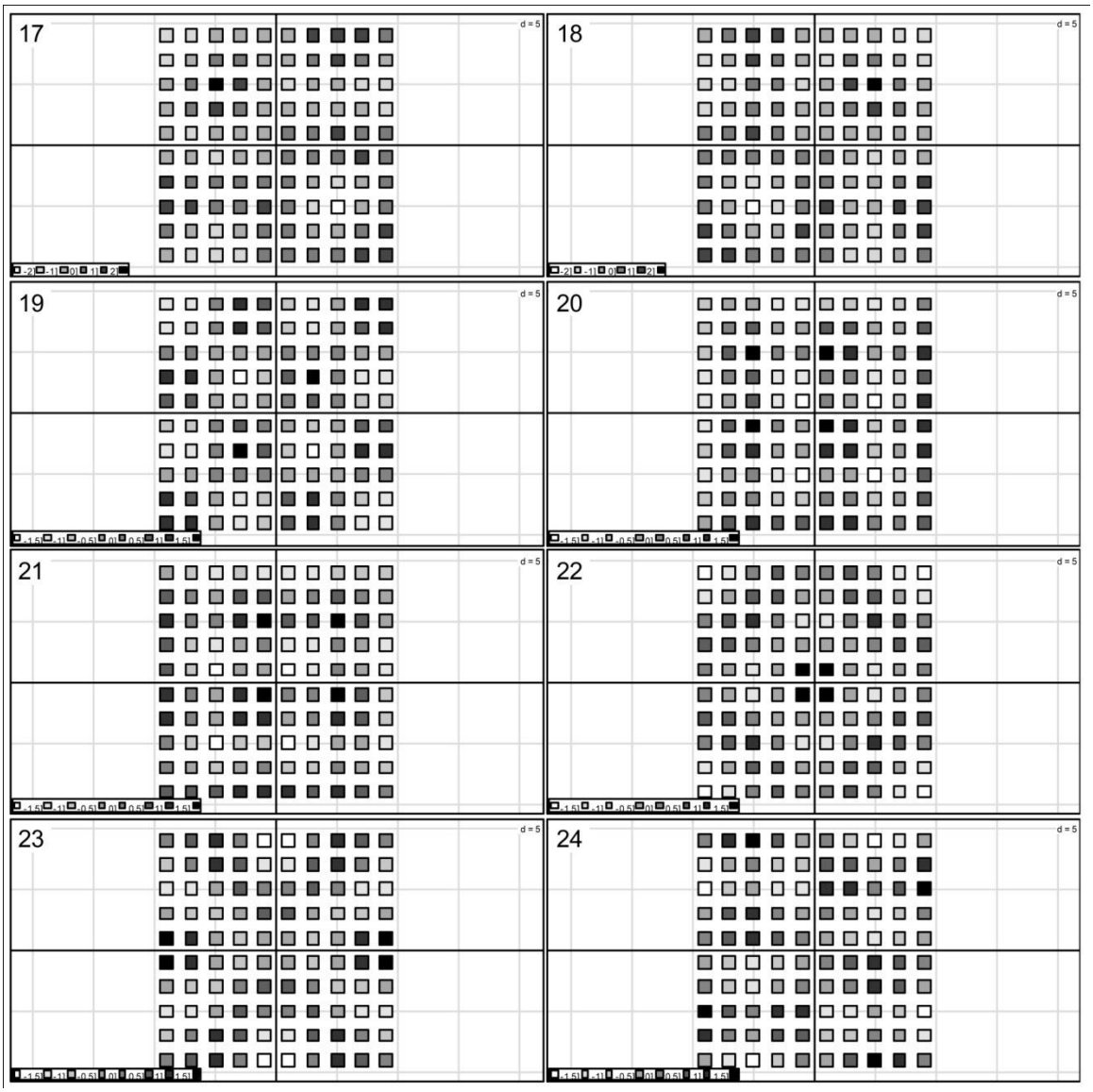
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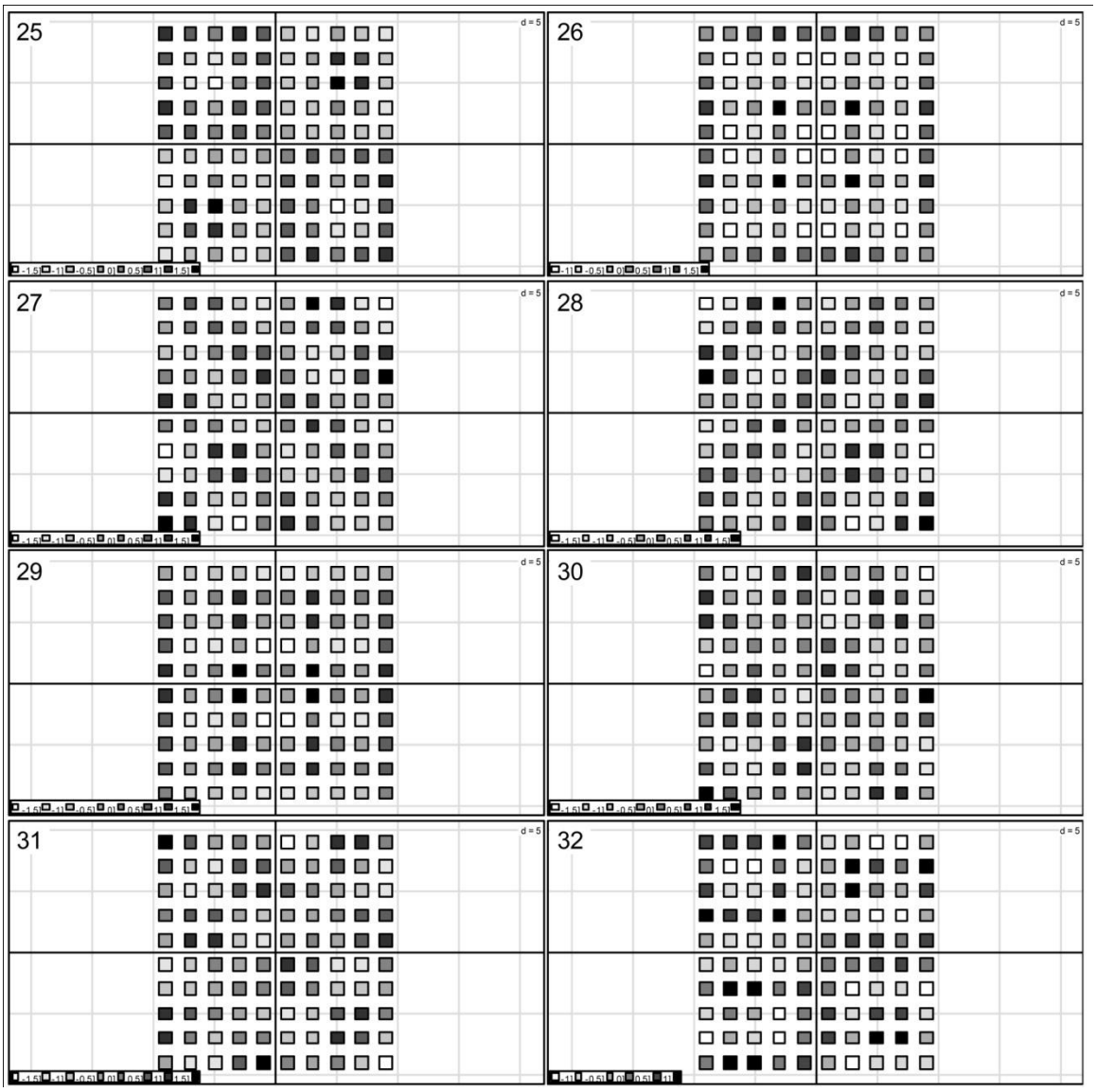
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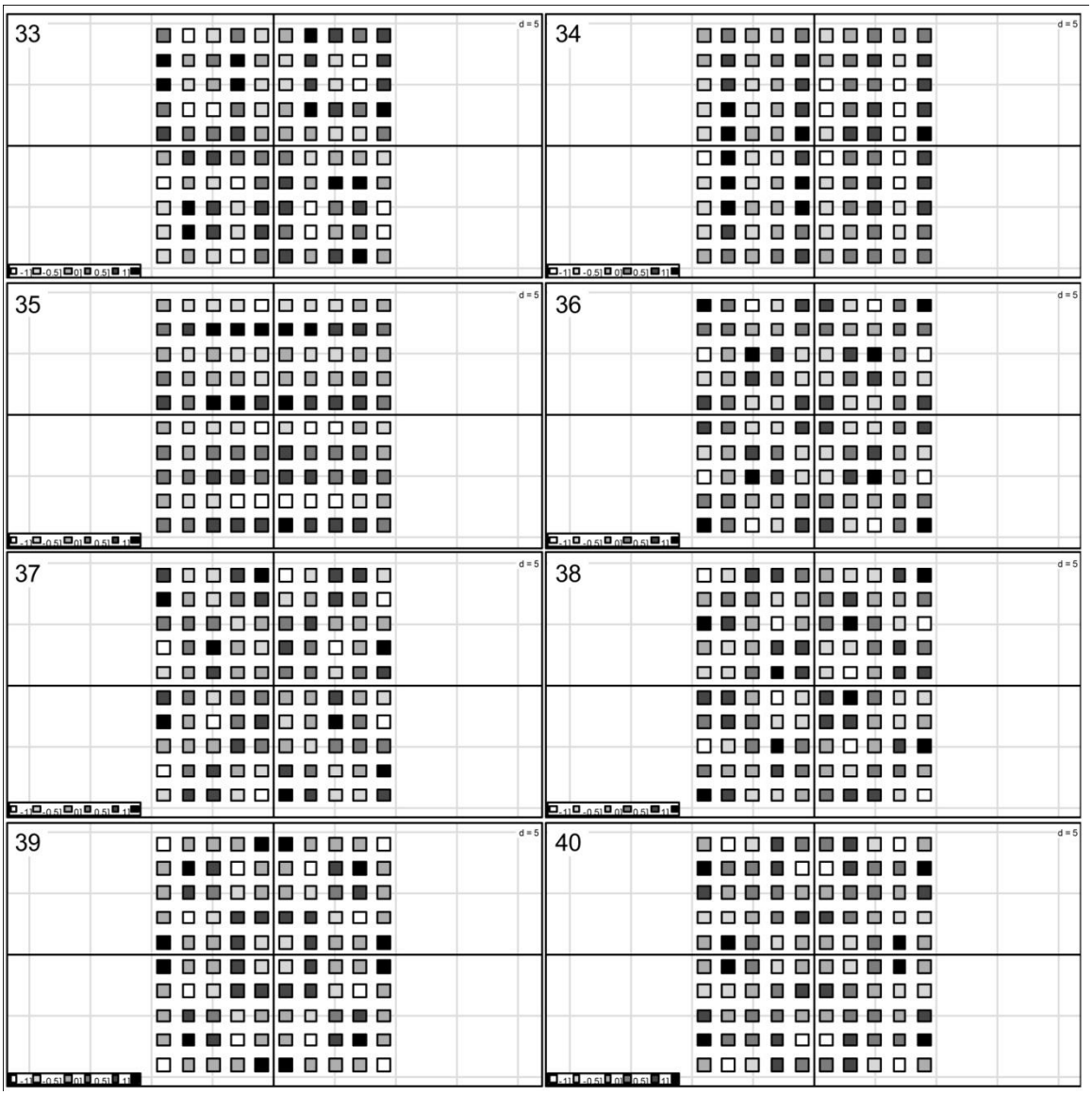
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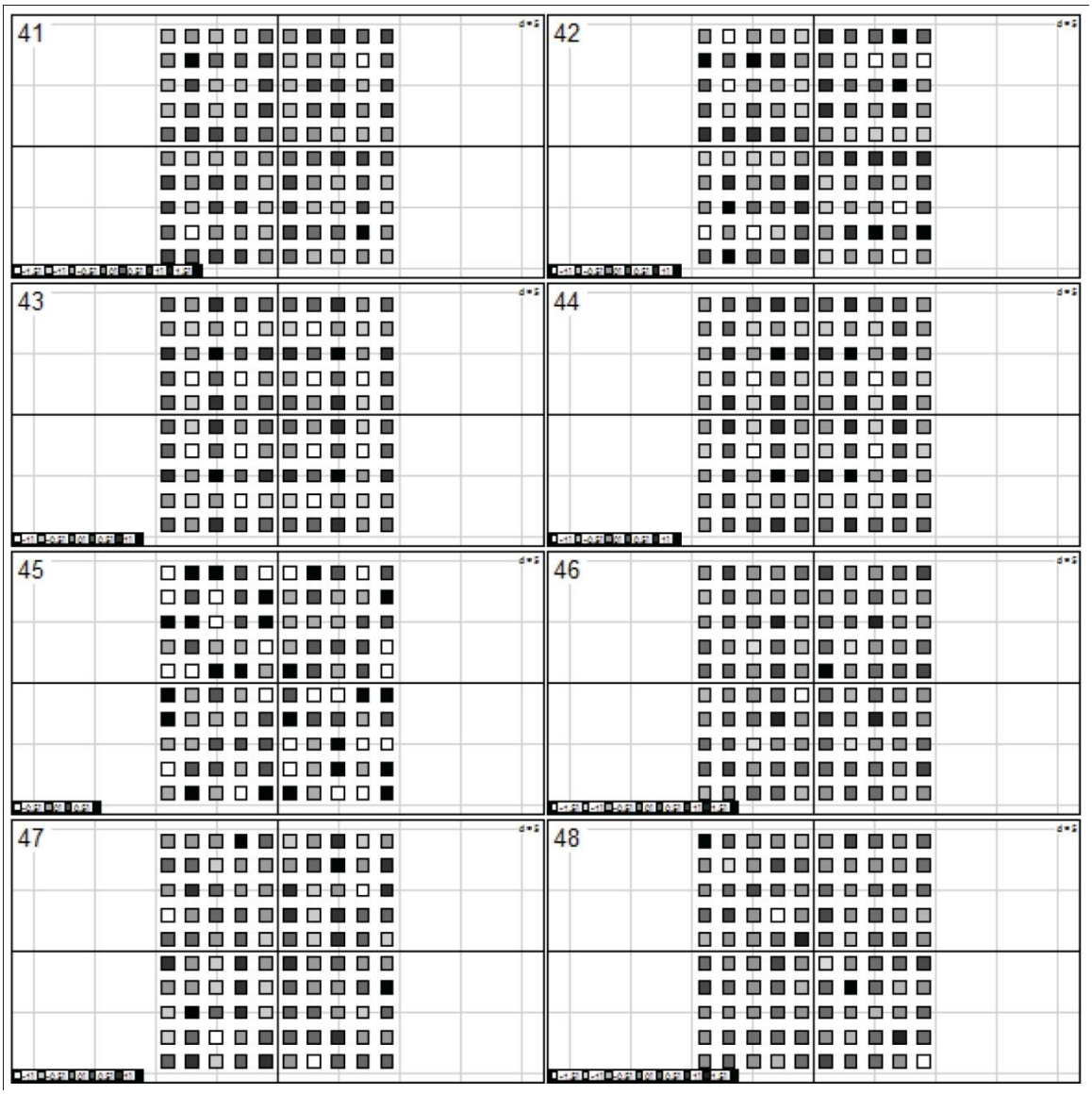
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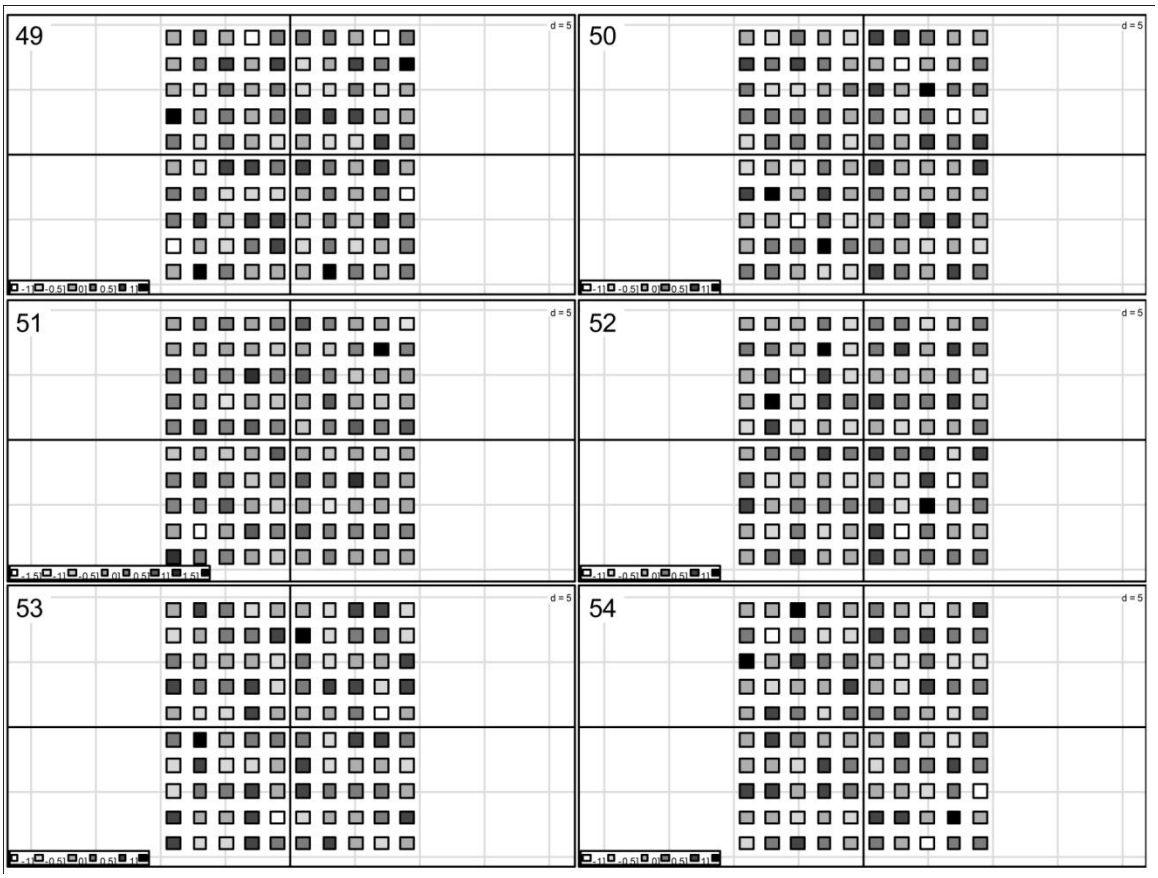
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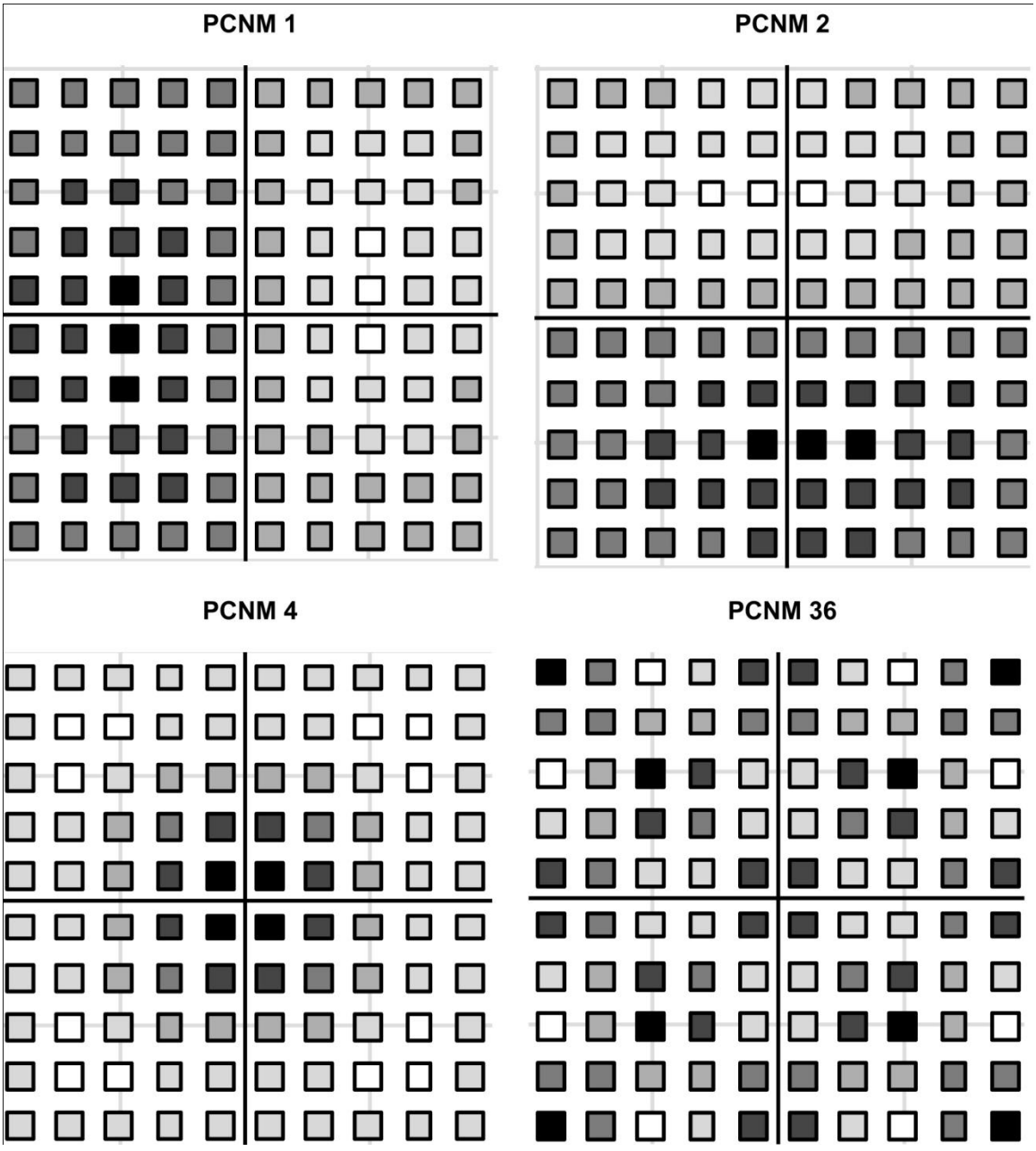
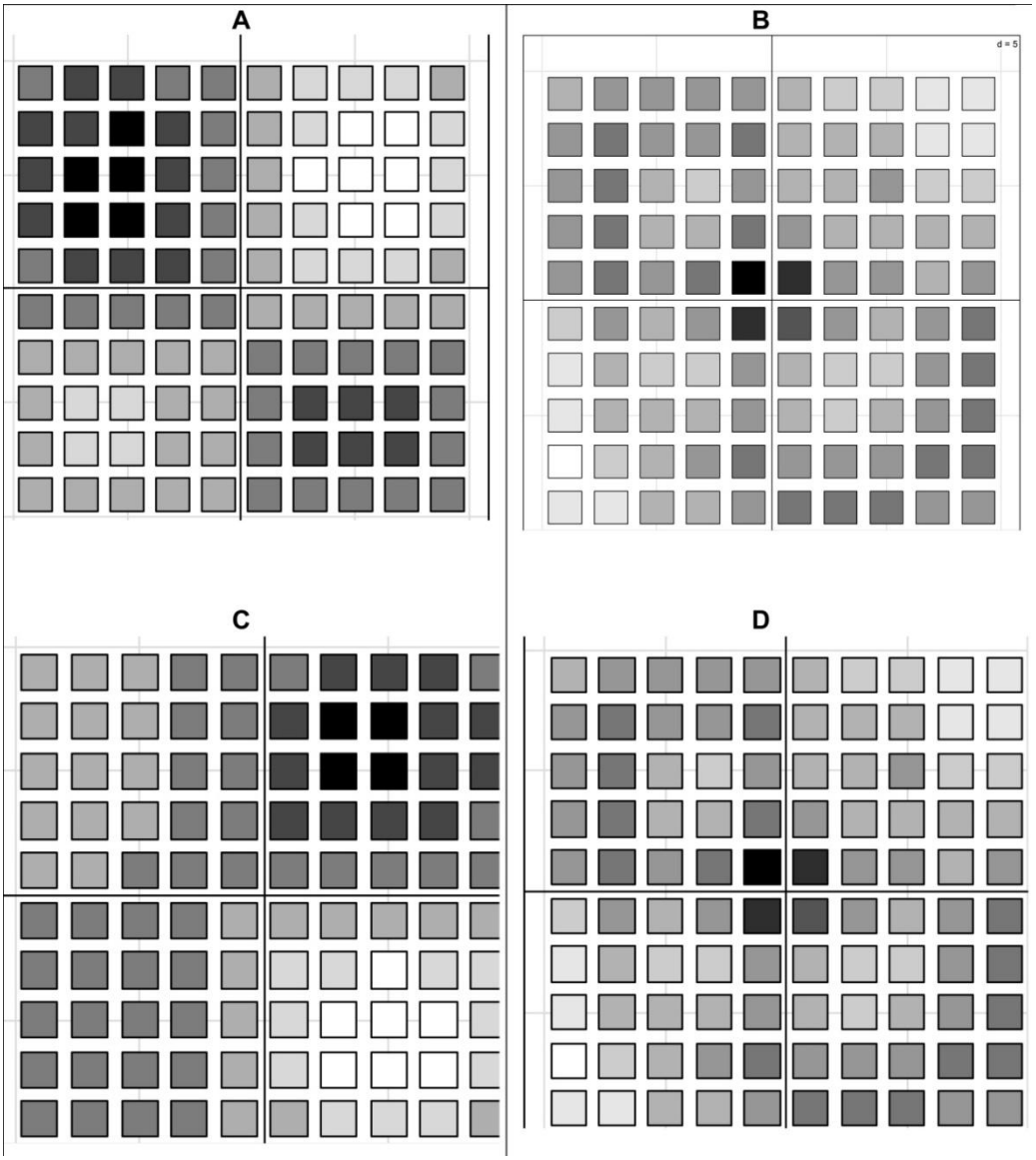
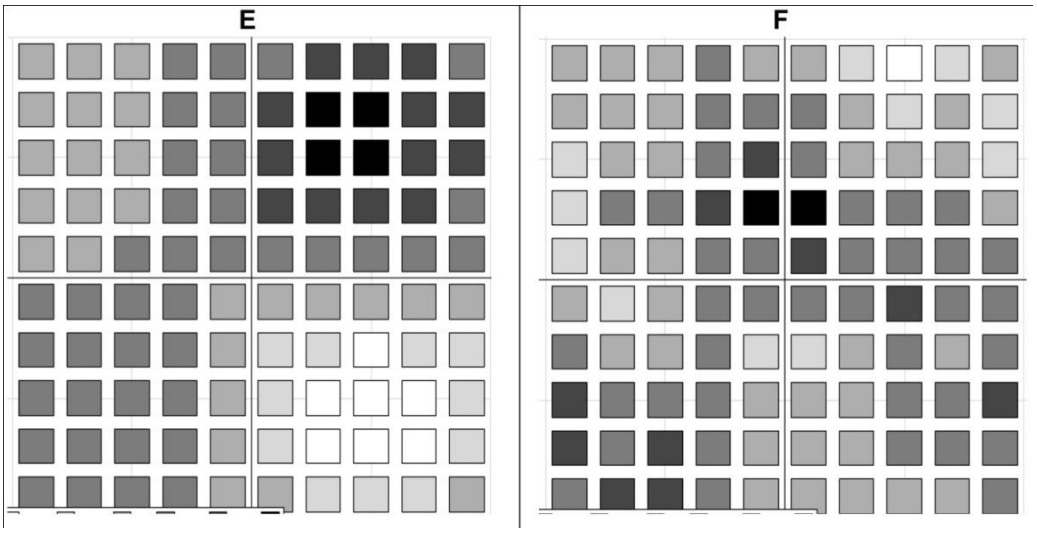
d = 5

Appendix D. Maps of some broad scale PCNM variables (1, and 2), representing the broad spatial structure (8 x8 m^2< patch area) and fine scale PCNM variables (4, and 36), representing the fine spatial structure (patch area ≤ 8 x 8 m^2). Black represents highest positive values and white represents lowest negative values.



Appendix E. Significant canonical axes of the ‘‘fitted site scores’’ ($p < 0.05$) plotted on the sampling location coordinates: (A) bigleaf maple pH: broad sub-model, axis 1; (B) bigleaf maple pH: fine sub-model, axis 1; (C) bigleaf maple NO_3 and NH_4: broad sub-model, axis 1; (D) bigleaf maple NO_3 and NH_4: fine sub-model, axis; (E) western hemlock pH: broad sub-model; (F) western hemlock pH: fine sub-model. Black represents highest positive values and white represents lowest negative values.

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Appendix F. Parameters of the (isotropic spherical) variogram for pH, and NH_4 derived using data for the nine new sample combinations (Fig. 2b–2j) in chapter 5 taken from the original field sampling pattern (Fig. 2a)

Soil property	Sampling design	Model	Nugget variance (Co)	Sill variance (C)	Nug/Sill (%)	C/(Co+C)	Range (m)
pH	(B)	Exponential	0.012	0.28	4.28	0.95	11.82
	(C)	Exponential	0.06	0.27	22.22	0.67	12.22
pH	(b)	Spherical	0.07	0.21	34.20	0.65	13.25
	(c)	Exponential	0.01	0.20	5.05	0.94	7.17
	(d)	Spherical	0.07	0.21	34.63	0.65	8.94
	(e)	Gaussian	0.10	0.26	38.62	0.61	12.12
	(f)	Spherical	0.10	0.23	44.30	0.55	13.08
	(g)	Spherical	0.06	0.25	25.24	0.74	12.75
	(h)	Spherical	0.09	0.25	36.58	0.63	12.27
	(i)	Spherical	0.04	0.13	36.17	0.63	10.73
	(j)	Spherical	0.51	0.25	201.32	0.79	11.01
NH_4	(b)	Gaussian	1460	13970	17.32	0.83	2.44
	(c)	Spherical	2970	21230	13.99	0.86	6.62
	(d)	Spherical	520	5932	8.77	0.91	2.19
	(e)	Spherical	1710	16660	10.26	0.90	2.91
	(f)	Spherical	1390	20400	6.81	0.93	3.10
	(g)	Spherical	3100	21330	14.53	0.86	6.67
	(h)	Spherical	1520	15690	9.69	0.90	2.96
	(i)	Gaussian	800	15520	5.15	0.95	4.82
	(j)	Spherical	1770	19410	9.12	0.91	5.13

Appendix G. Parameters of the (isotropic spherical) variogram for pH, and NH_4 derived using data for the nine new sample combinations (Fig. 2b–2j) in chapter 5 taken from the original field sampling pattern (Fig. 2a)

Rank	Site	δ
1	78	-0.20423
2	91	-0.13416
3	81	-0.11202
4	93	-0.10658
5	61	-0.10623
6	7	-0.10359
7	51	-0.10067
8	27	-0.09424
9	26	-0.08712
10	82	-0.08462
11	58	-0.08108
12	92	-0.08054
13	17	-0.08039
14	15	-0.07111
15	10	-0.06657
16	77	-0.06496
17	62	-0.06278
18	38	-0.06238
19	71	-0.06123
20	29	-0.05996
21	23	-0.05897
22	72	-0.05804
23	25	-0.05615
24	39	-0.04802
25	76	-0.04497
26	18	-0.04353
27	19	-0.04257

Rank	Site	δ
28	20	-0.04069
29	31	-0.04067
30	74	-0.03866
31	8	-0.03577
32	48	-0.02962
33	94	-0.02877
34	63	-0.02821
35	66	-0.02335
36	9	-0.02205
37	41	-0.02058
38	57	-0.02016
39	36	-0.01884
40	68	-0.01869
41	69	-0.01869
42	24	-0.01827
43	89	-0.01047
44	73	-0.00639
45	30	-0.00515
46	43	-0.00356
47	4	-0.00128
48	11	-0.00065
49	87	0.002927
50	21	0.003906
51	44	0.00638
52	5	0.00805
53	1	0.008903
54	52	0.010253
55	64	0.011534
56	53	0.014204
57	90	0.014494
58	79	0.014684
59	22	0.014773
60	28	0.015085

Rank	Site	δ
61	16	0.019025
62	100	0.019287
63	13	0.021011
64	47	0.021017
65	83	0.021578
66	12	0.022417
67	6	0.022566
68	34	0.028879
69	14	0.030728
70	88	0.03337
71	84	0.033412
72	54	0.034004
73	65	0.035324
74	67	0.036511
75	3	0.040528
76	60	0.042859
77	86	0.045133
78	95	0.047645
79	49	0.052395
80	80	0.053904
81	59	0.055377
82	35	0.056498
83	96	0.05832
84	40	0.060165
85	2	0.060602
86	99	0.061674
87	33	0.061838
88	50	0.069849
89	70	0.07021
90	42	0.082246
91	32	0.082804
92	37	0.084944
93	98	0.087051

Rank	Site	δ
94	75	0.099038
95	97	0.101002
96	85	0.104186
97	56	0.1457
98	45	0.153807
99	55	0.208867
100	46	0.217786