

AN ABSTRACT FOR THE DISSERTATION OF

Zane A. Haxton for the degree of Master of Science in Forest Resources presented July 8, 2010.

Title: An examination of several methods of quantifying forest structure in headwater riparian forests of western Oregon.

Abstract approved:

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Temesgen Hailemariam

Headwater streams are generally small, first-order streams that can comprise up to 80% (by stream length) of the drainage network in mountainous areas of the Pacific Northwest. These streams are intimately connected with downstream reaches, serving as a source of sediment, woody debris, organic matter and nutrients. The surrounding forests can strongly influence the ecology of headwater streams by regulating microclimate, influencing nutrient and organic matter cycling process, and providing habitat for wildlife species.

Central to the provision of ecosystem services by these headwater forests is their structure, the three-dimensional arrangement of trees, shrubs, snags and down wood in space. This thesis explored several methods of quantifying forest structure in headwater riparian forests of western Oregon.

N-tree distance sampling, a sampling method where the nearest n trees to a sample point are measured, was compared with fixed plot and variable plot sampling for estimation of density and basal area in a simulation study using stem-mapped data taken from 8 headwater sites across western Oregon. In general, variable plot sampling gave the best statistical performance for estimation of basal area, while fixed plot sampling gave the best statistical performance for estimation of density. While n-

tree distance sampling gave reasonable performance on some stem maps, the sampling method performed poorly for estimating density of populations with a clumped spatial pattern. Relative root mean square error of the best n-tree distance sampling estimator was up to 75% higher than for fixed plot sampling under these conditions.

Neighborhood-based indices are a set of diversity measures that are based on the relationship between a reference tree and a certain number of nearest neighbors (i.e. trees to which it has the lowest horizontal distance). I compared the bias and relative root mean square error of several different methods of choosing reference trees for neighborhood-based index calculation, using stem-mapped data from the same 8 headwater sites. The selection of a random tree from a fixed plot gave the lowest absolute relative bias, but results with this method were quite variable, with relative root mean square error ranging from 33-67% for the species mingling index and 21-25% for the diameter differentiation index. The nearest-tree (selection of the nearest tree to the sample point) and azimuth (selection of the first tree from north in a fixed plot) methods were biased, but had lower variability, with relative root mean square error ranging from 31-64% for the species mingling index and 18-22% for the diameter differentiation index. The variable plot method gave highly variable results for all species combined, but performed well for some individual species.

I close with an exploration of the use of measures of forest structure in characterizing the Trask Watershed, located in the headwaters of the northern Oregon Coast Range. The structure of the Trask Watershed is essentially even-aged, having regenerated in the aftermath of the Tillamook Burn. Douglas-fir and red alder are the most prevalent species, with western hemlock, western redcedar and noble fir locally abundant. While neighborhood-based indices were somewhat informative, they offered an impoverished picture of structural diversity in the Trask Watershed by ignoring the contribution made by tall shrubs such as vine maple and western hazelnut.

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An examination of several methods of quantifying forest structure in headwater  
riparian forests of western Oregon

by  
Zane A. Haxton

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I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

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Zane A. Haxton, Author

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## CONTRIBUTIONS OF AUTHORS

The stem-map data I used in Chapters 2 and 3 were collected by Theresa Marquardt. Dr. Temesgen Hailemariam provided extensive input on Chapters 2, 3 and 4. Dr. Bianca Eskelson provided professional expertise and logistical support to the sampling effort that is summarized in Chapter 4 and also assisted with the literature review on neighborhood-based indices that is presented in Chapters 3 and 4.

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## LIST OF SYMBOLS USED IN THE TEXT

| <u>Symbol</u> | <u>Definition</u>                              | <u>Units</u>       |
|---------------|--|--------------------|
| %CON          | Percent of total basal area in conifer species | %                  |
| BAF           | Basal area factor                              | m <sup>2</sup> /ha |
| BL13          | Bottom Line 13 (site)                          | -                  |
| CV            | Coefficient of variation                       | %                  |
| DBH           | Diameter at breast height                      | cm                 |
| DM            | Species mingling                               | -                  |
| G             | Basal area                                     | m <sup>2</sup> /ha |
| GS1           | Gus Creek 1 (site)                             | -                  |
| GS3           | Gus Creek 3 (site)                             | -                  |
| KM17          | Keel Mountain 17 (site)                        | -                  |
| KM18          | Keel Mountain 18 (site)                        | -                  |
| KM19          | Keel Mountain 19 (site)                        | -                  |
| KM21          | Keel Mountain 21 (site)                        | -                  |
| N             | Tree density                                   | trees/ha           |
| NTDS          | N-tree distance sampling                       | -                  |
| OM36          | O. M. Hubbard 36 (site)                        | -                  |
| PH2           | Pothole Creek 2 (site)                         | -                  |
| PH3           | Pothole Creek 3 (site)                         | -                  |
| PH4           | Pothole Creek 4 (site)                         | -                  |
| RK2           | Rock Creek 2 (site)                            | -                  |
| RK3           | Rock Creek 3 (site)                            | -                  |
| RRMSE         | Relative root mean square error                | %                  |
| TD            | Diameter differentiation                       | -                  |
| TH46          | Ten High 46 (site)                             | -                  |
| TH75          | Ten High 75 (site)                             | -                  |
| U             | Diameter dominance                             | -                  |
| UM3           | Upper Mainstem 3 (site)                        | -                  |
| VBA           | Visual Basic for Applications                  | -                  |

## LIST OF SPECIES

| <u>Common name</u> | <u>Scientific name</u>          |
|--------------------|---------------------------------|
| bigleaf maple      | <i>Acer macrophyllum</i>        |
| bitter cherry      | <i>Prunus emarginata</i>        |
| black cottonwood   | <i>Populus trichocarpa</i>      |
| bleeding heart     | <i>dicentra formosa</i>         |
| bracken fern       | <i>Pteridium aquilinum</i>      |
| Bunchberry         | <i>Cornus canadensis</i>        |
| Cascara            | <i>Rhamnus purshiana</i>        |
| deer fern          | <i>Blechnum spicant</i>         |
| devil's club       | <i>Oplopanax horridus</i>       |
| Douglas-fir        | <i>Pseudotsuga menziesii</i>    |
| dwarf Oregon-grape | <i>Berberis nervosa</i>         |
| Elderberry         | <i>Sambucus racemosa</i>        |
| false huckleberry  | <i>Menziesia ferruginea</i>     |
| field mint         | <i>Mentha arvensis</i>          |
| Foamflower         | <i>Tiarella trifoliata</i>      |
| Fringecup          | <i>Tellima grandiflora</i>      |
| golden chinquapin  | <i>Castanopsis chrysophylla</i> |
| grand fir          | <i>Abies grandis</i>            |
| Indian plum        | <i>Oemleria cerasiformis</i>    |
| inside-out flower  | <i>Vancouveria hexandra</i>     |
| lady fern          | <i>Athyrium filix-femina</i>    |
| maidenhair fern    | <i>Adiantum pedantum</i>        |
| Oceanspray         | <i>Holodiscus discolor</i>      |
| Pacific dogwood    | <i>Cornus nuttallii</i>         |
| Pacific yew        | <i>Taxus brevifolia</i>         |
| palmate coltsfoot  | <i>Petasites palmatus</i>       |
| piggyback plant    | <i>Tolmiea menziesii</i>        |
| red alder          | <i>Alnus rubra</i>              |
| red huckleberry    | <i>Vaccinium parvifolium</i>    |
| redwood-sorrel     | <i>Oxalis oregana</i>           |
| robert geranium    | <i>Geranium robertianum</i>     |
| Salal              | <i>Gaultheria shallon</i>       |



LIST OF SPECIES (Continued)

| <u>Common name</u>                 | <u>Scientific name</u>       |
|------------------------------------|------------------------------|
| Salmonberry                        | <i>Rubus spectabilis</i>     |
| Siberian miner's-lettuce           | <i>Claytonia siberica</i>    |
| skunk cabbage                      | <i>Lysichiton americanum</i> |
| Snowberry                          | <i>Symphoricarpus albus</i>  |
| spiny wood fern                    | <i>Dryopteris expansa</i>    |
| star-flowered false Solomon's-seal | <i>Smilacina stellata</i>    |
| sword fern                         | <i>Polystichum munitum</i>   |
| Thimbleberry                       | <i>Rubus parviflorus</i>     |
| trailing blackberry                | <i>Rubus ursinus</i>         |
| vanilla leaf                       | <i>Achlys triphylla</i>      |
| vine maple                         | <i>Acer circinatum</i>       |
| western hazelnut                   | <i>Corylus cornuta</i>       |
| western hemlock                    | <i>Tsuga heterophylla</i>    |
| western redcedar                   | <i>Thuja plicata</i>         |
| western trillium                   | <i>Trillium ovatum</i>       |
| wild cucumber                      | <i>Marah oreganus</i>        |
| wild ginger                        | <i>Asarum caudatum</i>       |
| wild rose                          | <i>Rosa spp.</i>             |

## DEDICATION

This work is dedicated to my mother, who would have liked to see its completion.

# AN EXAMINATION OF SEVERAL METHODS OF QUANTIFYING FOREST STRUCTURE IN HEADWATER RIPARIAN FORESTS OF WESTERN OREGON

## CHAPTER ONE

### INTRODUCTION

#### **Riparian forests of the Oregon Coast Range**

Riparian zones are “the interfaces between terrestrial and aquatic ecosystems... they encompass sharp gradients of environmental factors, ecological processes, and plant communities” (Gregory et al. 1991). In the Pacific Northwest, riparian ecosystems are an important component of the forested landscape, regulating stream microclimate (Brosofske et al. 1997; Moore et al. 2005), influencing nutrient and organic matter cycling processes (Triska et al. 1984; Richardson et al. 2007), and containing a high diversity of flora (Pollock et al. 1998; Gregory et al. 1991) and fauna (Olson et al. 2007; McComb et al. 1993; Gomez 1992). These riparian systems are also intimately linked with the life cycle of the Pacific salmon (Beechie and Sibley 1997), many subspecies of which are currently at critical risk of extinction (Nehlsen et al. 1991).

Interest in conservation and management of riparian forests in the Pacific Northwest has increased significantly in recent decades (Naiman et al. 2000). However, we continue to lack knowledge of the composition and function of many riparian forests. Forest managers wishing to restore or conserve natural (or “presettlement”) conditions are hampered by a lack of baseline knowledge of the species composition and structure of riparian forests prior to Euro-American settlement (Nierenberg and Hibbs 2000).

In the absence of scientific data, riparian forest management can be marked by controversy, such as on the appropriate role of red alder in riparian forests of the

northern Oregon Coast Range. An aggressive early-seral species favored by mineral soil disturbance (Newton and Cole 1994), red alder commonly dominates streamside areas. Widespread empirical evidence indicates that many of these red alder stands developed after early logging of large conifers in riparian areas (Hayes et al. 1996; Newton and Cole 1994). This evidence has informed the generally-accepted vision of presettlement riparian forests as having been dominated by large conifers, with a minimal hardwood component. This viewpoint has been strengthened by the recognition that large conifers provide streams with large, durable coarse woody debris, an important structural feature for fish habitat (Bilby and Bisson 2001; Harmon et al. 1986). Therefore, it has been suggested that conversion of hardwood stands (generally dominated by red alder) to conifer dominance is a legitimate silvicultural activity where “restoration” or “enhancement” of riparian habitat is a management objective (Newton et al. 1996; Berg 1995).

However, Nierenberg and Hibbs (2000) found that red alder was an important component of the unmanaged riparian forests they sampled, having been retained in the ecosystem through infrequent wildfire and more frequent small-scale disturbances (e.g. mass movement and flooding). They also suggest that conifers may have been widely spaced or patchily distributed, with red alder an important feature of the intervening vegetation. While an important finding, the scope of inference of this discovery was limited to the central Coast Range, with none of their study sites being located north of the Nestucca River or south of the Umpqua River.

In a more broadly-defined study encompassing unmanaged riparian forests in the central, north-central and southern Oregon Cascade Range, Pabst and Spies (1999) found a trend of increasing conifer abundance with distance from a stream, with hardwood abundance generally remaining constant within the first 48m from the stream. They found this trend to be similar across all stream orders. However, they acknowledge that the sites they studied may not be representative of all presettlement riparian forests, since their study sites were not a randomly selected sample of all

possible unmanaged riparian forest sites, nor could they be certain that the forests they sampled represented the full range of riparian forest conditions that existed prior to Euro-American settlement.

For a more complete picture of riparian forest dynamics, not only in unmanaged areas but in forests that exist as part of a managed landscape, there is a need for the development or identification of efficient methods of characterizing riparian forests that can be easily integrated into existing inventory programs. The implementation and analysis of these methods will be closely tied to the concept of forest structure.

### **Forest structure: a “key to the ecosystem”**

Forest structure is defined by Franklin et al. (2002) as “the variety of individual structures, such as trees, snags, and logs of various sizes and conditions, and the spatial arrangement of these structures, such as whether they are uniformly spaced or clumped.” The authors differentiate structure from function (the “work” carried out by an ecosystem) and composition (the variety and proportion of species present), and note that the importance of forest structure is increasingly recognized because, unlike the other two attributes, forest structure can be readily manipulated by managers. Because forest structure is so important, Spies (1998) has termed it a “key to the ecosystem”, a key to unlocking “an understanding of the history, function, and future of a forest ecosystem”.

The maintenance or creation of certain forest structures is increasingly considered an objective, rather than a byproduct, of forest management. As a local example, the Oregon Department of Forestry Northwest State Forests Management Plan specifies that a certain percentage of the land base be allocated each to one of five “stand structure types”, ranging from regeneration to older forest, in perpetuity (ODF 2001).

While forest structure is a useful concept, it is also inherently nebulous and impossible to quantify directly. Because things that cannot be quantified cannot be measured, a large body of research has been dedicated to the development of measures of forest structure (McElhinny et al. 2005). However, the unique application of these measures of forest structure to riparian forests has not yet been extensively studied.

### **Characterizing structure of riparian forests**

Most forested stream systems exhibit change in the composition and structure of adjoining forest ecosystems across two gradients: latitudinal (from streambed to ridgetop) and longitudinal (from the stream's confluence with a larger stream to its beginnings in the headwaters). These gradients are generally discernable over very different scales. Latitudinal change (typified in many parts of the Oregon Coast Range by a gradual or abrupt increase in the abundance of conifer trees with increasing distance from the stream bank) may be obvious at the scale of a few meters. However, longitudinal change (such as the gradual replacement of a hardwood-dominated streamside forest in the broad floodplain of a large stream by a conifer-dominated forest as you move towards the headwaters) may only be discernable over hundreds of meters of stream length.

Because riparian forests are so dynamic, many of the unique challenges associated with riparian monitoring consist of characterizing change throughout these systems. Therefore, point measures (measures that can be summarized in a single number per sample point) are considered to be preferable for characterizing riparian forest structure. The focus of this thesis is on evaluating different point measures and sampling methods for characterizing riparian forest structure.

Chapter 2 assesses the performance of n-tree distance sampling for estimating density and basal area in riparian forests. Chapter 3 evaluates the performance of several different sampling methods for estimating innovative indices of forest

structure. Chapter 4 offers a full characterization of the headwater sites sampled in the Trask Watershed. Finally, Chapter 5 summarizes the key findings of this study and offers some concluding thoughts regarding future challenges and opportunities in riparian forest inventory and monitoring.

*Note*

All species names given in this thesis are common names. See the List of Species for common and scientific names of all species mentioned in this thesis.

## CHAPTER TWO

### THE PERFORMANCE OF N-TREE-DISTANCE SAMPLING FOR ESTIMATING BASAL AREA AND DENSITY IN HEADWATER RIPARIAN FORESTS OF WESTERN OREGON

#### **Introduction**

Tentatively defined by Danehy and Ice (2007) as streams with “an average annual streamflow less than 2 cubic feet per second”, headwater streams feed larger, higher order streams and can comprise up to 80% of stream length in mountainous areas of the Pacific Northwest. These systems are intimately connected with downstream reaches, serving as a source of sediment, woody debris, organic matter and nutrients (MacDonald and Coe 2007). Forests adjoining non-fish-bearing (Type N) streams in western Oregon receive no legal protection from timber harvest (Adams 2007). Therefore, forest managers have the opportunity – and responsibility – to actively manage headwater riparian systems for a variety of wildlife habitat, watershed protection, and fiber production objectives.

Accurate and efficient estimation of stem density and basal area of trees on an area basis can be crucial to the success of active restoration or management programs in forests adjacent to headwater streams. Stem density is probably one of the most easily understood metrics used in forest inventory. It can be measured with a simple count of trees present on a fixed plot. Because it contains no information about relative tree sizes, it is of little use as a summary statistic in stands where tree size is highly variable. However, when all trees are approximately the same size, or when a particular size class is being referred to, it is a useful indicator of abundance. In a survey of second-growth riparian forest present in buffer strips in the Oregon Coast Range, Hibbs and Bower (2001) used a relative density metric (expressed as the proportion of the number of trees of a given species on a plot to the total number of



trees on the plot) to describe abundance of tree species. Because it is useful when all trees are the same size, it has also been used to quantify abundance of tree regeneration in studies of riparian areas (Pabst and Spies 1999; Nierenberg and Hibbs 2000; Hibbs and Bower 2001).

Basal area has been frequently used in the ecological literature to characterize riparian forest structure in western Oregon (Pabst and Spies 1999; Hibbs and Giordano 1996; Hibbs and Bower 2001). It can be measured with a simple count of trees using a Relaskope or prism, and it is a good measure of site occupancy since it incorporates information on both the abundance and quadratic mean diameter (QMD) of trees in one convenient metric, as shown below:

$$[2.1] \quad G = N * \left( \frac{\pi}{40,000} \right) * D_Q^2$$

where  $G$  is basal area per hectare,  $N$  is trees per hectare,  $\pi$  is the geometric constant and  $D_Q$  is the QMD (the diameter of the tree with average basal area).

In addition, sapwood basal area (the cross-sectional area of a tree stem that is covered in sapwood) has been shown to have a good relationship with leaf-area index for Douglas-fir (Marshall and Waring 1986), although the relationship between leaf area index and total basal area may be considerably weaker.

When precise estimates of tree density and basal area are desired, a number of alternative sampling techniques are possible. Circular fixed plot sampling, where every tree has an equal probability of selection, is a straightforward and commonly used approach for estimating a wide variety of forest attributes. Variable plot sampling, where the probability of selection for each tree is proportional to its basal area, is frequently used for timber cruising applications. In general, fixed plots are considered more efficient (that is, yielding a higher precision per unit of effort) for estimating density, while variable plot sampling is considered more efficient for providing estimates of volume and basal area (see Scott and Alegria 1990 for one

example). However, local conditions may override these general truisms. In rugged terrain of the Pacific Northwest, for example, the ease with which slope correction can be handled with the use of a Relaskope may make variable plot sampling the most efficient system where fixed plot sampling would be the system of choice on flatter ground.

N-tree-distance sampling (NTDS), also called k-tree-distance sampling, density-adapted sampling or simply “distance sampling”, is a method whereby the  $n$  trees nearest the sample point are selected ( $n$  being a pre-determined number that stays constant throughout the sampling effort). This approach has two theoretical benefits. First, since all plots contain the same number of trees, empty plots and plots which contain “too many” trees (“too many” being defined relative to the average number of trees desired by the sampler) can be avoided (Kleinn and Vilcko 2006a), thus increasing the consistency of the inventory work. Second, the distance-from-point information acquired for each tree as a byproduct of this system can be used to estimate parameters of the spatial distribution of trees within the forest (Lessard et al. 1994).

One important drawback of NTDS is that, unlike fixed plot sampling and variable plot sampling, selection probabilities of individual trees cannot be known unless many additional trees are sampled (Schreuder 2004). Therefore, general unbiased estimators using NTDS (as it is currently practiced) do not exist. An uncorrected method of expanding NTDS estimates to a per-area basis would be to use as the expansion factor the circular plot area that would just barely contain the  $n$ th tree. An estimator for density would be:

$$[2.2] \quad N_U = \frac{1}{m} \sum_{i=1}^m \left[ \frac{n}{A_i} \right]$$

where  $A_i = \pi(r_i^2/10,000)$  is the area of plot  $i$ ,  $r_i$  is the distance to tree  $n$  on plot  $i$ ,  $m$  is the number of plots and  $\pi$  is the geometric constant.

An estimator for basal area would be:

$$[2.3] \quad G_U = \frac{1}{m} \sum_{i=1}^m \left[ \frac{\sum_{j=1}^n g_j}{A_i} \right]$$

where  $g_j$  is the basal area of the  $j$ th tree.

Equations 2.2 and 2.3 extend the theory of fixed plot sampling to the special case where a circular plot is constructed such that the  $n$ th farthest tree from plot center is exactly borderline (i.e. on the thin line between being “in” or “out”). Because this situation rarely occurs in real-world applications of fixed plot sampling, we know intuitively that the plot size used by these naïve equations will almost always be too small, and therefore estimates produced will be too large (Lynch and Wittwer 2003). A large variety of estimators have been proposed to “correct” this bias under an equally large variety of assumptions about the spatial arrangement of trees in the forest type being sampled. Bias-corrected estimators can be classified into two different categories: empirical and model-based (Kleinn and Vilcko 2006a). Empirical estimators refine the naïve plot size with modifications that are rooted in logical intuition, while the model-based approach uses mathematical statistics to derive estimators that can be proven unbiased given some assumptions about the spatial arrangement of tree locations. Representatives of both approaches will be examined here.

A model-based estimator was suggested by Moore (1954) as a design-unbiased estimator when sampling a forest where tree locations are completely random. It was proven unbiased under these conditions by Eberhardt (1967). The estimators for density and basal area, respectively, are (Lessard 1994):

$$[2.4] \quad N_M = \frac{1}{m} \left( \frac{n-1}{n} \right) \sum_{i=1}^m \left[ \frac{n}{A_i} \right]$$

$$[2.5] \quad G_M = \frac{1}{m} \left( \frac{n-1}{n} \right) \sum_{i=1}^m \left[ \frac{\sum_{j=1}^n g_j}{A_i} \right]$$

An empirical estimator developed by Prodan (1968) follows the logic that, since the  $n$ th tree from the sample point is exactly borderline, it should only be counted as a half-tree. The estimators for density and basal area are, respectively (Lynch and Rusydi 1999):

$$[2.6] \quad N_P = \frac{1}{m} \sum_{i=1}^m \left[ \frac{n-0.5}{A_i} \right]$$

$$[2.7] \quad G_P = \frac{1}{m} \sum_{i=1}^m \left[ \frac{\sum_{j=1}^{n-1} g_j + 0.5g_n}{A_i} \right]$$

Finally, Kleinn and Vilcko (2006a) developed an empirical estimator, that requires a distance measurement for the  $(n+1)$ th closest tree to plot center. The logic is that, while a plot size based on the distance to the  $n$ th tree would result in a systematic overestimate, the plot size based on the distance to the  $(n+1)$ th tree would result in too large a plot size and hence, a systematic underestimate. The radius of the unbiased plot size would lie somewhere between these distances. Therefore, the proposed estimator uses a plot sized based on the arithmetic average of the two distances.

$$[2.8] \quad N_K = \frac{1}{m} \sum_{i=1}^m \left[ \frac{n}{Alt_i} \right]$$

$$[2.9] \quad G_K = \frac{1}{m} \sum_{i=1}^m \left[ \frac{\sum_{j=1}^n g_j}{Alt_i} \right]$$

where  $Alt_i = \pi(r_i^2/10,000)$  and

$$[2.10] \quad r_i = \frac{1}{2}(d_n + d_{n+1})$$

where  $d_n$  and  $d_{n+1}$  are the distances to the  $n$ th and “ $n+1$ ”th tree, respectively.

Recent studies have evaluated the performance of these estimators in practical inventory situations. Lessard et al. (1994) compared NTDS with fixed plot sampling and variable plot sampling in Northern Michigan, and found that in naturally regenerated stands the Moore estimator provided estimates of density, basal area, and volume that were fairly similar to those obtained from fixed plot sampling and variable plot sampling. They found that cost efficiency (when data collection time was considered) for NTDS was roughly comparable with that of fixed plot sampling and variable plot sampling. However, the Moore estimator gave downward-biased results for red pine plantations.

Lynch and Rusydi (1999) compared the Moore and Prodan estimators with fixed plot sampling and variable plot sampling in Indonesian teak plantations. They found that, while both gave downward-biased results, the Prodan estimator was the less biased of the two. They suggested that the Prodan estimator may be more appropriate for uniformly-spaced plantations.

Kleinn and Vilcko (2006a) compared the performance of their own estimator against several other NTDS estimators, as well as fixed plot sampling and variable plot sampling, in a simulation study involving a variety of spatial patterns. They found that their estimator was less biased than the Prodan estimator and approximately equivalent to the Moore estimator for random and clustered populations. Their estimator was superior to the Moore for uniform populations. In general, none of the NTDS estimators had better precision than fixed plot sampling for estimating density or variable plot sampling for estimating basal area.

The development of new NTDS estimators is currently an area of active research in Europe (Kleinn et al. 2009; Nothdurft et al. 2010; Magnussen et al. 2008),

and many new estimators have emerged in the last few decades. Unfortunately, many of these estimators are not easy to conceptualize or compute; for a good overview of some particularly esoteric estimators see Magnussen et al. (2008). Working from the assumption that any operationally viable estimator should not require advanced statistical training to understand or compute, nor should it require an excessive number of additional measurements (such as the partial stem-mapping suggested by Kleinn and Vilcko 2006b), I have chosen the estimators used in this study because of their simplicity in understanding and application, as well as the restricted number of measurements they require.

NTDS has a long history as a sampling protocol (see Kleinn and Vilcko 2006a for a good overview), but has not, to my knowledge, been operationally applied for forest inventory in the Pacific Northwest. However, it may be a good candidate system for sampling riparian forests, where tree density and basal area may be highly variable.

While bias from NTDS has been shown to be negligible in some forest types, the performance of NTDS estimators in forest types of this region is unknown. The objective of this study is to evaluate the performance of four selected NTDS estimators, in comparison with fixed plot sampling and variable plot sampling, in a series of stem-mapped plots from an array of headwater riparian forests in the Coast Range and Cascade Mountains of western Oregon.

## **Methods**

### ***Data***

Data were collected as part of the BLM Density Management and Riparian Buffer Study, an interdisciplinary study on the effect of management activities on wildlife habitat and other ecosystem attributes of riparian and upland systems (Cissel et al. 2006). Plots were stem-mapped at eight different sites: Bottom Line 13 (BL13), Keel Mountain 17 (KM17), Keel Mountain 18 (KM18), Keel Mountain 19 (KM19),

Keel Mountain 21, Ten High 46 (TH46), and Ten High 75 (TH75). Each plot comprised an area of 72m x 72m (0.5184 ha) that was centered on a headwater stream. Field procedures for data collection are detailed in Marquardt (2010). Site locations ranged throughout western Oregon, but were concentrated in the central-west and south-west portions of the state. Species composition for each site, by density and basal area, is given in Table 2.1.

Since the performance of different NTDS estimators is dependent on the spatial distribution of trees (Lessard et al. 1994; Lynch and Rusydi 1999), the spatial pattern of tree locations in each site was examined using the Clark-Evans aggregation index (Clark and Evans 1954):

$$[2.11] \quad CE = \frac{\bar{r}_{observed}}{E(r)}$$

where  $\bar{r}_{observed}$  is the observed average of the distances from each tree to its nearest neighbor and  $E(r)$  is the expected value of this average under a random (Poisson) spatial pattern:

$$[2.12] \quad E(r) = \frac{1}{2 * \sqrt{\frac{N}{A}}}$$

where  $N$  is the number of trees and  $A$  is the plot area.

The Clark-Evans index has a minimum value of 0 and a maximum value of 2.1491. An index value closer to 0 indicates regularity, while a value >1 indicates a clustered point process. A value of 1 indicates a perfectly random process. The program SIAFOR (Kint et al. 2004) was used to compute the Clark-Evans index for each site.

As measured by the Clark-Evans index, the spatial pattern was fairly close to random on most sites, with overall index values ranging from 0.96-1.22 (Table 2.2).

However, index values varied substantially by species. Conifer species tended to have index values closer to 1, although western redcedar had an index value far lower than 1 on one site (TH75). Index values for bigleaf maple and red alder were substantially lower than 1.

### *Analysis*

The eight stem maps were used as test populations in the simulation experiments. The Monte Carlo sampling program was written with the Visual Basic for Applications (VBA) v6.5 programming language (Microsoft Corp. 1987). Pseudo-random numbers were generated by VBA such that a different set of numbers was chosen for each simulation run. Each simulation was repeated 2,000 times because at this point results did not seem to be dependent on the particular set of random numbers used.

When performing simulations with stem-mapped plot data, edge correction is necessary in order to ensure that all trees have the appropriate probability of selection. I chose to use toroidal edge correction (see Yamada and Rogerson 2003) because it requires no assumptions about the inclusion probabilities of each tree and does not require the use of a buffer. Toroidal edge correction involves wrapping each plot edge around to the other side so that trees at the plot edge are not underselected relative to trees in the interior of the plot.

To provide comparable performance measures across a variety of stem maps (each with a unique value of density and basal area) and between the different sampling systems, a desired number of trees to be captured per sample point (hereby notated as  $n$ ) was used to determine the fixed plot radius, the variable plot basal area factor (BAF) and the number of trees to sample in NTDS. The fixed plot radius used for each combination was computed as:



$$[2.13] \quad R_{in} = \sqrt{\frac{10,000 * n}{\pi * N_i}}$$

where  $n$  is the desired number of trees per sample point and  $N_i$  is the number of trees per hectare in stand  $i$ .

The variable plot BAF was computed as:

$$[2.14] \quad B_{in} = \frac{G_i}{n}$$

where  $G_i$  is the basal area per hectare in stand  $i$ .

For each repetition of the simulation, four sample points were randomly and independently located on the stem map using the pseudo-random number generator function in VBA. The function returned a pseudo-random number, seeded from the system clock, such that a unique sequence of numbers was used for each run. Each generated number was assigned as the horizontal or vertical coordinate of a sample point, and was used only once.

At each sample point, fixed plot sampling, variable plot sampling and the four variants of NTDS were implemented. For each repetition, the four plot-level estimates were averaged to produce a single estimate for each estimator-attribute combination. For the NTDS estimators, estimates of density and basal area were compiled using Equations 2.2-2.9. For fixed plot sampling and variable plot sampling, estimates were compiled using standard equations that can be found in Avery and Burkhart (2002).

For each estimator-attribute combination, bias and root mean square error were calculated. Relative values were preferred for both statistics because they facilitated comparison between different stem maps and attributes.

The relative bias of each estimator-attribute combination, as a percentage of the known population parameter, was computed as:

$$[2.15] \quad RBias = \frac{\sum_{i=1}^{2,000} [\hat{Y}_i - Y] * 100}{Y * 2,000}$$

where  $\hat{Y}_i$  is the estimate and  $Y$  is the value of the parameter (i.e. the true density or basal area of the stem map).

The relative root mean square error (RRMSE) was computed as:

$$[2.16] \quad RRMSE = \sqrt{\frac{\sum_{i=1}^{2,000} [(\hat{Y}_i - Y)^2]}{2,000}} \left( \frac{100}{Y} \right)$$

The distribution of the estimates was also examined. A sampling method that produces a estimates with a uniform distribution was considered preferable to a method that produces estimates with a skewed distribution. Similarly, a method that produces estimates with a narrow range of relative bias was considered to be preferable to a method that produces estimates with a wide range. The skewness statistic was used to quantify the degree to which the estimates were normally distributed. It was calculated when  $n=6$  for each estimator-site-parameter combination, using the *moments* package for R, v. 0.11 (Komsta and Novometsky 2007). The minimum and maximum relative bias values for each estimator-site-parameter combination, when  $n=6$ , were also considered.

## Results

Results for relative bias and RRMSE will be presented in two formats. Because it is desirable to analyze the performance of estimators across a wide range of choices for  $n$ , results are presented graphically  $n=2, \dots, 10$ . So that subtle differences between estimators, which may not be apparent from the graphical display, may be considered, results are also presented in tabular format for the value of  $n=6$ .

### ***Relative bias***

As was expected, bias of variable plot sampling and fixed plot sampling was negligible, with bias for the Moore estimator being lowest among all NTDS estimators (Table 2.3). The Kleinn-Vilcko estimator was slightly less biased than the Prodan estimator.

For the sake of clarity of presentation and because they are design-unbiased, fixed plot sampling and variable plot sampling results have been omitted from the relative bias figures. For estimates of density, absolute value of relative bias for all NTDS estimators decreased with increasing  $n$  (Figure 2.1). The Moore estimator underestimated the true value on five sites for smaller values of  $n$ , while overestimating the true value on the other three. The other NTDS estimators consistently overestimated the true value. The Kleinn-Vilcko estimator was less biased than the Prodan estimator for small values of  $n$ , but the two appeared to converge for increasing values of  $n$ . The uncorrected estimator consistently performed worse.

Results were slightly different when basal area was the attribute of interest (Table 2.3; Figure 2.2). While the Moore estimator provided lower bias across the board than the Klein-Vilcko and Prodan estimators for five sites, the situation was less clear for the other three sites. The uncorrected estimator consistently performed the worst. Since the uncorrected NTDS estimator consistently performed quite poorly, it was not given further consideration in this study.

### ***RRMSE***

For  $n=6$ , fixed plot sampling had the lowest RRMSE for estimation of density (Table 2.4). Variable plot sampling had the highest RRMSE for low values of  $n$ , while NTDS estimators had the highest RRMSE for higher values of  $n$ . The Moore and Kleinn-Vilcko estimators had approximately equivalent RRMSE, while the Prodan estimator had somewhat higher RRMSE.

For the sake of visual clarity, results from variable plot sampling were omitted from the graphical presentation of results for RRMSE of tree density (Figure 2.3). Fixed plot sampling estimates generally had the smallest RRMSE across all values of  $n$ . For  $n > 3$ , the Moore estimator performed best among NTDS estimators, while the Kleinn-Vilcko estimator sometimes performed better for smaller values of  $n$ . The Prodan estimator gave the worst performance across the board.

For  $n = 6$ , variable plot sampling had the universally lowest RRMSE for estimation of basal area, with fixed plot sampling generally coming in second (Table 2.4). Results were similar to density estimation among NTDS estimators: the Moore estimator performed best, the Prodan estimator performed worse, and the Kleinn estimator was intermediate.

Results from fixed plot sampling were omitted from the graphical presentation of results for RRMSE of basal area (Figure 2.4). For  $n > 3$ , the Moore estimator performed slightly better than the Kleinn-Vilcko estimator on six sites, while the two estimators gave comparable performance on two sites. It is not clear which NTDS estimator performed best for smaller values of  $n$ . The Prodan estimator performed worst across all values of  $n$ .

### ***Distribution of the estimates***

Most skewness coefficients for density and basal area estimation were positive, indicating that the sampling distribution of the estimators tended towards right-skewness (Table 2.5). The sampling distributions of the NTDS estimators and, to a lesser extent, variable-plot sampling, were strongly skewed for density estimation in sites KM18, KM19 and TH75. However, all sampling methods had approximately normal sampling distributions for estimation of basal area. Interestingly, the skewness coefficients of the Moore and Kleinn-Vilcko estimators for density were identical across all sites. The average skewness of the Kleinn-Vilcko estimator was somewhat lower than for the Moore and Prodan estimators, for both density and basal area.

Fixed plot sampling had the narrowest range of relative bias for estimation of density (Table 2.6). Variable plot sampling had similar minimum values but tended toward much larger maximum values, as one would expect with a skewed distribution. The range of values given by the NTDS estimators were similar to those for variable plot sampling, although the minimum values tended to be higher than with variable plot sampling. The Kleinn-Vilcko estimator had the lowest average range, followed by the Moore and Prodan estimators.

Fixed plot and variable plot sampling had approximately equal ranges of relative bias for estimation of basal area. The maximum values given by the NTDS estimators tended to be somewhat higher. The Kleinn-Vilcko estimator had the lowest average range, followed by the Moore and Prodan estimators.

### **Discussion**

A major focus in several previous NTDS studies has been the amount of precision to be gained for different values of  $n$ . Lessard et al. (1994) tried values of 3, 5 and 7, and determined that 3-tree sampling performed best in forests of Michigan's Upper Peninsula. Lynch and Rusydi (1999) determined that 5-tree-sampling worked best for inventory of Indonesian teak plantations. For the sites I examined, RRMSE values seemed to be unacceptably high for  $n < 4$ , but tapered off quickly so that there did not seem to be much improvement for  $n > 6$ . Therefore, a value of  $n$  from 4-6 would have been best for sampling these sites.

Among the NTDS estimators examined, the Moore and Kleinn-Vilcko estimators were clearly superior to the Prodan and uncorrected estimators. No uniformly best estimator was evident, however. RRMSE of the Moore and Kleinn-Vilcko estimators was comparable, but the Moore estimator had generally lower long-run bias. However, the Moore estimator tended toward a larger range of relative bias, and a more skewed distribution. The lower long-run bias of the Moore estimator may

make it more appropriate for large inventory projects, but the less skewed distribution of estimates provided by the Kleinn-Vilcko estimator may cause it to be more desirable for smaller projects. However, the Moore estimator requires one fewer measurement per sample point in the field, and would therefore have been more practically efficient for inventorying these sites.

It is logical that most estimators tended toward right-skewness (i.e. a long positive tail), since relative bias values could not be lower than -100% (indicating an estimate of 0) but could be far larger than 100%. The sites KM18, KM19 and TH75 had unusually large skewness coefficients for density estimation when  $n=6$ , and these sites tended to also have unusually large RRMSE values (Table 2.6). It is unfortunate that the NTDS estimators had especially large skewness coefficients for density estimation on some sites, since NTDS has most often been promoted as a method of efficient density estimation in ecological field studies (Hall 1991; Sheil et al. 2003).

Among the sites examined, TH75 was of special interest because it was the only site with a substantial hardwood component. Bigleaf maple comprised 25% of the site as measured by density, but only 9% of the site as measured by basal area. Examination of Table 2.4 will tell an interesting story. For estimation of density, RRMSE values from variable plot sampling and all NTDS estimators were >50%, far greater than for all other sites. However, the same dramatic results were not evident for estimation of basal area, nor were the basal estimates for TH75 dramatically skewed (Table 2.5).

The population of bigleaf maple in TH75 was decidedly clumped (Figure 2.5), with a Clark-Evans index value of 0.58. This may account for the unusually poor precision of variable plot sampling and NTDS on this site. Since the expansion factor of every tree under NTDS is inversely proportional to the squared distance to the  $n$ th-closest tree (or the squared average of the distances to the  $n$ th- and  $(n+1)$ th-closest tree, in the case of the Kleinn-Vilcko estimator), estimates for a clumped population are likely to vary widely according to whether a sample point lands near a clump or

not, resulting in low precision. Since bigleaf maple made up a relatively small amount of the site's basal area, it makes sense that the precision of basal area estimates for the NTDS estimators was not as dramatically affected. Lessard et al. (1994) encountered similar difficulties applying the Moore estimator in clumped mixed hardwood stands.

Variable plot sampling also performed poorly for density estimation in TH75, even though it provided design-unbiased estimates. The QMD of the bigleaf maple trees was 19.9cm, well below the overall QMD of 34.6cm. The smaller plot sizes associated with the bigleaf maple stems under variable plot sampling increased the variability of this sampling method. While the RRMSE of fixed plot sampling in TH75 was higher than in most sites, it was not as inflated as with variable plot sampling and NTDS.

When density estimation is an inventory objective, and when the population of interest is highly clumped, the fixed and variable plot sampling methods will likely provide better estimates than NTDS. However, more sampling effort will be necessary to attain a certain level of precision than with a more uniformly-distributed population. When only a subpopulation (e.g. a certain species) has a clumped spatial distribution, it may be desirable to place that subpopulation into a separate strata, so that the higher sampling variability associated with it does not "infect" the overall estimate (Iles 2003, p288).

When a certain subpopulation has a QMD substantially smaller than for the overall population, variable plot sampling with a BAF appropriately selected for the overall population will give highly variable estimates for that subpopulation. One solution would be to place this subpopulation into a different stratum. A larger BAF or a fixed plot could then be used to sample the subpopulation, resulting in a less variable overall density estimate.

Results from this study should be extrapolated with caution. The sites examined were all headwater riparian forests of western Oregon. While the spatial pattern of most sites (excluding TH75) approximated randomness enough that the

Moore estimator gave relatively good results, many similar forest types may not. Riparian forests can be exposed to unique environmental stressors (e.g. landslides, seasonal flooding) and may be more likely to have a random spatial pattern than their upland counterparts. Lynch and Rusydi (1999) suggested that the superiority of the Prodan estimator in teak plantations stemmed from their uniformly spaced nature. If upland forests in the same region tend toward a uniform spatial pattern, the Prodan estimator may be a better alternative for sampling them.

On the other hand, many riparian forests of western Oregon may have a substantial hardwood component even in the headwaters. Poor results have been found when applying NTDS to clumped hardwood populations in this study and others (Lessard et al. 1994; Payandeh and Ek 1986). If density estimation is the primary sampling objective and the population to be sampled contains many trees that have a clumped spatial distribution, NTDS is probably a sampling scheme to be avoided. If basal area is the primary objective, variable plot sampling will likely have superior performance to either NTDS or fixed plot sampling.

In closing, a discussion on the practical (as opposed to statistical) efficiency of NTDS, when implemented as part of a forest inventory program, is warranted. Previous studies have claimed (generally in a fairly offhand manner) that NTDS is attractive for its ease and practicality of use (Kleinn and Vilcko 2006a, Jonsson et al. 1992, Hall 1991). Jonsson (1992) recommended NTDS using the Moore estimator as “an all-encompassing forest inventory method”, and believed that it would compare favorably with fixed plot sampling. There is no mention in his publication of variable plot sampling, which has been in existence since 1948 and can be highly efficient for volume estimation when only a small number of many counted trees are subsampled for volume measurement (Marshall et al. 2004). Of course, variable plot sampling will not be as efficient in the (rare) case that estimating density is the primary objective of an inventory program, and NTDS can be more validly compared with fixed plot sampling. Hall (1991) recommended 15- or 20-tree sampling in a montane forest in



Tanzania, stating “the most obvious practical application is its simplicity, regardless of the severity of the terrain.” While I have not been to Tanzania, I find this logic challenging to reconcile with my own knowledge of forest sampling. In my limited experience, even finding the four trees nearest to a given sample point may be a challenging endeavor, especially on steep and brushy ground. Steep terrain and brush will present difficulties to the user of a fixed or variable plot as well. However, correct application of NTDS presents an additional bookkeeping problem, since (unlike the previously mentioned sampling systems) the selection process is such that some trees will be sampled at the expense of others. Good memorization skills, or a highly efficient bookkeeping system, will be required on the part of the sampler. It is possible that new technology, or simply more experience on the part of forest samplers, will make this method more cost-effective than it is presently. As laser rangefinders become more refined and ever better at filtering out brush, NTDS will become more a more efficient sampling method. Of course, so will fixed plot sampling.

Some valid reasons to use NTDS do appear in the literature. For example, Picard (2005) recommended the method for use in estimating wood yield in Mali savanna, where trees are shrublike in form and fixed plots are difficult to apply. One of the most compelling reasons to use this system that I have found is when the population being sampled is relatively rare on the landscape. Kenning et al. (2005) evaluated a modification of NTDS for snag inventory in pine-hardwood forests of New England, and recommended the system when snags per hectare (as opposed to snag volume or basal area) was the attribute of interest, a large number of sampling points was possible, and design-unbiasedness was not an important criterion. Lynch and Wittwer (2003) adapted NTDS for increment core sampling of sparse, but highly clumped, populations of eastern cottonwood in the Cimarron National Grassland. Unfortunately, although the ability to control the number of trees measured at each sample point has practical appeal when sampling clumped populations, my findings, and the findings of others (Lessard et al. 1994; Payandeh and Ek 1986), illustrate the

potentially severe bias that may be incurred by NTDS when the population is strongly clumped.

NTDS has been promoted as a sampling technique for ecological field surveys (Hall 1991; Sheil et al. 2003). It is important to recognize that ecological research programs may have objectives that are inherently different from forest inventory programs, and NTDS may be well suited to meeting these objectives. Unlike forest inventory programs, which tend to be carried out by experienced samplers who are intimately familiar with the forest type in which they are working, ecological sampling is often done by academics or graduate students who may have little practical experience working in the area that they intend to sample. Therefore, considerable effort can be expended in trying to decide ahead of time on the “correct” fixed plot size or variable plot BAF, and NTDS, with its promise of always capturing the “right” number of trees, may be a comforting alternative, but inventory professionals are likely to find this selling point of NTDS to be much less compelling. Furthermore, field ecologists tend to be more interested in inventorying the presence and relative abundance of different tree species than in trying to estimate density, or any other attribute, in absolute terms. This difference in objectives may make the lack of design-unbiasedness of NTDS less of an issue. However, while it is permissible to have bias in ecological sampling, the bias should be consistent, so that it does not cause a change in the conclusions of the study regarding species abundance. Therefore, the strongly skewed behavior of the NTDS estimators on some stem maps, particularly where trees are spatially clumped, should be of concern.

While some of the NTDS estimators currently in existence or under development may offer possibilities for more robust estimation of density and basal area than the four NTDS estimators examined in this study, I doubt that NTDS will ever have much support as “an all-encompassing forest inventory method” in this forest type. Variable plot sampling will probably always be more efficient, in both a statistical and practical sense, where volume or basal area is of primary interest.

Where density estimation or the construction of stand tables is of primary interest, fixed plot sampling is design-unbiased and may well be more efficient. Where both basal area and density are of interest, a nested fixed/variable plot design, although not evaluated in this study, may be an optimal solution. Another possibility is to tally trees separately in fixed and variable plots, so that the size of fixed plots and the BAF of variable plots can be manipulated independently (Packard and Radtke 2007). When only the sampling methods evaluated in this study are considered, fixed plot sampling may be ideal for combined estimation of density and volume. Fixed plot sampling performed only slightly poorer than variable plot sampling for estimation of basal area, while performing much better for estimation of density. Fixed plot sampling generally outperformed NTDS for estimation of both density and basal area.

### **Conclusion**

NTDS is a sampling system for which an unbiased result cannot be guaranteed. The efficiency of this system, while in some cases comparable to fixed plot sampling and variable plot sampling (Lessard 1994; Lynch and Rusydi 1999), has not been shown to be dramatically greater. The potential for serious bias (Scheuder 2004), and the lack of a dramatic efficiency gain, are probably the two primary reasons why this system has not been widely adopted in the Pacific Northwest.

However, somewhat biased estimators and procedures are commonly used in forest inventory, and it is often less expensive to demonstrate that a given bias is negligible and accept it than to attempt to remove it entirely (Iles 2003, p33). In the case of the stem maps examined, long-run bias from this system was negligible when the Moore estimator was used, and RRMSE values were sometimes roughly comparable to those from fixed plot sampling and variable plot sampling for moderate-to-large values of  $n$ .

While NTDS may never be a mainstay of forest inventory, specific applications for this system may emerge in the evolving sampling needs of the future. Varying incarnations of distance sampling have long been popular in ecological studies (Pielou 1959; Hall 1991; Sheil 2003), and this trend is likely to continue. Wildlife studies, where some sort of distance sampling of tree characteristics is frequently applied (e.g. Mysterud 1996; Clotfelter 1998; Kelly 1993), may also be well positioned to make use of this method. If the spatial distribution of the population to be sampled is known to be fairly close to random, and if the prospect of taking accurate horizontal distance measurements is not too daunting, NTDS may a good candidate for forest sampling in this region, provide that its advantages and risks are fully known and considered.

Table 2.1: Species composition of each site. Species comprising less than 1% of total density were omitted. N – density (trees/ha); G – basal area (m<sup>2</sup>/ha).

|                  | BL13 |      | KM17 |      | KM18 |      | KM19 |      | KM21 |      | OM36 |      | TH46 |      | TH75 |      |
|------------------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|
|                  | N    | G    | N    | G    | N    | G    | N    | G    | N    | G    | N    | G    | N    | G    | N    | G    |
| Douglas-fir      | 272  | 38.6 | 120  | 25.9 | 162  | 23.1 | 243  | 31.4 | 133  | 21.8 | 336  | 33.8 | 303  | 45.4 | 422  | 54.1 |
| western hemlock  | -    | -    | 266  | 39.6 | 361  | 31.0 | 177  | 15.4 | 170  | 22.4 | 15   | 0.4  | 110  | 14.3 | 31   | 1.3  |
| western redcedar | -    | -    | -    | -    | 83   | 2.1  | 112  | 3.0  | 33   | 1.0  | 6    | 0.1  | -    | -    | 25   | 0.5  |
| grand fir        | -    | -    | -    | -    | -    | -    | -    | -    | -    | -    | 14   | 0.5  | -    | -    | -    | -    |
| red alder        | -    | -    | 37   | 2.7  | 37   | 2.6  | 12   | 0.8  | 42   | 3.4  | 25   | 2.4  | -    | -    | 15   | 1.1  |
| bigleaf maple    | 41   | 2.9  | -    | -    | -    | -    | -    | -    | -    | -    | -    | -    | -    | -    | 168  | 5.2  |
| Pacific dogwood  | 12   | 0.1  | -    | -    | -    | -    | -    | -    | -    | -    | -    | -    | -    | -    | -    | -    |
| Total            | 325  | 41.6 | 423  | 68.2 | 643  | 58.8 | 544  | 50.6 | 378  | 48.6 | 396  | 37.1 | 413  | 59.7 | 661  | 62.2 |

Table 2.2: Spatial information for each site. B – buffer used for edge-effect correction of Clark-Evans index (m); CE – Clark-Evans index value. The Clark-Evans index can take on a range from 0-2.14, with values <1 indicating a clumped population, a value of 1 indicating complete spatial randomness, and values >1 indicating a uniformly-distributed population.

| Species          | BL13 |      | KM17 |      | KM18 |      | KM19 |      | KM21 |      | OM36 |      | TH46 |      | TH75 |      |
|------------------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|
|                  | B    | CE   | B    | CE   | B    | CE   | B    | CE   | B    | CE   | B    | CE   | B    | CE   | B    | CE   |
| Douglas-fir      | 9.1  | 1.03 | 8.5  | 0.80 | 10.1 | 1.05 | 6.4  | 0.93 | 16.2 | 0.80 | 8.3  | 1.22 | 7.2  | 1.11 | 8.4  | 1.12 |
| western hemlock  | -    | -    | 8.0  | 1.08 | 8.0  | 0.97 | 8.8  | 0.90 | 14.1 | 0.75 | -    | -    | 12.0 | 0.84 | -    | -    |
| western redcedar | -    | -    | -    | -    | 14.6 | 0.81 | 12.7 | 0.82 | 16.7 | 0.86 | -    | -    | -    | -    | 12.6 | 0.48 |
| red alder        | -    | -    | 3.8  | 0.36 | -    | 0.37 | -    | -    | 28.9 | 0.54 | -    | -    | -    | -    | 0.0  | 0.24 |
| bigleaf maple    | 11.5 | 0.21 | -    | -    | -    | -    | -    | -    | -    | -    | -    | -    | -    | -    | 18.3 | 0.58 |
| All combined     | 8.3  | 0.99 | 6.6  | 1.22 | 6.5  | 1.09 | 4.3  | 0.96 | 6.7  | 0.99 | 8.3  | 1.25 | 7.4  | 1.14 | 7.9  | 1.08 |

Table 2.3: Relative bias of density and basal area estimates when  $n=6$ . FP – fixed plot; VP – variable plot; UN – n-tree uncorrected; MR – n-tree Moore; PD – n-tree Prodan; KN – n-tree Kleinn-Vilcko.

| Site and attribute | FP    | VP    | UN    | MR    | PD    | KN    |
|--------------------|-------|-------|-------|-------|-------|-------|
| <b>Density</b>     |       |       |       |       |       |       |
| BL13               | -0.65 | -2.27 | 18.57 | -1.19 | 8.69  | 7.25  |
| KM17               | -0.75 | -1.04 | 14.14 | -4.88 | 4.63  | 3.83  |
| KM18               | -0.96 | -0.67 | 18.44 | -1.3  | 8.57  | 7.08  |
| KM19               | 1.18  | 1.64  | 27.76 | 6.47  | 17.12 | 13.95 |
| KM21               | 0.67  | 0.15  | 20.9  | 0.75  | 10.83 | 9.59  |
| OM36               | 0.56  | -0.19 | 18.42 | -1.32 | 8.55  | 7.79  |
| TH46               | 0.83  | 0.54  | 17.85 | -1.79 | 8.03  | 7.43  |
| TH75               | 1.34  | 1.82  | 24.64 | 3.87  | 14.26 | 13.13 |
| <b>Basal area</b>  |       |       |       |       |       |       |
| BL13               | -0.31 | -1.36 | 17.69 | -1.92 | 7.62  | 6.51  |
| KM17               | -0.91 | -1.08 | 13.49 | -5.42 | 4.13  | 3.36  |
| KM18               | -1.31 | -1.15 | 16.1  | -3.25 | 6.57  | 5.08  |
| KM19               | -0.5  | -0.7  | 19.55 | -0.38 | 9.88  | 8.47  |
| KM21               | 1.23  | 0.84  | 19.56 | -0.36 | 9.65  | 8.49  |
| OM36               | 0.4   | 0.05  | 16.33 | -3.06 | 6.73  | 5.94  |
| TH46               | 0.05  | -0.36 | 16.28 | -3.1  | 6.59  | 5.94  |
| TH75               | 0.94  | 1.11  | 18.28 | -1.43 | 8.53  | 7.62  |

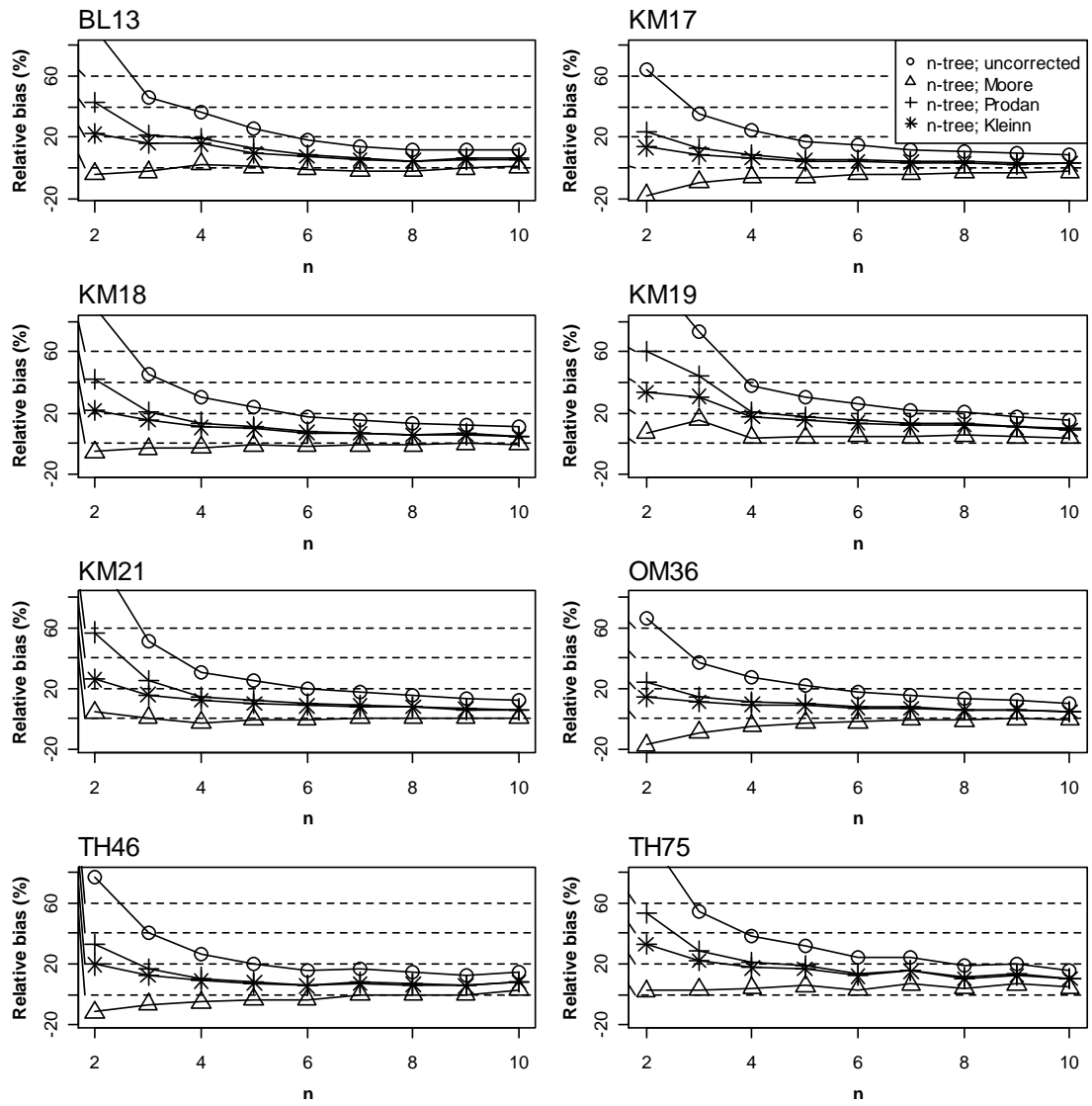


Figure 2.1: Relative bias of density estimates for  $n=2, \dots, 10$  trees.



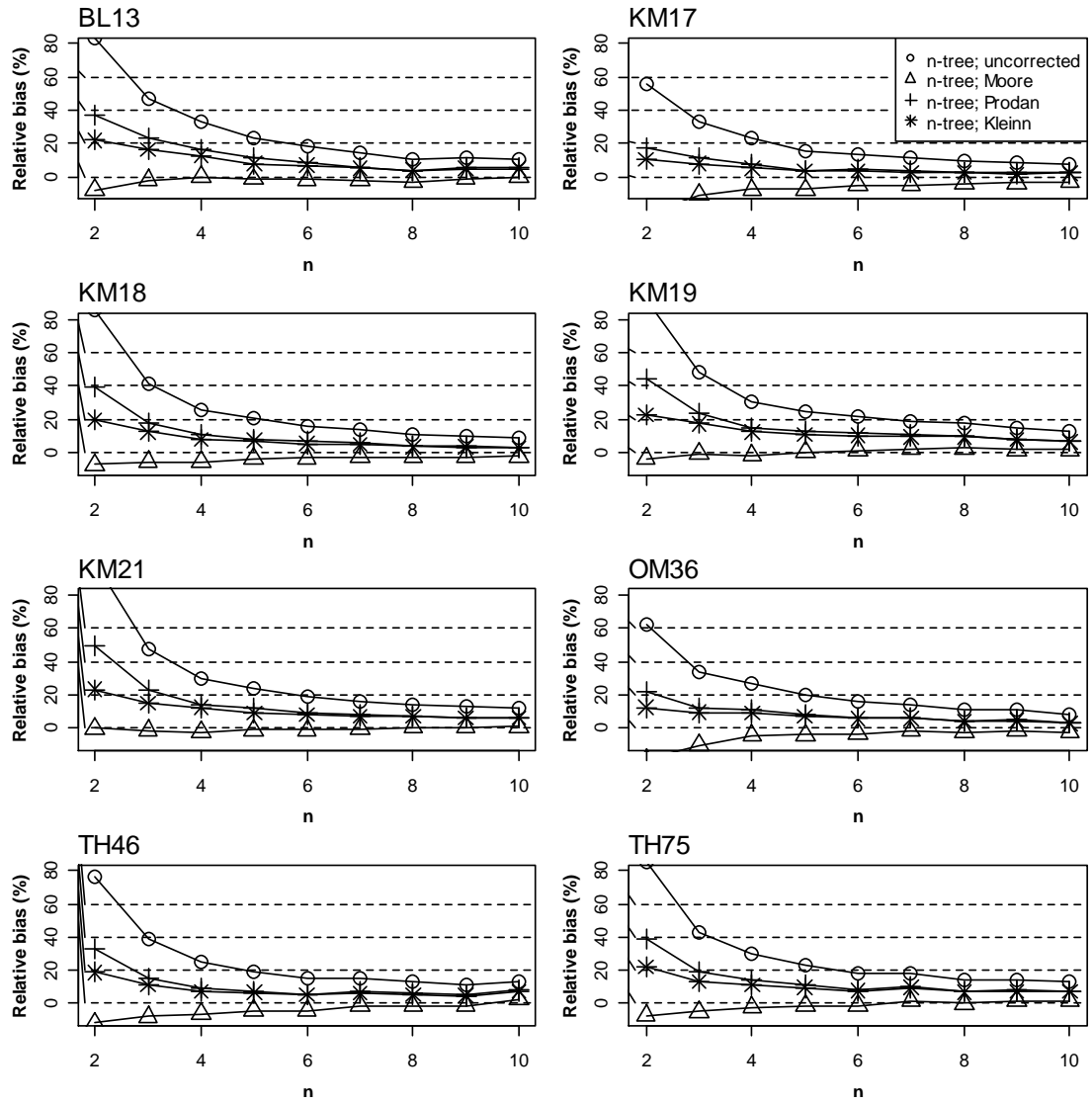


Figure 2.2: Relative bias of basal area estimates for  $n=2, \dots, 10$  trees.

Table 2.4: RRMSE of density and basal area estimates when  $n=6$ . FP – fixed plot; VP – variable plot; UN – n-tree uncorrected; MR – n-tree Moore; PD – n-tree Prodan; KN – n-tree Kleinn.

| Site and attribute | FP   | VP   | UN   | MR   | PD   | KN   |
|--------------------|------|------|------|------|------|------|
| <b>Density</b>     |      |      |      |      |      |      |
| BL13               | 20.7 | 28.3 | 33.2 | 22.9 | 26.6 | 23.0 |
| KM17               | 17.0 | 24.9 | 24.7 | 17.6 | 19.2 | 17.7 |
| KM18               | 18.9 | 35.9 | 40.9 | 30.5 | 34.6 | 30.4 |
| KM19               | 28.6 | 46.5 | 59.9 | 44.7 | 51.5 | 37.6 |
| KM21               | 21.1 | 36.5 | 37.4 | 25.8 | 30.4 | 27.7 |
| OM36               | 21.3 | 34.3 | 32.9 | 22.7 | 26.4 | 24.3 |
| TH46               | 21.1 | 26.2 | 31.4 | 21.6 | 25.0 | 23.3 |
| TH75               | 28.8 | 50.4 | 65.2 | 50.4 | 57.1 | 52.5 |
| <b>Basal area</b>  |      |      |      |      |      |      |
| BL13               | 20.9 | 18.7 | 34.1 | 24.4 | 27.2 | 24.4 |
| KM17               | 20.1 | 19   | 27.3 | 20.5 | 22.1 | 20.9 |
| KM18               | 20.6 | 16.2 | 33.1 | 24.3 | 27.8 | 24.8 |
| KM19               | 32.4 | 26.2 | 46.8 | 35.4 | 40.5 | 37.9 |
| KM21               | 23.2 | 20.2 | 35.6 | 24.8 | 29.1 | 27.0 |
| OM36               | 23.7 | 21.1 | 32.2 | 23.3 | 26.4 | 24.7 |
| TH46               | 19.3 | 18.6 | 29.3 | 20.5 | 23.3 | 21.4 |
| TH75               | 27.5 | 24.7 | 44.5 | 33.8 | 38.1 | 34.7 |

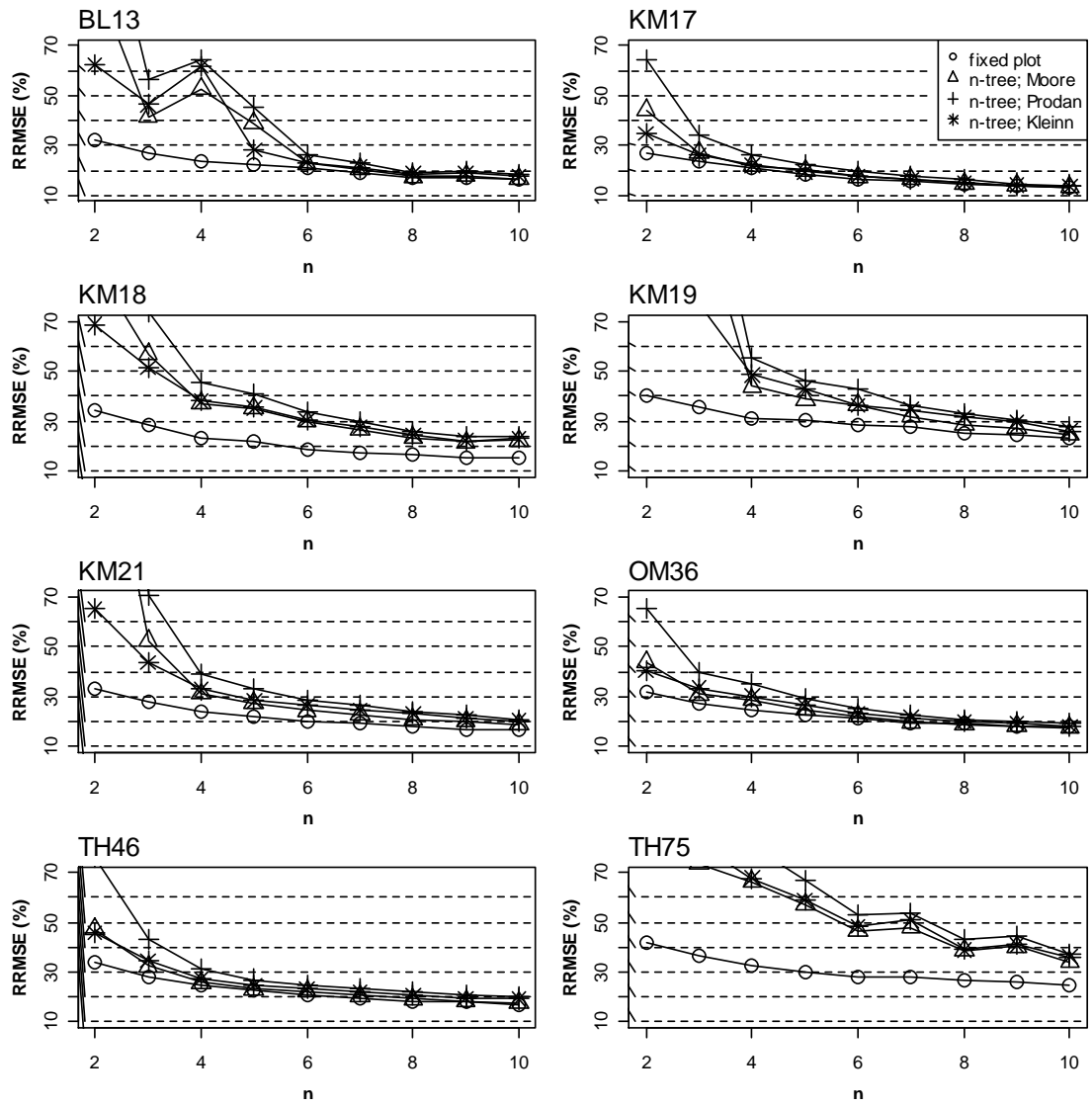


Figure 2.3: RRMSE of density estimates for  $n=2, \dots, 10$  trees.

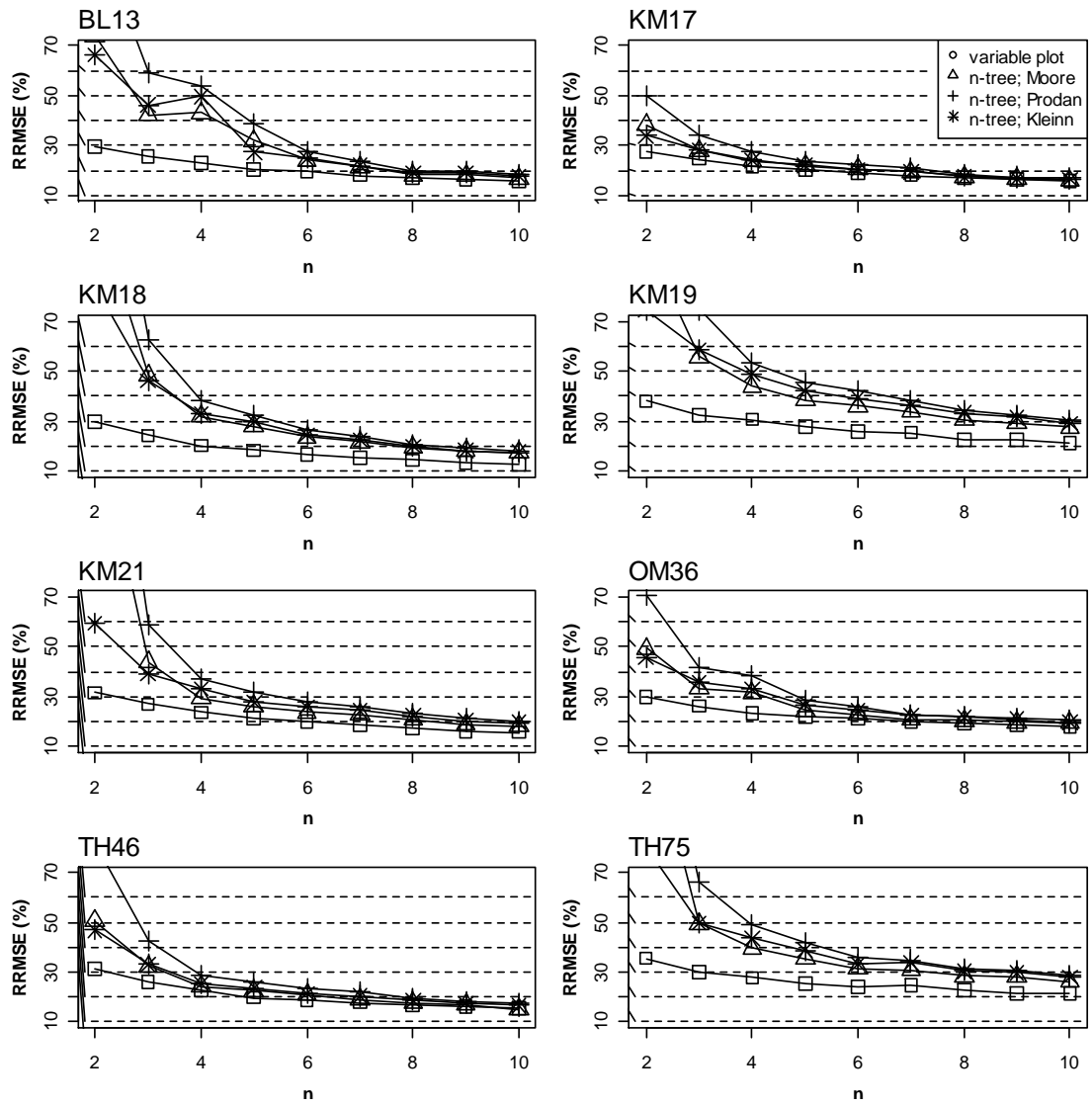


Figure 2.4: RRMSE of basal area estimates for  $n=2, \dots, 10$  trees.

Table 2.5: Skewness coefficients of density and basal area estimates when  $n=6$ . FP – fixed plot; VP – variable plot; MR – n-tree Moore; PD – n-tree Prodan; KN – n-tree Kleinn-Vilcko. Positive coefficients indicate right-skewness, negative coefficients indicate left-skewness and coefficients equal to 0 indicate a normal distribution.

| Site and attribute | FP    | VP    | MR   | PD   | KN   |
|--------------------|-------|-------|------|------|------|
| <b>Density</b>     |       |       |      |      |      |
| BL13               | 0.08  | 0.62  | 0.68 | 0.68 | 0.49 |
| KM17               | 0.07  | 1.00  | 0.45 | 0.45 | 0.39 |
| KM18               | 0.37  | 1.76  | 4.15 | 4.15 | 4.14 |
| KM19               | -0.14 | 1.37  | 2.02 | 2.02 | 1.00 |
| KM21               | 0.24  | 1.41  | 1.52 | 1.52 | 1.24 |
| OM36               | -0.02 | 1.26  | 0.58 | 0.58 | 0.48 |
| TH46               | 0.01  | 0.95  | 0.43 | 0.43 | 0.45 |
| TH75               | 0.30  | 2.15  | 4.38 | 4.38 | 4.10 |
| <b>Basal area</b>  |       |       |      |      |      |
| BL13               | 0.08  | 0.00  | 0.96 | 0.91 | 0.80 |
| KM17               | -0.09 | -0.12 | 0.26 | 0.26 | 0.13 |
| KM18               | 0.17  | -0.03 | 0.94 | 1.01 | 0.73 |
| KM19               | 0.25  | 0.10  | 1.12 | 1.24 | 1.17 |
| KM21               | 0.05  | 0.23  | 0.73 | 0.71 | 0.65 |
| OM36               | 0.29  | -0.01 | 0.40 | 0.39 | 0.33 |
| TH46               | 0.04  | -0.17 | 0.51 | 0.55 | 0.54 |
| TH75               | 0.32  | 0.35  | 1.52 | 1.42 | 1.05 |

Table 2.6: Minimum and maximum relative bias of density and basal area estimation when  $n=6$ . FP – fixed plot; VP – variable plot; MR – n-tree Moore; PD – n-tree Prodan; KN – n-tree Klein-Vilcko.

| Site and attribute | FP         | VP         | MR         | PD         | KN         |
|--------------------|------------|------------|------------|------------|------------|
| <b>Density</b>     |            |            |            |            |            |
| BL13               | (-58, 71)  | (-73, 153) | (-52, 113) | (-47, 134) | (-44, 106) |
| KM17               | (-54, 54)  | (-71, 160) | (-49, 58)  | (-44, 73)  | (-40, 67)  |
| KM18               | (-54, 79)  | (-73, 221) | (-44, 305) | (-38, 346) | (-40, 347) |
| KM19               | (-92, 83)  | (-89, 314) | (-63, 445) | (-59, 500) | (-58, 199) |
| KM21               | (-63, 75)  | (-67, 194) | (-48, 155) | (-42, 181) | (-42, 134) |
| OM36               | (-71, 67)  | (-72, 245) | (-60, 123) | (-56, 145) | (-55, 136) |
| TH46               | (-63, 67)  | (-65, 158) | (-57, 88)  | (-53, 106) | (-50, 106) |
| TH75               | (-75, 104) | (-70, 338) | (-60, 531) | (-56, 594) | (-54, 514) |
| <b>Basal area</b>  |            |            |            |            |            |
| BL13               | (-66, 65)  | (-58, 58)  | (-54, 119) | (-46, 140) | (-49, 111) |
| KM17               | (-63, 63)  | (-67, 58)  | (-59, 63)  | (-54, 82)  | (-53, 75)  |
| KM18               | (-57, 66)  | (-54, 46)  | (-59, 137) | (-55, 174) | (-52, 105) |
| KM19               | (-84, 98)  | (-71, 79)  | (-70, 222) | (-65, 273) | (-65, 262) |
| KM21               | (-70, 69)  | (-50, 71)  | (-60, 122) | (-56, 136) | (-54, 133) |
| OM36               | (-74, 91)  | (-67, 79)  | (-65, 89)  | (-60, 98)  | (-60, 97)  |
| TH46               | (-60, 59)  | (-58, 62)  | (-56, 77)  | (-51, 96)  | (-49, 88)  |
| TH75               | (-68, 86)  | (-62, 96)  | (-61, 248) | (-57, 247) | (-54, 179) |

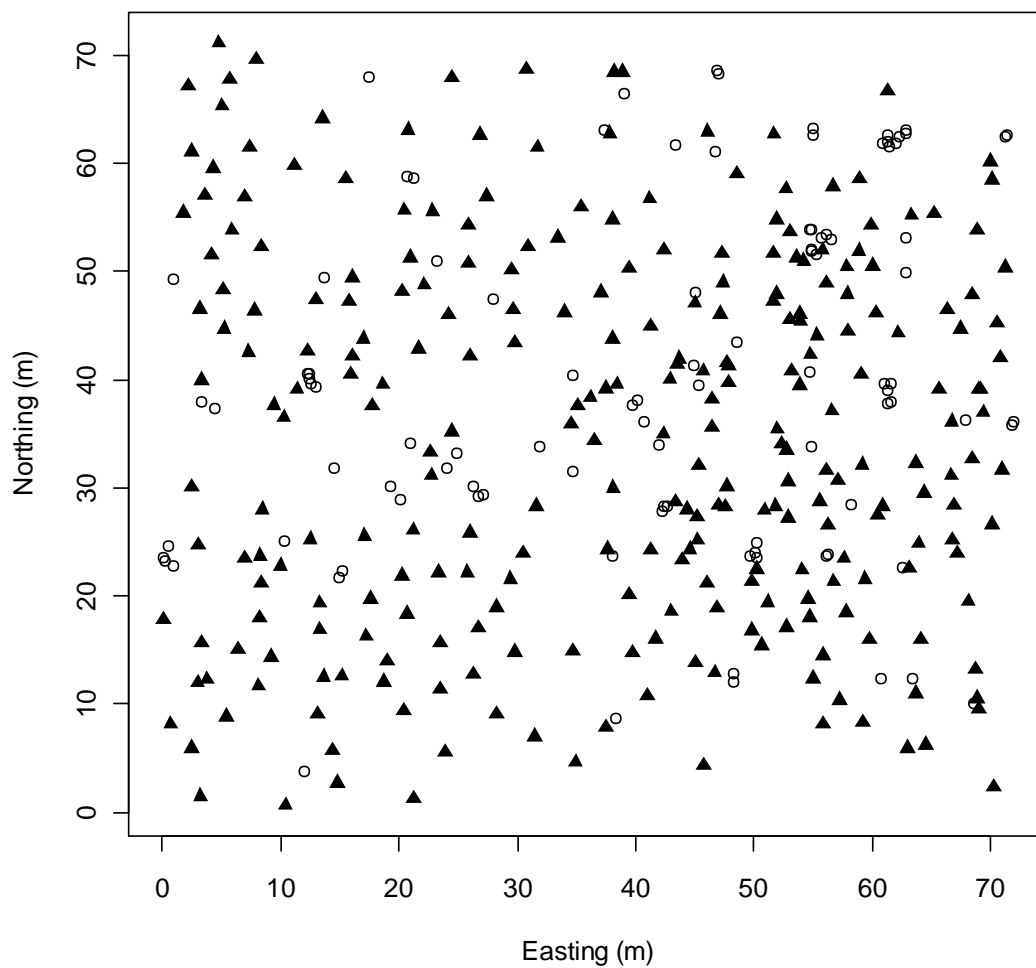


Figure 2.5: Overhead view of plot TH75. Triangles represent conifers; open circles represent hardwoods (predominately bigleaf maple). Note the clustered pattern of many of the hardwood trees.

## CHAPTER THREE

### AN EVALUATION OF FOUR METHODS OF ESTIMATING NEIGHBORHOOD-BASED INDICES IN HEADWATER RIPARIAN FORESTS OF WESTERN OREGON

#### **Introduction**

While the definition of forest structure includes not only the presence of individual objects but the spatial arrangement of these objects (Franklin et al. 2002), standard measures of structure (e.g. density, basal area or volume) contain no information on the spatial arrangement of live trees within a stand (Pommerening 2002). These parameters, and even more sophisticated presentations such as a stand table, can tell us “what is out there” but not “how what is out there is arranged”. Zenner and Hibbs (2000) present a hypothetical example where two different stands have identical tree densities, basal areas and diameter distributions, and yet have very different forest structures as a result of differing management regimes. Spatial functions, such as Ripley’s K (Ripley 1977) or the pair correlation function (Pommerening 2002), describe the spatial pattern of trees across a continuous range of inter-tree distances. However, they require knowledge of the coordinate positions of all trees within a plot, limiting their use in practical forest inventory applications. Furthermore, they can be difficult to explain to forest managers who may lack advanced statistical training.

In response to the need for a set of analytical tools that are easy to interpret and do not require stem-mapped plot data, a research group at the University of Gottingen (Germany) has developed a group of indices that allow the characterization of forest structure at the individual-tree level (Pommerening 2006). These indices are termed “neighborhood-based” because they are based upon the characteristics of the nearest trees (i.e. “neighbors”) surrounding a given “reference tree” that has been selected for



measurement. The number of neighbors  $n$  to be considered for each reference tree is not entirely standardized, but  $n=3$  or  $n=4$  are commonly suggested possibilities (Pommerening 2002; Gadow and Pogoda 2000). While any value of  $n$  may theoretically be used, index values may not remain constant for different values of  $n$ , and therefore it is important to use a fixed value of  $n$  when comparing index values for different populations.

Neighborhood-based indices can be seen as fine-scale measurements of structural diversity (whereas conventional data, such as stand tables, are measurements of diversity at the stand level). Several selected indices are described below. Out of respect for the German-speaking inventors of these indices, the original German acronyms will be retained throughout this thesis.

The species mingling index (DM) developed by Gadow and Hui (1999) provides a quantitative assessment of the degree of interspersion between trees of different species. Higher mingling values imply greater intermixing of species throughout a stand; lower values imply a tendency towards species-specific clumping and segregation. For a given reference tree  $i$ , mingling is calculated as:

$$3.1 \quad DM_i = \frac{1}{n} \sum_{j=1}^n v_j$$

where  $n$  is the number of neighbors considered and  $v_j$  is 0 if the  $j$ th neighbor is of the same species as the reference tree, and 1 otherwise.

The differentiation index developed by Gadow and Hui (1999) describes the degree of interspersion of trees of different sizes. While this index can describe the differentiation of any size-related variable (e.g. diameter at breast height (DBH), height, or volume), only diameter differentiation (the differentiation of DBH) will be considered here. Higher values imply higher differentiation (i.e. more fine-scale variability in size); lower values imply lower differentiation. For the  $i$ th reference tree and its  $j$ th nearest neighbor, diameter differentiation (TD) is calculated as:

$$3.2 \quad TD_i = \frac{1}{n} \sum_{j=1}^n \left[ 1 - \frac{\min (dbh_i, dbh_j)}{\max (dbh_i, dbh_j)} \right]$$

where  $\min (dbh_i, dbh_j)$  is the smaller DBH of the two trees, and  $\max (dbh_i, dbh_j)$  is the larger. Pommerening (2002) has proposed the following interpretation system for the TD index:

- 1) TD index values from 0.0-0.3 are evidence of “small” differentiation. The tree with the smaller DBH is 70% or more of the neighboring tree’s DBH.
- 2) TD index values from 0.3-0.5 are evidence of “average” differentiation. The tree with the smaller DBH is 50-70% of the neighboring tree’s DBH.
- 3) TD index values from 0.5-0.7 are evidence of “big” differentiation. The tree with the smaller DBH is 30-50% of the neighboring tree’s DBH.
- 4) TD index values from 0.7-1.0 are evidence of “very big” differentiation. The tree with the smallest DBH is less than 30% of the neighboring tree’s size.

The dominance index (U) was proposed by Hui et al. (1998) and quantifies the dominance of a given species in a stand by estimating the proportion of nearest neighbors that are smaller (as indicated by height or DBH) than the reference tree. Again, this analysis will focus on DBH as the variable of interest. Larger values imply greater dominance in the stand (Aguirre et al. 2003). For a given reference tree  $i$ , dominance is calculated as:

$$3.3 \quad U_i = \frac{1}{n} \sum_{j=1}^n v_j$$

where  $v_j$  is 1 if the DBH of the reference tree is larger than the DBH of the  $j$ th neighbor.

Neighborhood-based indices have been explored using a wide array of stem-mapped datasets from natural and managed stands across the world (e.g. Pommerening 2002; Aguirre et al. 2003; Mason et al. 2007; Saunders and Wagner 2008), providing an excellent set of baseline information on the interpretation and use of these indices. However, despite the fact that neighborhood-based indices were specifically designed to be easy to measure in the field, minimal guidance exists for practitioners seeking to integrate these indices into sampling protocols. In particular, little is known about the best method of selecting reference trees. Gadow and Pogoda (2000) suggest what will be known in this paper as the “nearest-tree” method: the selection of the tree that is closest to a given sample point. However, this method of selection is known to be biased if the inherently unequal selection probabilities involved are not accounted for in compiling the estimate (Iles 2009). Computation of selection probabilities, which would involve estimating the area within which a given reference tree is the “nearest tree”, would be too cumbersome to consider further. However, the bias of this method may be negligible in a practical sense.

Kint et al. (2004) compared two sampling methods, “distance sampling” and “plot sampling” for estimation of neighborhood-based indices. They defined distance sampling as the random selection of reference trees from a tree list. Plot sampling was defined as the selection of the nearest trees within a randomly-chosen sample point, and is analogous to the n-tree distance sampling that was discussed in the Chapter II. However, this is not a comparison of two sampling systems that are likely to be ever implemented in the field. The distance sampling method would require all trees within the stand to be enumerated beforehand, and is obviously impractical. Plot sampling is more practical, but is also theoretically biased (see the discussion in Chapter II), and is unlikely to be a common inventory choice in the Pacific Northwest in the near future.

Given their familiarity, design-unbiasedness, and long history of use in forest sampling applications in the Pacific Northwest, fixed and variable plots may be appropriate for selecting reference trees. As with the plot sampling of Kint et al.

(2004), these systems sample trees in a cluster, which can be less statistically efficient but more practically efficient, since more trees can be sampled with less travel time. Sterba (2008) estimated the TD index by measuring the nearest neighbor (i.e.  $n=1$ ) to every tree selected in a variable plot cruise in the Austrian Alps. However, he did not compare results from this method to any other sampling system. The possibility of selecting reference trees using fixed plots does not appear to have been previously studied.

Another possible method of reference tree selection, unique to a fixed plot setting, is the selection of the “first tree from north”; that is, the first tree encountered in a clockwise sweep from true north. This method, which is sometimes used in the Pacific Northwest (and perhaps elsewhere), has been referred to as the “azimuth” method by Iles (1979, p23). It is known to be theoretically biased (Bell 1996). However, as with the nearest-tree method of selection, the practical bias of this method has not been well explored.

There appears to be no study comparing multiple methods of selecting reference trees in a realistic field setting. The first objective of this study was to quantify the sampling variability of each neighborhood-based index as applied to headwater riparian forests of western Oregon. The second objective was to compare the performance, in terms of relative bias and RRMSE, of four reference tree selection methods (fixed plot, variable plot, nearest-tree and azimuth) for estimation of neighborhood-based indices in this forest type. While neighborhood-based indices were specifically designed so that the frequency distribution of index values was the basic unit of information (Pommerening 2006), the analysis was simplified by focusing on the relative bias and RRMSE of the estimation of the arithmetic mean index value. While a frequency distribution contains more information than an arithmetic mean, a mean can be calculated from a frequency distribution, and mean values have been used to complement frequency distributions in presentation of neighborhood-based index values (Aguirre et al. 2003). It is assumed that a method

that leads to a biased and highly variable estimate of the mean is also likely to lead to a biased and highly variable estimated frequency distribution, and vice versa.

## Methods

### *Data*

As with Chapter Two, I used 8 stem-mapped plots collected as part of the BLM Density Management and Riparian Buffer Study: Bottom Line 13 (BL13), Keel Mountain 17 (KM17), Keel Mountain 18 (KM18), Keel Mountain 19 (KM19), Keel Mountain 21, Ten High 46 (TH46), and Ten High 75 (TH75). The DM, TD and U indices for the plots used are shown in Tables 3.1, 3.2 and 3.3, respectively.

### *Analysis*

The coefficient of variation (CV) was used to quantify variability in index values between trees for a given species at a given site:

$$3.4 \quad CV(\%) = \frac{SD_{ij}}{m_{ij}} * 100$$

where  $m_{ij}$  is the arithmetic mean index value for site  $i$  and species  $j$ , and  $SD_{ij}$  is the population standard deviation. If both the mean and the population standard deviation were 0 (producing a divide-by-0 error), the CV was given as 0. This metric could also be used to quantify variation in index values among trees at a given site as a whole.

To determine what factors may be correlated with variability of index estimation, I also explored the strength of the association between CV, index value, and percent of total density occupied by individual species for each index. For lack of a better term, the percent of total density occupied by a given species will be referred to as the “relative density” of that species. This usage presents a potential conflict with

the terminology of stand density indices, none of which will be discussed in this thesis.

The intent of the sampling algorithm was to simulate the bias and precision of different methods of tree selection in a realistic setting. A Monte-Carlo simulation was written in the VBA programming language (Microsoft Corp. 1987) that was similar to the one used in Chapter Two. The major difference in the basic setup was that it was necessary to have two levels of edge-effect correction. Toroidal edge effect correction, as explained in Chapter 2, was used to ensure that all trees on the plot had an equal long-run probability of selection. However, it was also necessary to correct for the fact that the nearest neighbors of trees near the edge of the plot may not be within the plot, therefore resulting in distortions of the index calculations (Pommerening 2002). This possibility was minimized through the use of the computer program SIAFOR (Kint 2004), which is capable of calculating neighborhood-based indices for stem-mapped plots. SIAFOR calculates a buffer that is equal to “the greatest observed distance between a tree within the buffer and its  $n$ th nearest neighbor ( $n$  depending on the calculated index)” (Kint 2004). SIAFOR calculates all neighborhood-based indices using three neighbors, and therefore I also used three neighbors in my analysis. While interpretation of neighborhood-based indices does not depend on any particular number of neighbors, For readers interested in re-creating my methods, important details about SIAFOR and its use are given in Appendix A.

For each site, I ran SIAFOR and entered the calculated buffer width into my sampling program. The sampling program clipped the stem map to the appropriate dimensions, thereby removing trees within the buffer from the analysis. Dimensions of the clipped stem maps, and the number of live trees included within them, are given in Table 3.4.

Four plots were used at each of 5,000 repetitions. However, since systematic sampling is far more common than random sampling in most forestry sampling applications, this method of sample point placement was simulated. The first point

was randomly located within the lower-left quadrant of the stem map using the pseudo-random number generator function in VBA. Subsequent points were placed on a 36mx36m grid. The fixed plot radius and variable plot BAF were scaled to capture an average of six trees at each sample point. In order to make the analysis “fair”, it was necessary to keep the number of measurements equal between selection methods. Since the nearest-tree and azimuth methods only select one tree per plot, only one tree was selected from the fixed and variable plots at each sample point. This tree was randomly selected from the trees that were captured at each plot type. Since the probability of selecting a tree as reference tree in this way varies with the number of trees captured at the tree’s sample point, it is necessary to factor the number of trees per sample point into the weighted sample estimate produced by this selection process (Iles 2003, p562). For fixed plot sampling, each neighborhood-based index was estimated by:

$$3.5 \quad u_i = \frac{\sum_{i=1}^4 [m_i * v_i]}{\sum_{i=1}^4 m_i}$$

where  $m_i$  is the number of trees captured in the  $i$ th sample point and  $v_i$  is the calculated index value for the reference tree selected at the  $i$ th sample point.

For variable plot sampling, each neighborhood-based index was estimated by:

$$3.6 \quad u_i = \frac{\sum_{i=1}^4 \left[ \frac{m_i}{b_i} * v_i \right]}{\sum_{i=1}^4 \frac{m_i}{b_i}}$$

where  $b_i$  is the basal area of the reference tree selected at the  $i$ th sample point.

Since the selection probabilities of trees selected with the nearest-tree and azimuth methods are impossible to calculate in a practical sense, the probabilities were left out of the compilation, and the estimate of a neighborhood based index for a given repetition was the arithmetic average of the four plot-level estimates.

The relative bias of estimation was calculated as:

$$3.7 \quad RBias = \frac{\sum_{i=1}^{5,000} [\hat{Y}_i - Y] * 100}{Y * 5,000}$$

where  $\hat{Y}_i$  is the estimate and  $Y$  is the value of the neighborhood-based index when calculated using only trees included in the buffer.

RRMSE was calculated as:

$$3.8 \quad RRMSE = \sqrt{\frac{\sum_{i=1}^{5,000} [(\hat{Y}_i - Y)^2]}{5,000}} \left(\frac{100}{Y}\right)$$

Because estimation of neighborhood-based index values for individual species is of interest in addition to index values calculated for all species, I also calculated the relative bias and relative root mean square error of index value estimation for five of the most common species. Finally, the frequency distributions of the estimates for each combination of index and sampling method were graphed and assessed for normality.

## Results

For estimation of the DM index for all species combined, fixed plot sampling had the lowest bias on six sites (Table 3.5). Estimates from variable plot sampling tended to be biased downward, while estimates from the nearest-tree and azimuth selection methods were generally biased upward. The azimuth selection method had the lowest RRMSE on five sites, with the nearest-tree selection method having the lowest RRMSE on the other three sites. The DM index estimates for all sampling methods at site TH75 were approximately normally distributed (Figure 3.1), although the distributions for the nearest-tree and azimuth methods lacked the smooth



continuity of the fixed and variable plot methods. The distribution for the variable plot method had a clearly negative mode.

Fixed plot sampling had the lowest bias on seven sites for estimation of the TD index (Table 3.6). The nearest-tree selection method had the lowest RRMSE on four sites, while the azimuth method had the lowest RRMSE on the other four sites. The TD index estimates for all sampling methods at site TH75 were distinctly right-skewed (Figure 3.2). There did not seem to be an obvious difference between the distributions.

To simplify analysis of the species-specific results, absolute relative bias and RRMSE values for each species and index were averaged over the eight sites. For estimation of the DM index, fixed plot sampling had the lowest mean absolute relative bias for all species examined (Table 3.7). Variable plot sampling had the lowest mean RRMSE for three species. Fixed plot sampling had the lowest absolute relative bias for all species for the estimation of the TD index, while variable plot sampling had the lowest RRMSE for three species (Table 3.8). For the U index, fixed plot sampling had the lowest absolute relative bias for three species, and nearest-tree plot sampling had the lowest RRMSE for three species (Table 3.9).

For all species combined, there was a strong relationship between RRMSE of estimation and CV of the DM index (Figure 3.3). There was also a strong relationship for individual species (Figure 3.4). There was a relationship between RRMSE of estimation and CV of the TD index for all species combined (Figure 3.5) as well as for individual species (Figure 3.6). There was also a relationship between RRMSE of estimation and CV of the U index for individual species (Figure 3.7).

Having established a relationship between CV and RRMSE for individual species across all indices and sampling methods, I explored the strength of the association between CV, index value, and relative density. All relationships discussed in the following sections are significant at the  $\alpha=0.05$  level unless otherwise stated. All

p-values are two-sided, and are not provided when relationships are strongly significant ( $p\text{-value}<0.001$ ).

### ***Species mingling (DM)***

There was a strong negative relationship between the CV and mean DM index value for all species combined ( $R^2=0.96$ ) and for individual species ( $R^2=0.88$ ). There was a moderately strong negative relationship between relative density and mean DM index for individual species ( $R^2=0.62$ ). The outlier in this relationship was red alder, which had widely varying mean index values across a constricted range of density levels (Figure 3.8). The relationship was much stronger ( $R^2=0.89$ ) with red alder excluded. There was a moderately strong negative relationship between the CV of the DM index and relative density ( $R^2=0.73$ ), with red alder again being an important outlier (Figure 3.9). The removal of red alder substantially improved the strength of the relationship ( $R^2=0.89$ ).

### ***Differentiation (TD)***

There was very little evidence that the CV of the TD index for all species combined was related to the mean TD index value ( $p\text{-value}=0.14$ ;  $R^2=0.21$ ). There was moderately strong evidence of a relationship between the CV and mean TD index value for individual species ( $R^2=0.66$ ). The relationship between the mean TD index and relative density was statistically significant but weak ( $p\text{-value}=0.0029$ ;  $R^2=0.26$ ). The relationship between CV of the TD index and tree density was not significant ( $p\text{-value}=0.086$ ;  $R^2=0.072$ ).

### ***Dominance (U)***

The relationship between the CV and mean U index value for individual species was not statistically significant ( $p\text{-value}=0.13$ ). This lack of statistical significance was caused by one instance of western hemlock, and one instance of western redcedar, in which there was only one tree in the population and that tree's

index value was 0 (Figure 3.10). Because this situation is not likely to occur in a real-world sampling application, these outliers were excluded from further analysis. The relationship was much stronger with the outliers excluded ( $p\text{-value} < 0.001$ ;  $R^2 = 0.83$ ). The relationship between the U index and relative density was statistically significant but weak ( $p\text{-value} = 0.047$ ;  $R^2 = 0.11$ ). There was little evidence that the CV of the U index was related to relative density ( $p\text{-value} = 0.98$ ).

## **Discussion**

### *Population variability of neighborhood-based indices*

It was not surprising that the RRMSE of the estimate for all indices was strongly associated with the CV of the population. A more variable population will lead to a more variable estimate. It was interesting that some indices were much more variable than others. The maximum CV for the TD index was much lower (65%) than the maximum CV for the DM (188%) or U (159%) indices. This lower CV range was generally reflected in lower RRMSE values for the TD index than for the other two indices. It is difficult to know whether this result can be generalized to other areas or whether it was a phenomenon associated with the specific areas that were sampled. However, the lower variance may be a byproduct of the continuous nature of the TD index. As opposed to the DM and U index, where individual trees can take on only four discrete values, a much larger set of values is possible for the TD index, and that may make it inherently less variable attribute.

In trying to determine what made index values for some species much more variable than others, some surprisingly clear trends emerged. There was a negative relationship between the CV and the average index value for all indices. That is, sites and site-species combinations with higher average index values also had index values that were less variable from tree to tree. As a basic principle of sampling theory, a doubling in the CV of a population will require a quadrupling of sampling effort in

order to achieve a given level of precision (Iles 2003, p52). Therefore, if this finding is generally true for other tree species and in other forest types, it has implications for sampling design when estimating neighborhood-based indices.

The DM index generally decreased with increasing relative density. This is not surprising when the nature of the DM index is considered. In general, when a given species (say Douglas-fir) is a minor component of a site, it will exist within a matrix of trees of other species and will tend to be highly mingled with its neighbors. Along a gradient in which Douglas-fir occupies an ever-larger proportion of the total stem density, the average DM index for Douglas-fir will inevitably decrease because more and more Douglas-fir trees will be neighbors to other Douglas-fir trees. However, tree-to-tree variability of the DM index will also increase, since the DM level of Douglas-fir is not dictated by its abundance, as when Douglas-fir is a minor component. Douglas-fir may exist in homogeneous patches in some parts of the site, and be intimately mingled with other species in other parts of the site. In theory, the CV of the DM index for Douglas-fir would decrease when Douglas-fir (or any species) could dominate the site to such an extent that inherently very few Douglas-fir trees would be mingled with other species. However, my analysis showed an increasing trend in CV even with species that comprised >80% of total stem density.

The exception to the gradient previously described is red alder. Both the mean index value and the CV for the DM index exhibited very weak correlation with density of red alder. Instead, red alder varied widely in these values across a constricted range of densities. This high variability in behavior may be explained by the “clumpy” nature of red alder. As presented in Chapter 2, the red alder population in these sites is very strongly clumped, with Clark-Evans statistics ranging from 0.24-0.54 (Table 2.8). This clumping behavior allowed red alder to have low mingling values even at very low abundance levels. While red alder did not always have abnormally low mingling values, the DM index for red alder did not appear to be influenced by its relative density.

The TD index was not strongly associated with relative density. Unlike with the DM index, we have no theoretical reason to believe that there would be a correlation. There would be a correlation if the CV of tree diameter for a given species was small and different species had very different average tree diameters. In this case, a higher relative density for a given species would result in more nearest-neighbor pairs where both trees were of that species. This, in turn, would result in a lower TD index. This situation was not necessarily the case for the species examined. Neither is there a theoretical reason to believe that there would necessarily be any correlation between the U index value and relative density, unless relative density was positively correlated with tree diameter. However, a weak correlation did seem to exist for all species except red alder. For lower values of relative density, the U index increased quickly with increasing relative density, but leveled off for relative density >30%.

### ***Sampling neighborhood-based indices***

The selection of trees for measurement of neighborhood-based indices could be accomplished in a number of different ways. For example, one might wish to collect neighborhood-based information on every tree captured at a subset of fixed plots measured (i.e. every third or fourth plot). This is a form of cluster sampling (Marshall et al. 2004), and might be advantageous if there is a cost savings in grouping multiple measurements in one location (e.g. if field crews are more efficient at collecting neighbor-hood based information for the remaining trees once they have gotten in practice by collecting neighborhood-based information for the first two trees at a sample point). However, if there are only sufficient resources to collect neighborhood-based information on a limited number of reference trees, and if (as seems likely) values of neighborhood-based indices could be expected to be more similar for trees that are closer together than farther apart, it would be more statistically efficient to evenly distribute the neighborhood-based measurements

throughout a given area by taking measurements at one reference tree per sample point. This paper examined four methods of selecting reference trees for this purpose.

For estimation of the DM and TD indices for all species combined, fixed plot sampling generally produced the lowest absolute relative bias, while either the nearest-tree or azimuth sampling methods always had the lowest RRMSE. This is an example of the trade-off in forest sampling between a theoretically unbiased estimator with a larger variance and a theoretically biased estimator with a smaller variance. One of the factors leading to the greater variance of fixed plot sampling may have been the unequal selection probabilities of reference trees, which then had to be corrected for with a weighted mean that might have been more variable.

One alternative to unequal-probability selection of reference trees was described by Bell (1996) and proceeds thusly: prior to the sampling effort, the maximum number of trees likely to occur at any given sample point is determined. At each sample point, a random number between 0 and this fixed maximum tree count is drawn. If the random number drawn corresponds to a tree at that sample point, that tree is designated a reference tree. If the random number is greater than the number of trees captured at that sample point, neighborhood-based information is not taken at that sample point. While having the advantage that every tree has an equal selection probability, it has the potential disadvantage that some sample points will lack neighborhood-based information. Another method of equal-probability sampling from fixed plots that could be applied here would be to sample only those trees that lie within a smaller fixed plot with a radius scaled to capture one tree on average.

For overall estimation of the DM and TD indices, variable plot sampling seemed to be a poor choice. Variable plot sampling underestimated the DM index in all but one case (site TH46) and underestimated the TD in all cases. The RRMSE was also quite high for the DM and TD indices on all sites.

However, the case against variable plot sampling in this application became less clear when its performance was evaluated on a per-species basis. Variable plot

sampling had the lowest RRMSE for DM index estimation of Douglas-fir, western redcedar and red alder. This method also had the lowest RRMSE for TD index estimation of western hemlock, western redcedar and bigleaf maple. However, variable plot sampling had high absolute relative bias, and high RRMSE, for U index estimation of all species except for Douglas-fir.

The explanation for this apparent paradox – variable plot sampling performing well for individual-species DM and TD index estimation and poorly for overall DM and TD index estimation – seems to be rooted in the nature of variable plot sampling as a tree selection method. Variable plot sampling selects trees with probability proportional to their basal area. It is still a theoretically unbiased selection method for estimation of neighborhood-based indices, because trees are weighted inversely proportional to their size in the estimate. However, the weighted average seemed to fail often in this simulation, since the sample size (4 trees) was so low.

While variable plot sampling will select a species with probability proportional to its basal area on a given site, the weight a species has in determining the overall index value is determined by its density. Since minor species on these sites (western redcedar, grand fir, red alder, bigleaf maple and Pacific dogwood) always comprised a greater percentage of the total density than the total basal area (Table 3.10), they were not adequately represented in the estimation of overall DM and TD index values when variable plot sampling was used. Where there were differences in TD and DM index values between these species and the frequently dominant species Douglas-fir and western hemlock, this difference was expressed as a bias.

However, for estimation of DM and TD index values of individual tree species, variable plot sampling frequently had lower RRMSE values than fixed plot sampling. This is because, unlike with estimation of the overall DM and TD indices, there was no penalty applied for failing to select a minor species on a given repetition of a simulation program. Most species, however minor, were selected at least a few times over the 5,000 iterations of the simulation, and the trees selected provided accurate

estimates of the DM and TD indices for some species. In addition, while variable plot sampling was frequently more biased than fixed plot sampling, it also seemed to provide less variable results.

It should be noted that these indices can be manipulated to represent different aspects of forest structure. I have only considered here a framework wherein the “true” index value is the arithmetic mean of the values of all trees in a stand. In other words, each tree has an equal vote in determining the overall outcome. I have used this understanding because all of the presentations of neighborhood-based indices that I have encountered in the literature appear to have used this “democratic” approach to calculating index values from stem-mapped plot data (Aguirre et al. 2003; Kint et al. 2004; Kint 2005; Pommerening 2002). However, Gadow, one of the leading developers of the neighborhood-based approach, has suggested that “structural attributes of reference trees do not represent the relative share of the number of trees but proportions of forest area” (2000). In other words, trees with more space around them should have their index values count more. In this case, the nearest-tree method of sampling, which will select a given tree with probability proportional to the area in which it is the nearest tree, is the unbiased (and greatly preferred) method of selecting reference trees. While certainly valid, and perhaps more common in Europe, this “area-based” approach will not be a very familiar concept to forest managers in the United States, and interpretation of index values may be more difficult when individual values are weighted in this way. Another valid approach would be to weight index values according to basal area, in which case variable plot sampling would probably be a much more attractive option. The weighting system used could be dictated by the sampling objectives for a given tract. If it is considered important to monitor long-term trends in development of an even-aged forest, weighting by basal area might be most appropriate, since it will be cause estimates to be minimally affected by smaller trees (which tend to appear and die at greater rates than larger trees). However, if an uneven-aged forest were being inventoried, we may prefer to



keep index values unweighted, since all size classes of trees might be equally of interest.

In any case, it should be recognized that different weighting systems have the potential to give very different results. No matter what weighting system (if any) is used in the calculation of neighborhood-based indices, it is imperative that one approach be consistently utilized. The wider adoption of neighborhood-based indices in operational settings will be greatly encumbered otherwise.

### **Conclusion**

While this study demonstrated some trends in population variability and sampling of neighborhood-based indices, caution should be used in extending inference beyond the stem maps. While it seems reasonable to suggest that these findings could extend to other forests in this region, the neighborhood-based indices are functions of the spatial arrangement of trees of different species and sizes, and these patterns may be very different for other forests. Hardwoods such as bigleaf maple and red alder were not generally abundant on these stem maps, and their spatial distribution may be different in other areas where they are more abundant. Conversely, the conifer populations in these riparian sites may behave have a different spatial distribution than conifer populations in upland forest.

In the sites examined, fixed plot sampling had the lowest absolute relative bias across the board, but the variability of estimates produced by this sampling method was high. Variable plot sampling performed poorly for estimating overall DM and TD index values, but performed well for estimating these indices for some species. Despite their theoretical bias, the nearest-tree and azimuth methods had the lowest RRMSE for overall estimation of the DM and TD indices, indicating that the variability of these methods was quite low. The nearest-tree and azimuth methods also performed well for species-specific estimation of the U index.

Inventory professionals intending to incorporate neighborhood-based indices into inventory programs would be advised to establish clear objectives for the sampling program. If estimation of overall index values is most important, fixed plot, azimuth or nearest-tree sampling may be most appropriate. If estimation of index values for certain species is more important, variable plot sampling may perform better. However, in the sites examined, samplers should be aware that variable plot sampling may not capture minor species in proportion to the percentage of total density they occupy.

While fixed plot sampling proved to be highly variable in this simulation, it may not be inherently so. A different method of selecting trees from fixed plots may provide better results. This possibility could be more fully examined in future studies. In the meantime, nearest-tree and azimuth sampling may be good choices, despite being biased in the long run. As Iles (2003, p35-36) notes, it is possible for a known biased method to provide better results at the stand level, whereas an unbiased method would provide better results for landscape-level estimation with a far larger sample size. Therefore, the appropriate selection method may depend on the scale of the inventory project.

Based upon the results of this study, the nearest-tree method of selection is recommended as the best option for estimating neighborhood-based indices in similar forest types with a small sample size. While it is a biased selection method, the probabilities of selection are simpler to calculate for this method than for the azimuth method. Furthermore, this method was recommended by Gadow and Pogoda (2000) for sampling neighborhood-based indices. For landscape-scale estimation with a large sample size, the unbiasedness of fixed plot sampling would probably make it the selection method of choice. It will be necessary for future studies, using different stem-mapped plots and perhaps including several different unbiased methods of selecting from fixed plots, to confirm or modify these recommendations.

Table 3.1: Arithmetic mean DM (species mingling) index values, by species and for all species combined. DM index values range between 0 and 1. Higher index values indicate greater species mingling; lower values indicate less species mingling.

| Species           | BL13 | KM17 | KM18 | KM19 | KM21 | OM36 | TH46 | TH75 |
|-------------------|------|------|------|------|------|------|------|------|
| all combined      | 0.21 | 0.41 | 0.53 | 0.51 | 0.45 | 0.20 | 0.35 | 0.41 |
| Douglas-fir       | 0.12 | 0.68 | 0.73 | 0.42 | 0.45 | 0.11 | 0.25 | 0.31 |
| western hemlock   | -    | 0.32 | 0.36 | 0.56 | 0.38 | 1.00 | 0.67 | 1.00 |
| western redcedar  | -    | 1.00 | 0.89 | 0.60 | 0.94 | 0.78 | -    | 0.85 |
| grand fir         | -    | -    | -    | -    | -    | 0.83 | -    | -    |
| Pacific yew       | 1.00 | -    | -    | -    | -    | -    | -    | -    |
| red alder         | -    | 0.52 | 0.67 | 0.58 | 0.36 | 0.33 | -    | 0.79 |
| bigleaf maple     | 0.72 | -    | -    | -    | -    | -    | -    | 0.46 |
| Pacific dogwood   | -    | -    | -    | -    | -    | -    | -    | -    |
| black cottonwood  | -    | -    | -    | 1.00 | -    | 1.00 | -    | -    |
| golden chinquapin | -    | -    | -    | -    | -    | -    | -    | -    |

Table 3.2: Arithmetic mean TD (diameter differentiation) index values, by species and for all species combined. TD index values range between 0 and 1. Higher index values indicate greater diameter differentiation; lower values indicate less diameter differentiation.

| Species           | BL13 | KM17 | KM18 | KM19 | KM21 | OM36 | TH46 | TH75 |
|-------------------|------|------|------|------|------|------|------|------|
| all combined      | 0.31 | 0.24 | 0.35 | 0.35 | 0.32 | 0.33 | 0.24 | 0.37 |
| Douglas-fir       | 0.30 | 0.23 | 0.38 | 0.35 | 0.35 | 0.30 | 0.23 | 0.34 |
| western hemlock   | -    | 0.22 | 0.30 | 0.34 | 0.28 | 0.68 | 0.27 | 0.44 |
| western redcedar  | -    | 0.67 | 0.48 | 0.39 | 0.43 | 0.54 | -    | 0.36 |
| grand fir         | -    | -    | -    | -    | -    | 0.52 | -    | -    |
| Pacific yew       | 0.77 | -    | -    | -    | -    | -    | -    | -    |
| red alder         | -    | 0.39 | 0.38 | 0.26 | 0.28 | 0.43 | -    | 0.31 |
| bigleaf maple     | 0.34 | -    | -    | -    | -    | -    | -    | 0.42 |
| Pacific dogwood   | -    | -    | -    | -    | -    | -    | -    | -    |
| black cottonwood  | -    | -    | -    | 0.26 | -    | 0.58 | -    | -    |
| golden chinquapin | -    | -    | -    | -    | -    | -    | -    | -    |

Table 3.3: Arithmetic mean U (dominance) index values by species. U index values range between 0 and 1. Higher index values indicate greater dominance of a species; lower values indicate less dominance.

| Species           | BL13 | KM17 | KM18 | KM19 | KM21 | OM36 | TH46 | TH75 |
|-------------------|------|------|------|------|------|------|------|------|
| Douglas-fir       | 0.55 | 0.69 | 0.67 | 0.62 | 0.58 | 0.58 | 0.54 | 0.62 |
| western hemlock   | -    | 0.46 | 0.49 | 0.50 | 0.48 | 0.00 | 0.50 | 0.38 |
| western redcedar  | -    | 0.00 | 0.14 | 0.30 | 0.21 | 0.11 | -    | 0.33 |
| grand fir         | -    | -    | -    | -    | -    | 0.00 | -    | -    |
| pacific yew       | 0.00 | -    | -    | -    | -    | -    | -    | -    |
| red alder         | -    | 0.48 | 0.63 | 0.58 | 0.56 | 0.57 | -    | 0.83 |
| bingleaf maple    | 0.28 | -    | -    | -    | -    | -    | -    | 0.36 |
| pacific dogwood   | -    | -    | -    | -    | -    | -    | -    | -    |
| black cottonwood  | -    | -    | -    | 0.67 | -    | 0.00 | -    | -    |
| golden chinquapin | -    | -    | -    | -    | -    | -    | -    | -    |

Table 3.4: Summary statistics about the clipped plots used for this simulation.

| Site | Size (ha) | Number of trees |
|------|-----------|-----------------|
| BL13 | 0.279     | 90              |
| KM17 | 0.288     | 116             |
| KM18 | 0.304     | 188             |
| KM19 | 0.336     | 199             |
| KM21 | 0.284     | 122             |
| OM36 | 0.208     | 108             |
| TH46 | 0.293     | 141             |
| TH75 | 0.301     | 243             |

Table 3.5: Relative bias and RRMSE of DM (species mingling) index estimation by site and selection method. Bolded values indicate the sampling method with the lowest absolute relative bias or RRMSE for a particular site.

| Site                 | Fixed       | Variable    | Nearest-tree | Azimuth     |
|----------------------|-------------|-------------|--------------|-------------|
| <b>Relative bias</b> |             |             |              |             |
| BL13                 | <b>-1.0</b> | -11.1       | 18.4         | 15.0        |
| KM17                 | <b>0.1</b>  | -1.7        | 8.1          | 2.7         |
| KM18                 | <b>-0.6</b> | -4.5        | 1.3          | 1.6         |
| KM19                 | 3.1         | <b>-0.5</b> | 5.7          | 3.7         |
| KM21                 | <b>0.4</b>  | -6.2        | 1.6          | 0.6         |
| OM36                 | <b>0.8</b>  | -24.6       | -8.2         | -8.1        |
| TH46                 | -0.2        | <b>0.2</b>  | 2.6          | 4.7         |
| TH75                 | <b>0.7</b>  | -7.7        | 3.5          | 2.0         |
| <b>RRMSE</b>         |             |             |              |             |
| BL13                 | 67.7        | 77.6        | <b>61.7</b>  | 64.2        |
| KM17                 | 39.9        | 43.3        | 37.8         | <b>36.1</b> |
| KM18                 | 33.0        | 36.6        | <b>29.3</b>  | 31.6        |
| KM19                 | 35.9        | 38.6        | 32.2         | <b>31.3</b> |
| KM21                 | 39.1        | 44.3        | 36.0         | <b>34.5</b> |
| OM36                 | 73.1        | 88.4        | 70.8         | <b>68.8</b> |
| TH46                 | 47.4        | 51.4        | <b>40.1</b>  | 40.8        |
| TH75                 | 48.7        | 53.8        | 47.2         | <b>45.7</b> |

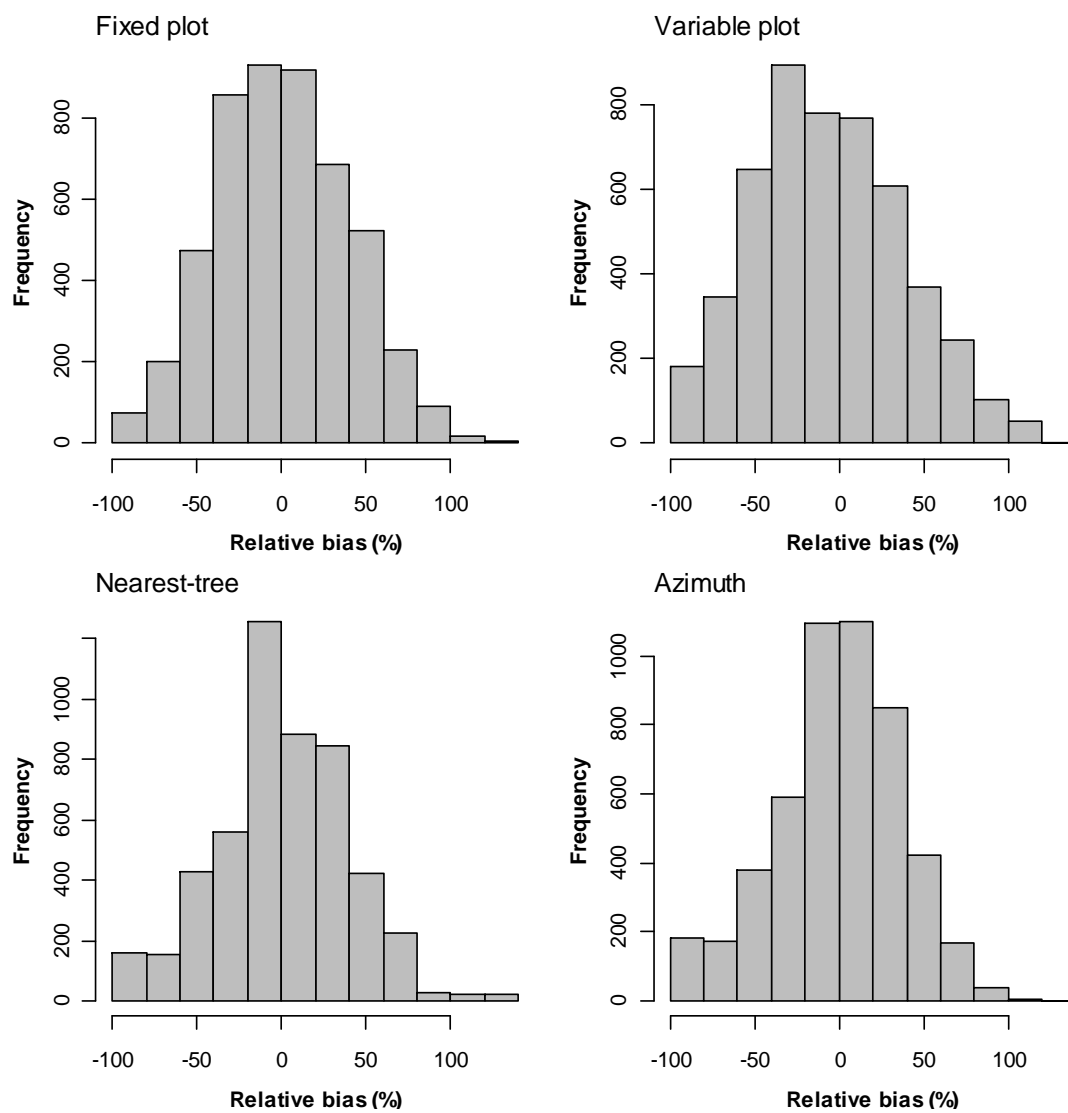


Table 3.1. Relative bias distribution for estimation of the DM index at site TH75.



Table 3.6: Relative bias and RRMSE of TD (diameter differentiation) index estimation by site and selection method. Bolded values indicate the sampling method with the lowest absolute relative bias or RRMSE for a particular site.

| Site                 | Fixed       | Variable | Nearest-tree | Azimuth     |
|----------------------|-------------|----------|--------------|-------------|
| <b>Relative bias</b> |             |          |              |             |
| BL13                 | <b>-0.6</b> | -2.2     | -0.2         | -3.9        |
| KM17                 | <b>-1.1</b> | -5.0     | 5.2          | 5.5         |
| KM18                 | <b>-0.8</b> | -4.5     | -1.8         | -2.1        |
| KM19                 | <b>0.8</b>  | -4.4     | 1.1          | 1.2         |
| KM21                 | -0.5        | -5.8     | <b>-0.3</b>  | -2.7        |
| OM36                 | <b>-0.2</b> | -6.0     | -2.2         | -1.0        |
| TH46                 | <b>-0.3</b> | -3.7     | -0.4         | -2.0        |
| TH75                 | <b>0.5</b>  | -5.0     | -3.8         | -4.1        |
| <b>RRMSE</b>         |             |          |              |             |
| BL13                 | 21.1        | 22.7     | 18.5         | <b>18.4</b> |
| KM17                 | 25.3        | 27.1     | <b>23.5</b>  | 24.0        |
| KM18                 | 25.3        | 25.7     | 23.4         | <b>23.1</b> |
| KM19                 | 20.9        | 23.9     | <b>20.1</b>  | 20.3        |
| KM21                 | 25.1        | 24.7     | <b>20.1</b>  | 21.8        |
| OM36                 | 21.7        | 24.6     | 21.2         | <b>19.3</b> |
| TH46                 | 25.2        | 23.7     | 22.2         | <b>21.6</b> |
| TH75                 | 24.4        | 25.7     | <b>22.4</b>  | 22.8        |

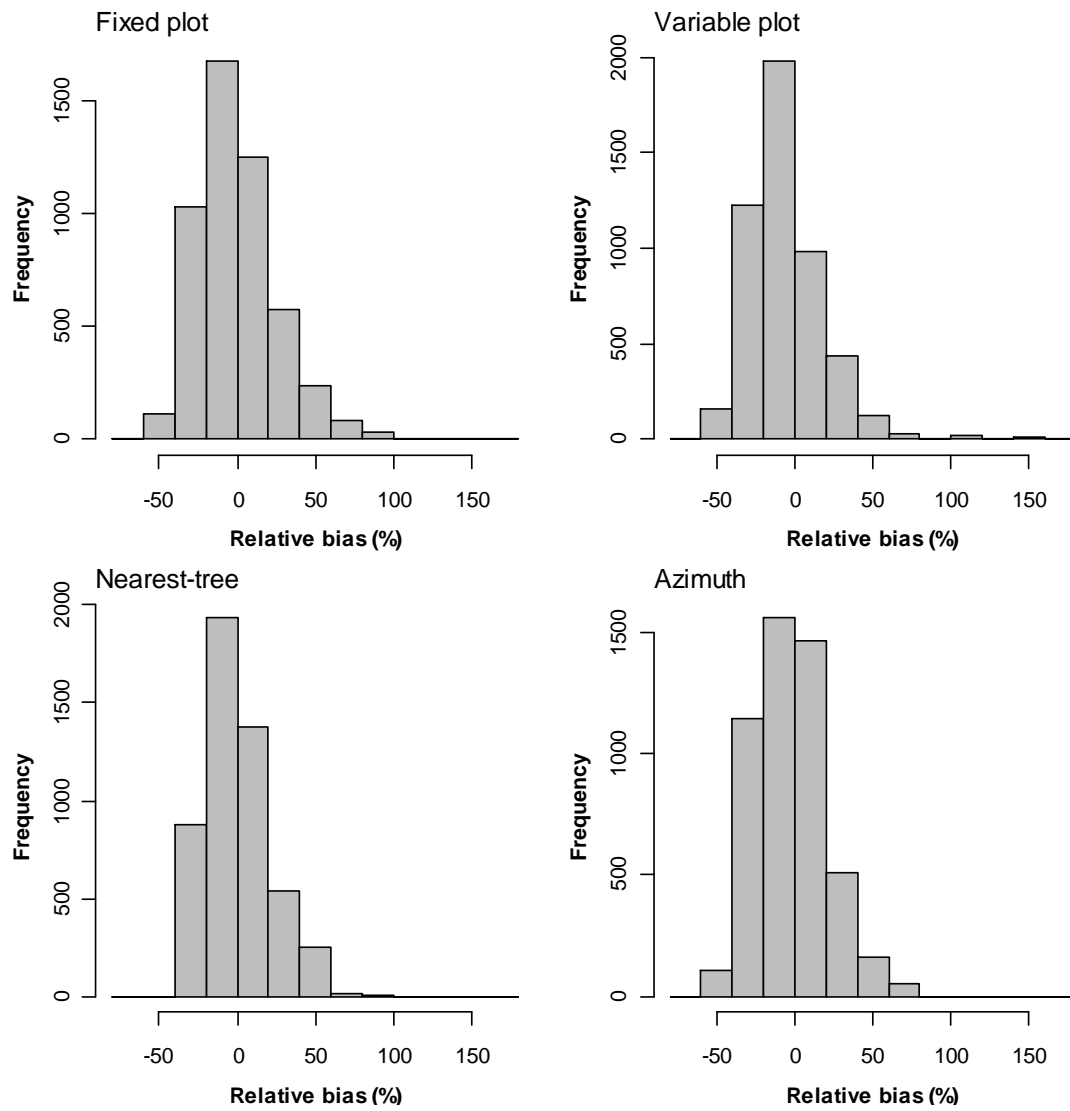


Figure 3.2. Relative bias distribution for estimation of the TD index at site TH75.

Table 3.7: Mean absolute relative bias and RRMSE of DM (species mingling) index estimation for the 5 most common species, averaged over all sites where each species was present. Bolded values indicate the sampling method with the lowest mean absolute relative bias or RRMSE for a particular species.

| Species                       | Fixed       | Variable    | Nearest-tree | Azimuth     |
|-------------------------------|-------------|-------------|--------------|-------------|
| <b>Absolute relative bias</b> |             |             |              |             |
| Douglas-fir                   | <b>2.0</b>  | 3.3         | 5.6          | 4.2         |
| western hemlock               | <b>3.5</b>  | 7.1         | 4.3          | 5.2         |
| western redcedar              | <b>1.8</b>  | 4.9         | 3.7          | 2.4         |
| red alder                     | <b>3.4</b>  | 4.5         | 8.7          | 6.6         |
| bigleaf maple                 | <b>9.1</b>  | 15.0        | 20.0         | 21.3        |
| <b>RRMSE</b>                  |             |             |              |             |
| Douglas-fir                   | 63.7        | <b>62.7</b> | 62.7         | 63.5        |
| western hemlock               | 45.5        | 45.6        | 45.4         | <b>44.2</b> |
| western redcedar              | 20.9        | <b>20.7</b> | 20.8         | 21.3        |
| red alder                     | 53.0        | <b>49.0</b> | 54.2         | 55.0        |
| bigleaf maple                 | <b>45.4</b> | 50.1        | 47.6         | 47.6        |

Table 3.8: Mean absolute relative bias and RRMSE of TD (diameter differentiation) index estimation for the 5 most common species, averaged over all sites where each species was present. Bolded values indicate the sampling method with the lowest mean absolute relative bias or RRMSE for a particular species.

| Species                       | Fixed      | Variable    | Nearest-tree | Azimuth     |
|-------------------------------|------------|-------------|--------------|-------------|
| <b>Absolute relative bias</b> |            |             |              |             |
| Douglas-fir                   | <b>1.2</b> | 3.9         | 2.0          | 3.5         |
| western hemlock               | <b>1.5</b> | 11.6        | 3.6          | 3.3         |
| western redcedar              | <b>1.2</b> | 8.7         | 2.2          | 3.1         |
| red alder                     | <b>3.9</b> | 5.9         | 9.1          | 5.8         |
| bigleaf maple                 | <b>2.9</b> | 9.8         | 8.2          | 7.1         |
| <b>RRMSE</b>                  |            |             |              |             |
| Douglas-fir                   | 30.1       | 30.8        | <b>28.3</b>  | 28.3        |
| western hemlock               | 38.1       | <b>32.9</b> | 38.5         | 37.9        |
| western redcedar              | 27.2       | <b>25.7</b> | 27.7         | 27.7        |
| red alder                     | 39.8       | 40.4        | 41.9         | <b>39.2</b> |
| bigleaf maple                 | 40.6       | <b>37.1</b> | 44.1         | 41.6        |

Table 3.9: Mean absolute relative bias and RRMSE of U (dominance) index estimation for the 5 most common species, averaged over all sites where each species was present. Bolded values indicate the sampling method with the lowest mean absolute relative bias or RRMSE for a particular species.

| Species                       | Fixed      | Variable | Nearest-tree | Azimuth     |
|-------------------------------|------------|----------|--------------|-------------|
| <b>Absolute relative bias</b> |            |          |              |             |
| Douglas-fir                   | <b>1.2</b> | 14.2     | 3.1          | 2.8         |
| western hemlock               | <b>2.5</b> | 27.9     | 7.6          | 5.3         |
| western redcedar              | <b>6.4</b> | 24.6     | 18.4         | 14.1        |
| red alder                     | 3.6        | 15.7     | 5.9          | <b>2.5</b>  |
| bigleaf maple                 | 4.6        | 62.0     | 13.3         | <b>2.8</b>  |
| <b>RRMSE</b>                  |            |          |              |             |
| Douglas-fir                   | 42.7       | 42.3     | <b>40.0</b>  | 40.1        |
| western hemlock               | 58.2       | 62.2     | 58.4         | <b>57.7</b> |
| western redcedar              | 99.1       | 112.9    | <b>97.1</b>  | 98.3        |
| red alder                     | 49.1       | 49.7     | 51.2         | <b>48.9</b> |
| bigleaf maple                 | 94.7       | 118.2    | <b>92.6</b>  | 97.7        |

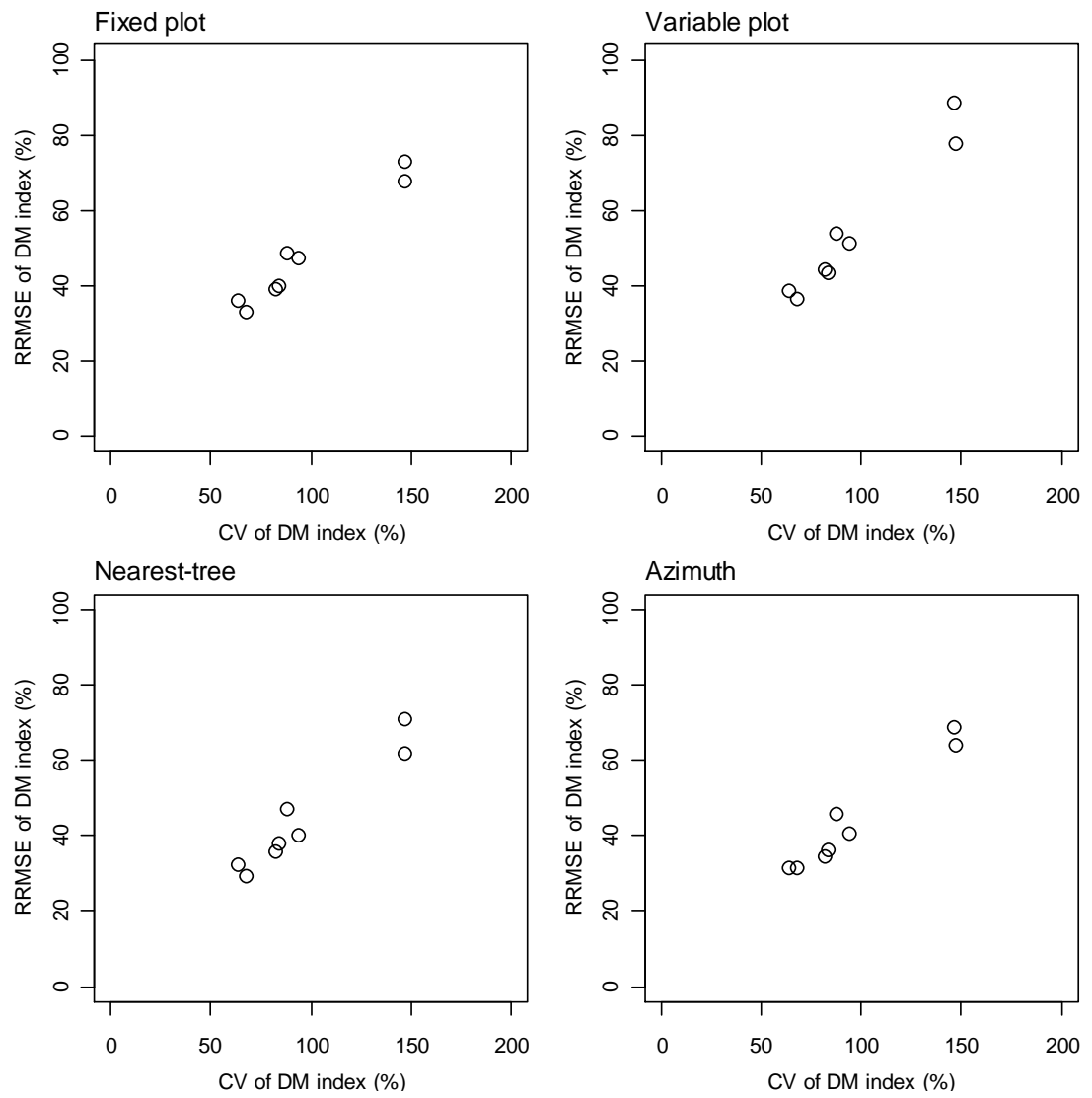


Figure 3.3. Relationship between RRMSE and CV of overall DM (species mingling) index estimation. Each dot represents one site.

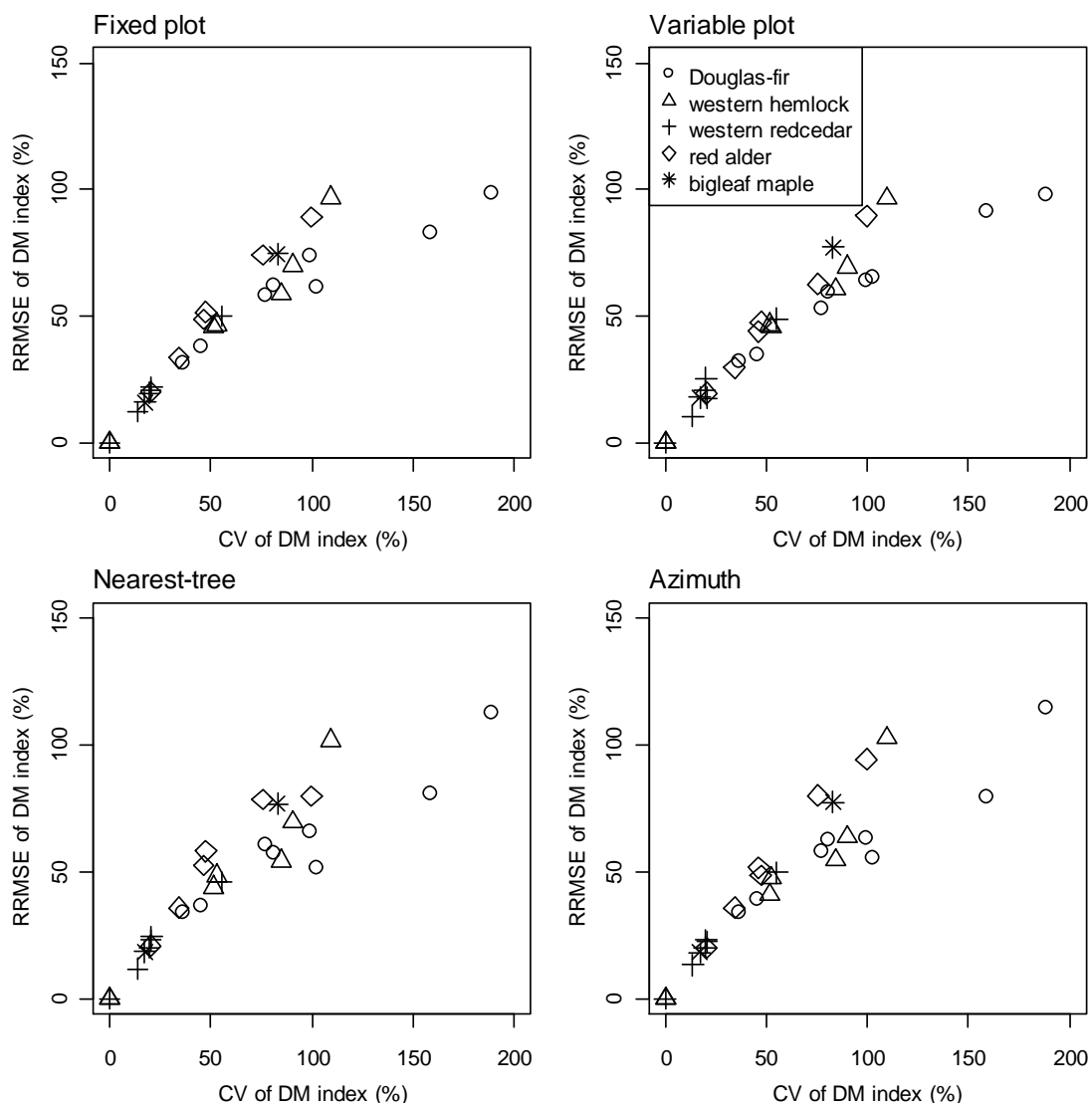


Figure 3.4. Relationship between RRMSE and CV of overall DM (species mingling) index estimation. Each dot represents an instance of a tree species at a site.

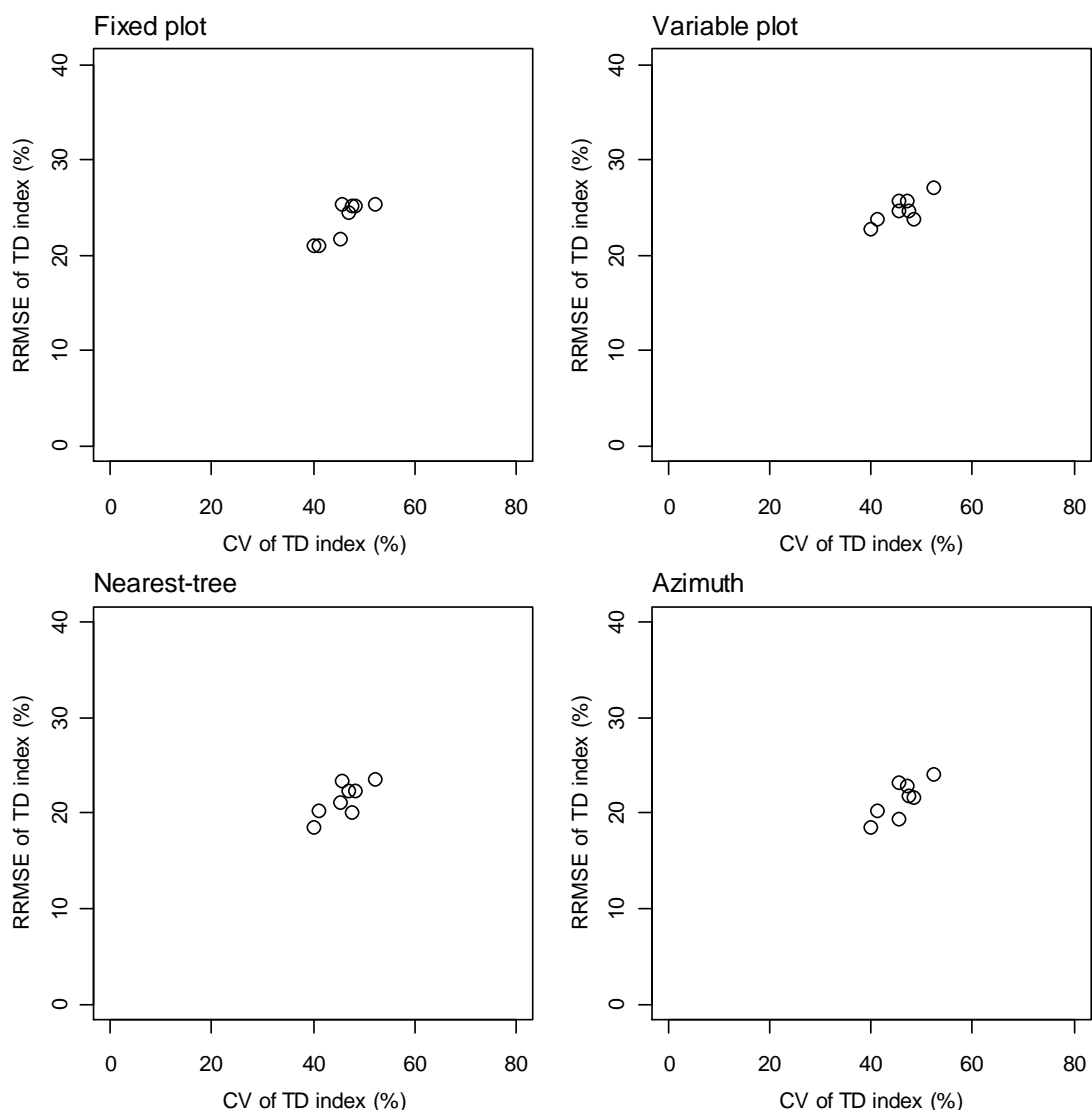


Figure 3.5. Relationship between RRMSE and CV of overall TD (diameter differentiation) index estimation. Each dot represents one site.



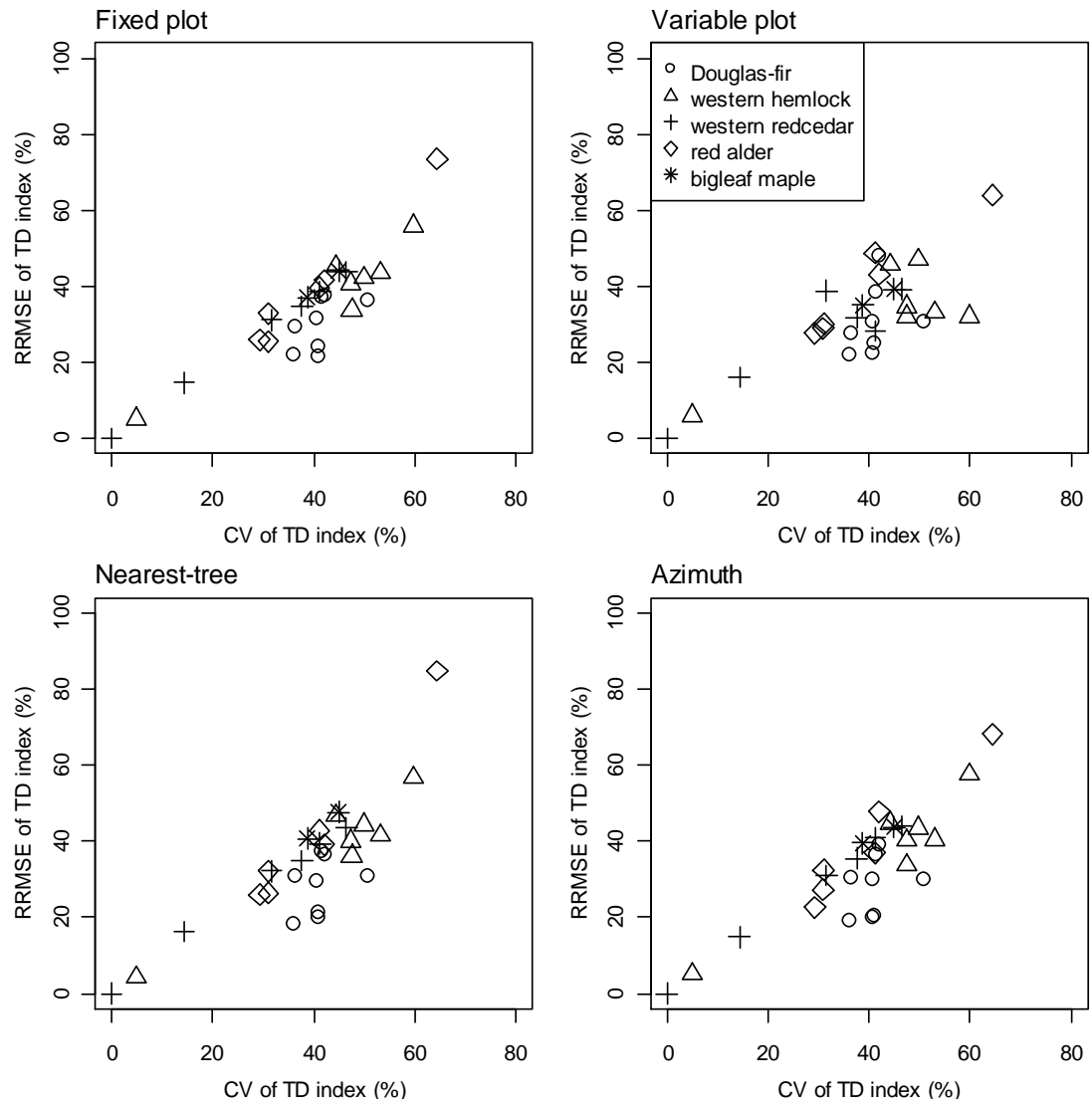


Figure 3.6. Relationship between RRMSE and CV of overall TD (diameter differentiation) index estimation. Each dot represents an instance of a tree species at a site.

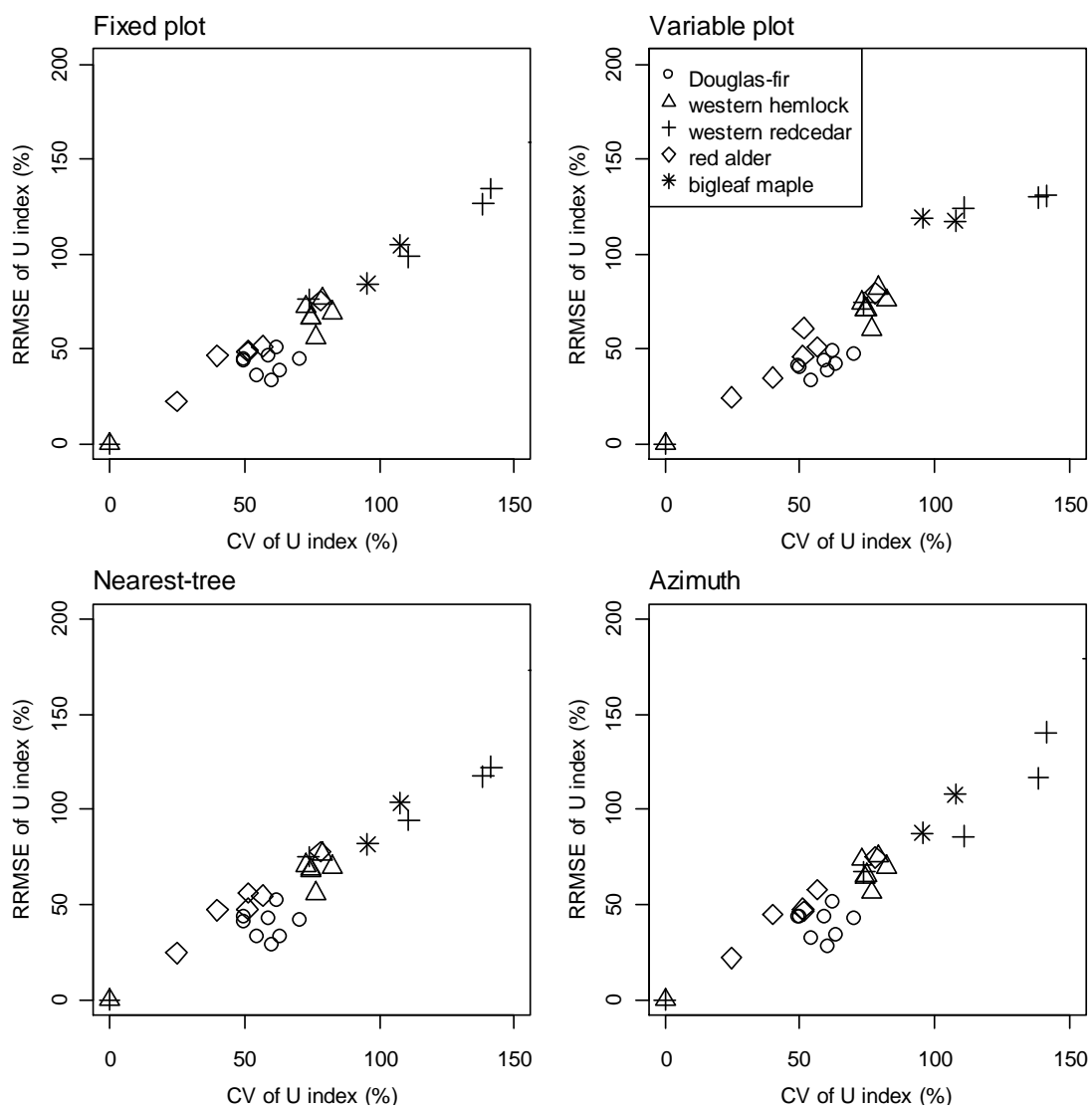


Figure 3.7. Relationship between RRMSE and CV of overall U (dominance) index estimation. Each dot represents an instance of a tree species at a site.

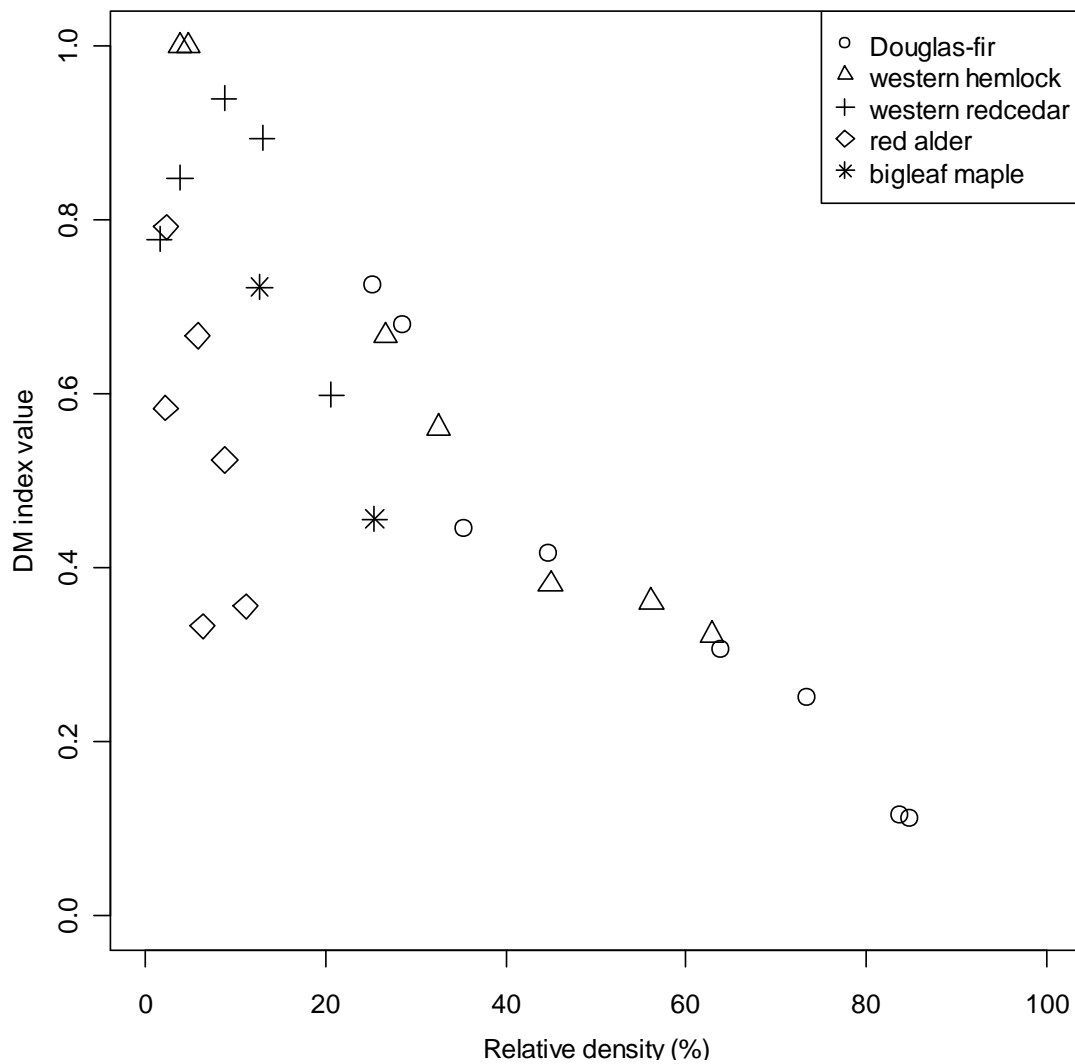


Figure 3.8. Relationship between mean DM index value and relative density. Each dot represents an instance of a species at a site. Note the broad DM index value range of red alder across a constricted range of relative density values.

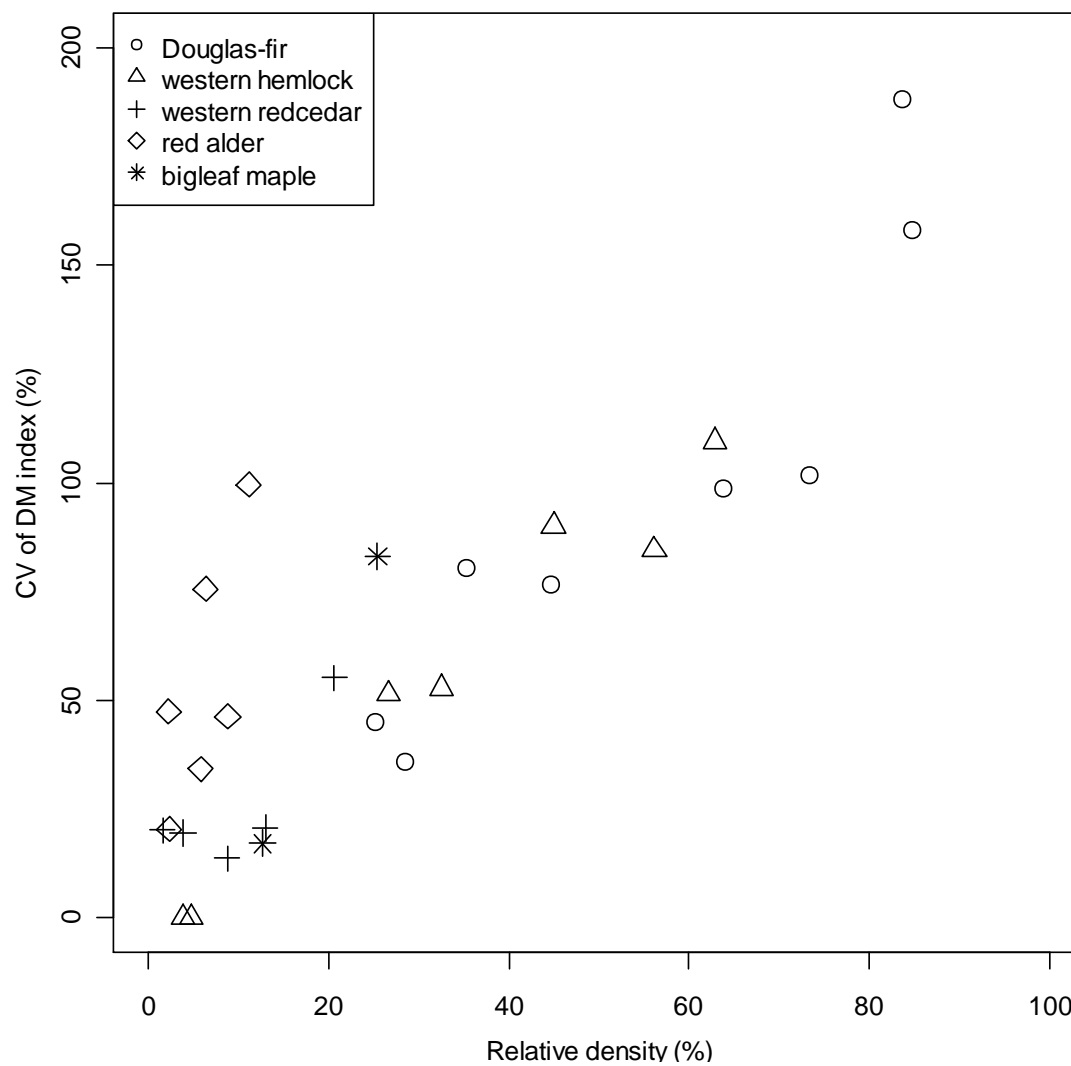


Figure 3.9. Relationship between CV of DM index estimation and relative density. Each dot represents an instance of a species at a site. Note the broad CV range of red alder across a constricted range of relative density values.

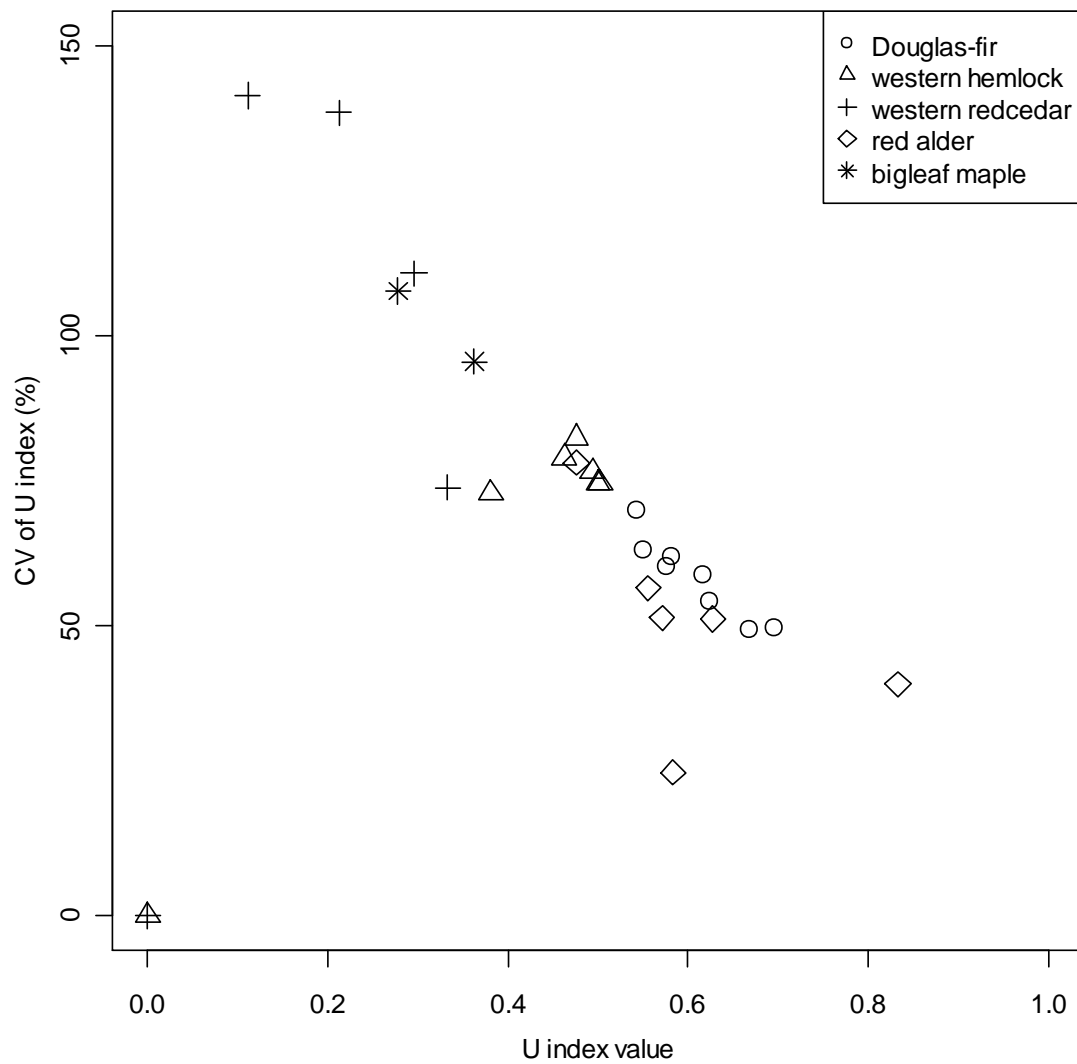


Figure 3.10. Relationship between CV of U index estimation and U mean index value. Each dot represents an instance of a species at a site. Note the instances of western hemlock and red alder in which the mean U index value is 0.

Table 3.10. Percentage of total density (N) and basal area (G) for species comprising at least 1% of total density.

|                  | BL13 |    | KM17 |    | KM18 |    | KM19 |    | KM21 |    | OM36 |    | TH46 |    | TH75 |    |
|------------------|------|----|------|----|------|----|------|----|------|----|------|----|------|----|------|----|
|                  | N    | G  | N    | G  | N    | G  | N    | G  | N    | G  | N    | G  | N    | G  | N    | G  |
| Douglas-fir      | 84   | 93 | 28   | 38 | 25   | 39 | 45   | 62 | 35   | 45 | 85   | 91 | 73   | 76 | 64   | 87 |
| western hemlock  | -    | -  | 63   | 58 | 56   | 53 | 33   | 30 | 45   | 46 | 4    | 1  | 27   | 24 | 5    | 2  |
| western redcedar | -    | -  | -    | -  | 13   | 4  | 21   | 6  | 9    | 2  | 2    | 0  | -    | -  | 4    | 1  |
| grand fir        | -    | -  | -    | -  | -    | -  | -    | -  | -    | -  | 4    | 1  | -    | -  | -    | -  |
| red alder        | -    | -  | 9    | 4  | 6    | 4  | 2    | 2  | 11   | 7  | 6    | 6  | -    | -  | 2    | 2  |
| bigleaf maple    | 13   | 7  | -    | -  | -    | -  | -    | -  | -    | -  | -    | -  | -    | -  | 25   | 8  |
| Pacific dogwood  | 4    | 0  | -    | -  | -    | -  | -    | -  | -    | -  | -    | -  | -    | -  | -    | -  |

## CHAPTER FOUR

### A CHARACTERIZATION OF OVERSTORY AND UNDERSTORY DYNAMICS IN THE TRASK WATERSHED, OREGON

#### **Introduction**

Headwater streams are tightly coupled with their terrestrial surroundings. By shading stream reaches, providing food for aquatic biota, and delivering coarse woody debris to stream systems, riparian forests exert considerable influence on their associated stream systems (Bilby and Bisson 1992). The nature of this influence can depend heavily on the structure and composition of the riparian forest. Conifers such as Douglas-fir and western hemlock cast perennially dense shade over stream channels and can provide streams with large, durable coarse woody debris, an important structural feature for fish habitat (Bilby and Bisson 2001; Harmon et al. 1986). Hardwoods such as red alder and bigleaf maple cast lighter shade and allow exposure to sunlight when leaves are off during winter and early spring. Leaf litter from hardwoods has higher nutritional value to stream biota than that from conifers (Richardson et al. 2005), and hardwoods along streambanks provide diverse wildlife habitat in an otherwise conifer-dominated landscape (Hagar 2007; McComb 1993).

Because of their ability to quantify structural diversity at the between-tree scale, the neighborhood-based indices described in Chapter 3 may be ideally suited to characterize riparian areas. However, they require more information, and therefore, a more intensive sampling effort, to calculate than conventional metrics of forest structure such as density and basal area. Therefore, it is important to determine whether the additional information they provide is worth the additional cost.

The Trask Watershed Study is a paired-watershed study that was initiated to evaluate the effects of timber harvest on headwater streams, which receive less

protection under the Oregon Forest Practice Act than many larger-order streams (TRWS 2008, p2). To characterize the pre-harvest condition of this area, sampling of overstory and understory vegetation was completed during the summer of 2009. The sampling effort was designed to fulfill the following objectives:

- 1) Evaluate the effectiveness of neighborhood-based indices, in comparison with conventional plot-level inventory data, for conveying information about riparian forest structure in the Trask Watershed.
- 2) Characterize the abundance of trees, understory flora, snags and down wood in the Trask Watershed.
- 3) Provide insight into the past and present structural development of the Trask Watershed.

## **Methods**

### ***Study area***

The study area, known hereafter as the Trask Watershed, comprises the upper 25 km<sup>2</sup> of the East Fork of the South Fork of the Trask River, with elevation ranging from 275-1100m (TRWS 2007, p3). It is located in townships 2S7W, 3S7W, 2S6W and 3S6W, approximately 45 minutes northeast of McMinnville, Oregon. Geology is characterized by a mix of igneous and sedimentary formations, and climatic features of note include wet winters, dry summers and mild temperatures year-round (TRWS 2007, p4). The study area is within the western hemlock vegetation zone described by Franklin and Dyrness (1973).

Most of the study area is comprised of second-growth conifer forest. Judging from maps of burned areas, this area was affected by two Tillamook Burn fires: the Saddle Mountain fire of 1939 and the North Fork/Elkhorn fire of 1951. Between catastrophic wildfire and timber harvest (which began in the study area before 1936),



most of the conifer overstory was removed by the 1950s (TRWS 2007, p17-18). Some commercial thinning has been done since the mid-1990s within the headwater reaches of the study area. Riparian areas within the study area are comprised of conifer, hardwood, and mixed conifer/hardwood stands (TRWS 2007, p19).

### *Sites sampled*

To study the effects of different harvest practices on headwater stream systems, 15 different “sites” had been delineated. Each site is a headwater sub-basin that drains into one of four different headwater streams: Gus Creek (also known as Bob & Sherri Creek), Pothole Creek, Rock Creek and Upper Main (Figure 4.1). We collected data at eight of these sites in July and August of 2009: GS1, GS3, PH2, PH3, PH4, RK2, RK3 and UM3. The priorities guiding site selection were: to sample at least one site in each stream system; to characterize a range of forest types within the Watershed; and to sample at least some of the areas used for songbird research, and therefore increase the possibilities for interdisciplinary collaboration.

### *Transect location*

Near the downstream end of each site, a 100m “habitat reach” was installed by previous researchers for the collection of hemispherical stream photos, stream slope measurements, and prior vegetation transects (Ashkenas 2008). The downstream “start” of each habitat reach was marked with a monumented rod. The sampling method was intended to characterize the 200-300m of riparian stream area upstream from this rod. This was accomplished through the use of transects, running perpendicular to the stream, located systematically at set intervals.

Transects were established independently on both sides of each stream. The side on which sampling was initiated varied by site. For the first side sampled, transects were laid out as follows:

The monumented start of the habitat reach was used as an anchor point. The first transect was placed at a random distance on the interval 0-20m upstream from this point for a random start. Subsequent transects were placed systematically at intervals of 40m (for sites GS1 and GS3) and 60m (for all other sites). However, the between-transect distance varied on occasion according to local conditions; for example, the site RK3 had some extreme instances of stream bending such that two transects placed 60m apart would come very close to crossing; in this case we travelled an additional 60m to locate a subsequent transect. While the initial random start was measured with a tape, subsequent between-plot distances were estimated by pacing. This was considered to be the most efficient method since it allowed for the most flexibility when dealing with extreme stream bending, brushy conditions, and steep terrain.

Transect layout of the other side of the stream could begin in one of two ways. If sampling on one side was completed during the middle of a working day, we would cross the stream and continue upstream a random distance on the interval 0-20m, where the first transect on the other side would be established. We would then continue back downstream, systematically locating transects at the prescribed spacing (40m or 60m). If sampling on one side was completed at the end of a working day, we would begin sampling the next morning using the same protocol for initiation of sampling described previously.

If the stream crossed a road upstream from the habitat reach, which happened in sites PH2, PH3, PH4 and UM3, a 40m buffer was placed on both sides of the road, within which no transect could be located. To ensure adequate coverage of the whole site, we established at least four transects were on each side of a stream. Additional transects were established as time allowed.

### ***Location of sample points within transects***

The combined transect/sample point layout is shown in Figure 4.2. Transects were oriented roughly perpendicular to the direction of streamflow at the point where the stream intersected the transect. The first sample point on the transect was located at a random distance on the interval 3.99-7.98m from the edge of the incised stream channel. A second sample point was located 11.97m from the first sample point. The purpose of this design was to introduce some randomization while still ensuring good coverage of the 20m nearest the stream bank.

While the protocol called for two sample points to be established on each transect, this was not done in every case. In some rare cases slopes were so steep (>100%) that the first plot was well beyond anything that could be defined as a riparian zone, and the second plot was not sampled. In other cases the terrain was so steep and unstable that only one plot was installed for safety reasons.

### ***Information collected at each sample point***

For each sample point, the azimuth (degrees), slope (%) and horizontal distance from the stream (m) were measured. For some transects in GS1, slope and horizontal distance to the stream were collected for every sample point. The disadvantage of this method became apparent whenever there was a break in the slope such that the stream was hidden from view at the second sample point on a transect. For the rest of the transects, horizontal distance from, and slope to, the stream were collected for the first sample point in the transect; and horizontal distance from, and slope to, the first plot were collected for the second sample point in the transect.

In some cases, a sample point fell closer to a “secondary stream” than the stream that the transect was based off of (the “primary stream”). This could occur for one of several reasons: 1) the transect went over a slight ridge into an adjacent drainage; 2) the stream experienced an “oxbow bend”, looping around and coming

close to the transect on the other side, such that the primary and secondary streams were really the same stream); 3) the area was poorly drained and there was a ponded area near a sample point (which may or may not have been an actual stream); or 4) the area was a point of convergence for multiple streams. Because the effect of standing or running water in structuring plant communities was assumed to be similar regardless of size or other characteristics, and because the distribution of plant communities was expected to be most strongly controlled by the nearest stream or other body of water, the distance to and height above the primary stream were replaced by their respective secondary stream attributes. This occurred on 13 out of 170 sample points.

A nested design was used at each sample point (Figure 4.3). Large trees were captured using a variable-radius plot. Seedlings and smaller trees were tallied within a 3.99m fixed-radius plot. Two 4m<sup>2</sup> shrub subplots and two 1m<sup>2</sup> herb subplots were used to capture understory vegetation. Data collection procedures for each category will be explained in detail below.

### *Trees*

Trees, classified as stems of Douglas-fir, noble fir, western hemlock, western redcedar, bigleaf maple and red alder  $\geq 5$ cm in DBH, were sampled using a nested variable/fixed radius plot. The fixed radius was 3.99m for all sites, but the variable plot used a basal area factor (BAF) that varied by site (Table 4.1). For each site, the BAF was set using prior knowledge of the basal area obtained from a previous survey (Ashkenas 2008), with a goal of capturing an average of four trees per sample point. For each site, a limiting DBH was calculated such that a tree with that DBH, located exactly 3.99m away from the sample point, would be exactly borderline. Any tree with a smaller DBH, falling within 3.99m of the sample point, was tallied in the fixed plot; any tree with a larger DBH was tallied in the variable plot.

For each tallied live tree, species and DBH (always rounded down to the nearest 0.1cm) were collected. For all tallied trees  $\geq 13$ cm, the two nearest neighbors

(as measured by the shortest horizontal distance between tree centers at breast height) were identified and species and DBH information for these trees was recorded. Only live trees  $\geq 13$ cm in DBH were considered as nearest neighbors.

For each tallied snag  $\geq 13$ cm in DBH and  $\geq 2$ m tall, species and DBH were collected, and height was measured. Decay class was estimated using a five-point system adapted from Thomas (1979). In many areas of the Trask Watershed, high stumps remain from the old-growth logging era. While these stumps enhanced structural diversity where they were present, we did not tally them as snags or record their presence in any way.

To explore the use of the nearest-tree method for estimating neighborhood-based index values, the nearest live tree that was  $\geq 13$ cm in DBH was identified. This tree was usually an “in-tree” in the nested plot, but not always. The species and DBH of this tree, and its four nearest neighbors, were recorded.

The most commonly-encountered tree species were Douglas-fir and red alder. To derive height-diameter equations for these two species at each site, two Douglas-fir trees and two alder trees, if possible, were selected for height measurement at each sample point. These trees were selected randomly from among all the live trees that were measured at the sample point. Trees with dead tops or obvious defects that would have affected height growth were excluded from height measurement, although red alder trees with significant lean were still permitted. However, we were not able to measure four trees per sample point at all sample points. Many sample points did not have two trees of both species. In addition, the “broken” terrain and brush conditions made it difficult to measure the heights of all trees that were selected.

Because one of the objectives of sampling was to learn more about the history of each headwater site, we cored up to two dominant trees at each sample point for total age. We attempted to select trees of a variety of species whenever possible.

### ***Shrubs, saplings and seedlings***

Shrubs were tallied in two categories within each shrub plot: “low” cover (<1.37m tall) and “high” cover (>1.37m tall but <2m tall). This “height” referred to is a function of the height of the shrub above the land surface. Therefore, a patch of huckleberry growing on a high stump (as was frequently observed) was considered high cover even if that same patch would only be considered low cover when growing on the ground. Each species that was present in one of the two categories (high and low) was recorded using a six-point cover class system from Daubenmire (1959; Table 4.2). Most ferns were tallied only in herb plots. However, sword fern was tallied in both herb and shrub plots because it is herbaceous but perennially erect (Hibbs and Bower 2001). All seedlings ( $\geq 0.5$ m tall and <2cm DBH) and saplings ( $\geq 2$ cm DBH and <5cm DBH) were tallied.

### ***Herbs and ferns***

Cover of graminoids (i.e. grasses), moss, ferns and forbs was recorded within each 1x1m herb plot using the cover classes described previously. In addition, the number of unique forb species and the most abundant forb species (if applicable) was recorded.

### ***Coarse woody debris***

At each sample point, a 7.98m transect was established for coarse woody debris. The transect was centered on the sample point and oriented in a random direction that was independently drawn for each plot (that is, it extended 3.99m in the randomly-selected direction and 3.99m on the other side of the sample point in the opposite direction). The diameter at intersection, length and decay class were recorded for each piece  $\geq 10$ cm in diameter intersecting the transect. Decay class was defined as: 1) the piece was sound and had its original color, with or without bark intact; 2) the

piece was softened and darker than original, with little or no bark intact; or 3) the piece was soft, dark, and without structural integrity.

### *Analysis*

The physiographic variable used in this analysis was height above stream. Height above stream has been used to characterize the distance-from-stream gradient in previous studies of riparian forest condition (Hibbs and Bower 2001; Sarr and Hibbs 2007). Unlike horizontal distance from stream, it is a measure not only of distance but also of slope, and therefore allows a sample point in a steep, v-shaped canyon to be treated differently than a sample point in a broad, shallow floodplain, although both sample points may be equally far from the stream in terms of horizontal distance (D. Hibbs, pers. comm. 5/09). This is especially important in some riparian systems, which may contain broad floodplains and steep canyons within the same watershed.

For each tree captured in the nested plot, the expansion factor (i.e. the number of trees/ha represented by that tree) was calculated. For trees captured in the fixed plot, the expansion factor was 200, since a circular plot with a radius of 3.99m occupies 1/200 ha. For each tree captured in the variable plot, the expansion factor was given by:

$$4.1 \quad EF = \frac{BAF}{BA_t}$$

where  $BA_t$  is the basal area of the tree in  $m^2$  and  $BAF$  is the BAF (in  $m^2/ha$ ) used to select the tree.

The percentage of basal area in conifer species (%CON) was used. If  $CON + HARD > 0$ , %CON was calculated as:

$$4.2 \quad \%CON = \frac{CON}{CON + HARD} * 100$$

Otherwise, %CON was given as 0.

Neighborhood-based index were calculated using the equations introduced in Chapter 3 and briefly summarized here. The species mingling index (DM) developed by Gadow and Hui (1999) the degree of interspersion between trees of different species. For a given reference tree  $i$ , mingling is calculated as:

$$4.3 \quad DM_i = \frac{1}{n} \sum_{j=1}^n v_j$$

where  $n$  is the number of neighbors considered and  $v_j$  is 0 if the  $j$ th neighbor is of the same species as the reference tree, and 1 otherwise.

The differentiation index developed by Gadow and Hui (1999) describes the degree of interspersion between trees of different sizes. It can be used with diameter or height as a variable. For the  $i$ th reference tree and its  $j$ th nearest neighbor, diameter differentiation (TD) is computed as:

$$4.4 \quad TD_i = \frac{1}{n} \sum_{j=1}^n \left[ 1 - \frac{\min (dbh_i, dbh_j)}{\max (dbh_i, dbh_j)} \right]$$

where  $\min (dbh_i, dbh_j)$  is the smaller DBH of the two trees, and  $\max (dbh_i, dbh_j)$  is the larger. Similarly, height differentiation (TH) is computed as:

$$4.5 \quad TH_i = \frac{1}{n} \sum_{j=1}^n \left[ 1 - \frac{\min (height_i, height_j)}{\max (height_i, height_j)} \right]$$

where  $\min (height_i, height_j)$  is the smaller DBH of the two trees, and  $\max (height_i, height_j)$  is the larger.

The following interpretation system, proposed by Pommerening and introduced in Chapter 3, will be used for the TD and TH indices:



- 1) TD or TH index values from 0.0-0.3 are evidence of “small” differentiation. The tree with the smaller size is 70% or more of the neighboring tree’s size.
- 2) TD or TH index values from 0.3-0.5 are evidence of “average” differentiation. The tree with the smaller size is 50-70% of the neighboring tree’s size.
- 3) TD or TH index values from 0.5-0.7 are evidence of “big” differentiation. The tree with the smaller size is 30-50% of the neighboring tree’s size.
- 4) TD or TH index values from 0.7-1.0 are evidence of “very big” differentiation. The tree with the smallest size is less than 30% of the neighboring tree’s size.

The dominance index (U) was proposed by Hui et al. (1998) and quantifies the dominance of a given species in a stand by computing the proportion of nearest neighbors that are smaller (as indicated by height or DBH) than the reference tree. Again, this analysis will focus on DBH as the variable of interest. Larger values imply greater dominance in the stand (Aguirre et al. 2003). For a given reference tree  $i$ , dominance is calculated as:

$$4.6 \quad U_i = \frac{1}{n} \sum_{j=1}^n v_j$$

where  $v_j$  is 1 if the DBH of the reference tree is larger than the DBH of the  $j$ th neighbor.

Neighborhood-based index values were calculated using the nearest-neighbor information for the reference tree (the nearest tree to plot center), and were not weighted in any way. Although this method may be theoretically biased depending on how the indices are considered (see the discussion in Chapter 3), the variance is low

and there is less potential for serious bias than when the indices are calculated using nearest-neighbor information for trees selected in variable radius plots. In addition to the TD index discussed in Chapter 3, the height differentiation (TH) index was calculated for every reference tree.

In order to compute the TH index, it was necessary to derive height estimates for every tree. Site-specific height-diameter equations for Douglas-fir and red alder were produced using weighted nonlinear least squares regression. The equation form used was:

$$4.7 \quad H = 4.5 + \exp (a + [b * D^c])$$

where  $H$  is tree height in feet,  $D$  is DBH in inches, and  $a$ ,  $b$  and  $c$  are the regression coefficients. This equation form is one of the most common for height-diameter equations in the Pacific Northwest, and has been successfully used in previous studies (Wang and Hann 1988; Hanus et al. 1999; Larsen and Hann 1987). Imperial units were used so that the coefficients provided by Hanus et al. (1999) could be input as starting values for the nonlinear search algorithm.

The coefficients and root mean square error values for the resulting equations for Douglas-fir are given in Table 4.3. Only five Douglas-fir trees (out of a total of 13 encountered) were sampled for height at site PH3. Because reliable height estimation was not possible with such a small sample size, the equation developed for site PH4 was used for this site.

While the Douglas-fir equations were adequate, the precision of the red alder equations produced was quite poor. This may be partially due to measurement error, as it was difficult to differentiate the tops of individual red alder trees when they were grouped together, as was frequently the case. However, the height-diameter equation for red alder provided by Hanus et al. (1991) had a higher mean square error than for Douglas-fir, indicating that the height-diameter relationship for red alder may be inherently more variable than for Douglas-fir.

Since the height-diameter equations constructed for red alder were too poor to use, and since no height data were collected for western hemlock, western redcedar, noble fir and bigleaf maple, it was necessary to estimate heights of these species using equations from previous work. Equations for red alder, western hemlock and western redcedar were provided by Hanus et al. (1999). The equation for bigleaf maple was provided by Wang and Hann (1988). For noble fir, I used the “N. Oregon Coastal” equation constructed by Garman et al. (1995).

The categorical format in which the understory cover data were collected did not facilitate quantitative analysis. Therefore, the original Daubenmire cover classes were replaced by the numerical value of the midpoint of each cover class (Table 4.2). In constructing confidence intervals for shrub cover, high and low cover were analyzed separately. The two quadrats at each sample point were not treated as independent samples, and the sample size was considered to be the number of sample points at each site. Therefore, cover values between the two quadrats was averaged at each site. For each species at each site, 95% confidence intervals for cover were constructed as:

$$4.8 \quad 95\%CI = \frac{s}{\sqrt{n}} * t$$

where  $s$  is the standard deviation of average cover among sample points,  $n$  is the number of sample points, and  $t$  is the appropriate multiplier for a t-distribution with  $n-1$  samples.

95% confidence intervals for attributes pertaining to coarse woody debris were constructed similarly.

## Results

### *GSI*

The terrain adjoining this stream was gentle to moderate, with an average slope of 24% (range: 11-67%). The largest height above stream sampled was 6.69m. Only two species, Douglas-fir and red alder, were encountered at this site. They tended to occur in discrete patches so that at sample points where Douglas-fir was abundant, red alder was far less abundant and vice versa (Figure 4.4).

The relative abundance of Douglas-fir and red alder did not appear to be readily linked to the height-above-stream variable. At least one live tree was captured at each sample point.

Red alder was the most abundant species, as measured in basal area and tree density (Table 4.4). Stand and stock tables show a broadly bell-shaped diameter distribution of Douglas-fir and red alder, with a diameter range from 5-80cm for Douglas-fir and 5-70cm for red alder. The QMD of the two species was similar (34.8cm for Douglas fir vs. 35.1 cm for red alder), so the difference in basal area between the two species is mostly a result of the high density of red alder. Most of the density of snags was in the 15cm and 25cm diameter classes, with some conifer snags found in the 55cm diameter class. Most snags tallied were conifers. Dominant Douglas-fir trees cored at this site were 44-57 years old. Dominant red alder trees cored at this site were 38-53 years old.

The neighborhood-based information confirmed our visual observations. Most reference trees sampled had very low DM and TH index values (Figure 4.5). However, approximately 30% of all reference trees sampled had TD index values in the 0.3-0.5 range. The vast majority of Douglas-fir and red alder trees DM=0. The TD index values were similar for Douglas-fir and red alder, with most trees having “small” or “average” differentiation. While the TH index for Douglas-fir was similar to the TD index for red alder, all red alder trees had “small” height differentiation. The U index

was fairly evenly distributed for both Douglas-fir and red alder, although a higher proportion of Douglas-fir trees sampled were larger than their neighbors.

The most abundant low shrub species was sword fern, with salmonberry also abundant. Snowberry, huckleberry and evergreen blackberry were present in minor quantities (Table 4.5). Fool's huckleberry, cascara, vine maple, wild rose, and thimbleberry were noted, but did not have cover values differing significantly from 0. Vine maple, sword fern, wild rose, salmonberry and huckleberry were noted as high cover. No species had a high cover value that was significantly different from 0.

The distribution of forb cover was bell-shaped and centered on Class 2 (25-50% cover; Figure 4.6) Redwood-sorrel was the most abundant herb at most sample points, although wild ginger, star-flowered false Solomon's-seal, piggyback plant, bunchberry and Siberian miner's-lettuce were locally abundant. Among fern species encountered, sword fern occurred at 96% of all sample points, while bracken fern was noted at 12%, lady fern was noted at 23%, and deer fern was noted at 7.6% of all sample points, respectively.

We found an average of 445 m<sup>3</sup>/ha (95% CI: 175-715 m<sup>3</sup>/ha) and 219 pieces/ha (95% CI: 79-360 pieces/ha) of coarse woody debris  $\geq$ 10cm in diameter. Most pieces found were moderately decayed.

### **GS3**

The terrain adjoining this stream was gentle to moderate, with an average slope of 38% (range: 15-70%). The largest height above stream sampled was 12.24m. We encountered four species: Douglas-fir, noble fir, red alder and western hemlock. Most sample points that contained live trees had 60% or more of their basal area in conifer species (Figure 4.4), and conifer species tended to be dominant at a wide variety of heights above stream. At least one live tree was captured at each sample point.

Stand and stock tables show an approximately bell-shaped diameter distribution of Douglas-fir and red alder (Table 4.6). The distribution of noble fir was

bimodal, with a younger cohort of pole-sized trees (5-20cm) and an older cohort of canopy dominants (60-100cm). The distribution of red alder was narrowly bell-shaped, with tree diameters ranging from 20-60cm. The few western hemlock trees present were from 10-40cm. The QMD for Douglas-fir was 49.1cm, substantially larger than the QMD for noble fir (39.4cm) and red alder (36.7cm). The QMD for western hemlock was 24.4cm. Only conifer snags were tallied, with all snags in the 13-60cm diameter range. Dominant Douglas-fir trees cored at this site were 57-69 years old, while the one dominant noble fir tree cored was 55 years old. The one dominant red alder tree cored was 44 years old.

The distribution of the DM index for all species was skewed to the right (Figure 4.7), and over 50% of reference trees sampled had  $DM \geq 0.25$ . While the TH index was distributed similarly to the TH indices for site GS1, the TD index had a larger proportion of trees in the “average” and “big” differentiation classes. The DM index for Douglas-fir mirrored the overall DM index, while the DM index for red alder showed that a lower proportion of red alder trees were intimately mingled with other species. In contrast, all noble fir reference trees had  $DM \geq 0.75$ . The TD index for Douglas-fir was bell-shaped, with most trees having “average” differentiation. All noble fir trees sampled had “small” differentiation, while red alder had an approximately 60/40 ratio of “small” to “average” differentiation. Distribution of the TH index for Douglas-fir was similar to site GS1, while all red alder and noble fir reference trees had the lowest possible category of differentiation. Results for the U index showed that the majority of Douglas-firs sampled were highly dominant in the stand, while most noble firs had an intermediate or codominant position. Most red alder trees were overtopped by 25-50% of their nearest neighbors.

The most abundant low shrub species present was sword fern, with huckleberry also abundant (Table 4.7). Evergreen blackberry, vine maple, salmonberry and devil’s club were also present as low cover. Salal, fool’s huckleberry, dwarf

Oregon-grape and wild rose were noted but did not have cover values differing significantly from 0. Vine maple and huckleberry were noted as high cover. Fool's huckleberry and salmonberry were noted but did not have high cover values differing significantly from 0.

The distribution of forb cover was slightly skewed to the right and centered on Class 2 (5-25% cover; Figure 4.6). Redwood-sorrel was the most abundant herb at most sample points, although wild ginger and star-flowered false Solomon's-seal were locally abundant. Among fern species encountered, sword fern was found at 95% of all sample points, while lady fern was noted at 35% and deer fern was noted at 5.0% of all sample points, respectively.

We found an average of 206 m<sup>3</sup>/ha (95% CI: 40-371 m<sup>3</sup>/ha) and 374 pieces/ha (95% CI: 163-584 pieces/ha) of coarse woody debris  $\geq$ 10cm in diameter. Most pieces found were moderately decayed.

## ***PH2***

The terrain adjoining this stream was moderate to rugged, with an average slope of 96% (range: 47-123%). The largest height above stream sampled was 22.20m. Some of the more rugged slopes were unstable, and we observed evidence of rock-slide activity. Three species were encountered: Douglas-fir, red alder and a minor amount of bigleaf maple. This site tended to be dominated by Douglas-fir at almost all heights above stream (Figure 4.4). Only one sample point failed to capture any live trees.

The diameter distribution for Douglas-fir was bell-shaped, with a diameter range from 10-80cm (Table 4.8). The QMD for Douglas-fir was 39.0cm. We also sampled a smaller number of red alder trees (in the 55cm diameter class) and bigleaf maple trees (in the 45cm diameter class). Only conifer snags were tallied, with most snags in the 13-30cm range. However, snags up to 130cm were tallied. The dominant

Douglas-fir trees cored at this site were 39-48 years old, while the one dominant red alder tree cored was 46 years old.

Only Douglas-fir trees were sampled as reference trees (Figure 4.8). Most trees sampled for neighborhood-based indices had DM=0.00, with fairly low TD and TH index values. The U index was fairly evenly distributed, indicating that Douglas-fir trees sampled occupied a range of canopy positions within the site.

The most abundant low shrub species present was sword fern (Table 4.9). Minor low shrub species present were dwarf Oregon-grape, oceanspray, wild rose, thimbleberry, evergreen blackberry and huckleberry. Vine maple, California hazelnut, salal, fool's huckleberry, Indian-plum and snowberry were noted but did not have low cover values differing significantly from 0. Vine maple, California hazelnut, oceanspray, fool's huckleberry, Indian-plum and huckleberry were present as high cover but did not have values differing significantly from 0.

Most forb quadrats were in Classes 1 (0-5% cover) and 2 (5-25% cover; Figure 4.6). No one species was clearly identifiable as most abundant on many quadrats. Redwood-sorrel was the most abundant species on 8 quadrats, while inside-out flower was the most abundant species on 4 quadrats. Vanilla leaf and wild cucumber were locally abundant. Among fern species encountered, sword fern was found at 100% of all sample points, while bracken fern was noted at 38% of all sample points.

We found an average of 157 m<sup>3</sup>/ha (95% CI: 39-274 m<sup>3</sup>/ha) and 125 pieces/ha (95% CI: 51-199 pieces/ha) of coarse woody debris  $\geq$ 10cm in diameter. Most pieces found were fresh or moderately decayed.

### ***PH3***

The terrain adjoining this stream was gentle to moderate, with an average slope of 20% (range: 7-42%). The largest height above stream sampled was 5.48m. Only Douglas-fir and red alder were encountered. This site tended to be dominated by red



alder at all heights above stream (Figure 4.4). However, two sample points were predominately Douglas-fir. Three sample points failed to capture any live trees.

The relatively few Douglas-fir trees sampled were concentrated in the 30-70cm diameter range (Table 4.10). The QMD for Douglas-fir was 53.8cm. The diameter distribution for red alder was more broadly bell-shaped, with most trees in the 10-80cm diameter range. One red alder tree sampled was in the 105cm diameter class. The QMD for red alder was 43.7cm. No snags were tallied. Both Douglas-fir trees cored at this site were 51 years old. The one red alder tree cored was 46 years old.

Most trees had  $DM=0.00$  and “small” values of height and diameter differentiation (Figure 4.9). However, a small number of trees sampled had “big” diameter differentiation. All Douglas-fir trees sampled had  $DM=0.25$ , while the vast majority of red alder trees had  $DM=0.00$ . Douglas-fir trees were evenly split between “small” and “average” diameter differentiation, but several red alder trees had “big” diameter differentiation. All trees sampled had “small” height differentiation. Half of all Douglas-fir trees sampled had  $U=0.25$  and half had  $U=0.75$ . The U index distribution for red alder was skewed to the left, and the majority of red alder trees sampled were larger than their neighbors.

Vine maple and sword fern were the most abundant low shrub species, while California hazelnut and evergreen blackberry were frequently-present minor species (Table 4.11). Indian-plum, cascara, thimbleberry, salmonberry and huckleberry were noted, but did not have low cover values significantly different from 0. Vine maple was fairly abundant as high cover. California hazelnut, sword fern, cascara, and salmonberry were present as high cover but did not have values significantly different from 0.

The distribution of forb cover was fairly even, from Classes 1 (0-5% cover) to 5 (75-95% cover; Figure 4.6). Many quadrats had no one species clearly identifiable as most abundant. Redwood-sorrel was frequently the most abundant species, while wild

cucumber and herb robert were locally abundant. Palmate coltsfoot and piggyback plant were also noted. Among fern species encountered, sword fern was found at 63% of all sample points, while bracken fern was noted at 13% and lady fern was noted at 6.3% of all sample points, respectively.

We found an average of 135 m<sup>3</sup>/ha (95% CI: 7-263 m<sup>3</sup>/ha) and 141 pieces/ha (95% CI: 5-276 pieces/ha) of coarse woody debris  $\geq$ 10cm in diameter. Most pieces found were moderately decayed.

#### ***PH4***

The terrain adjoining this stream was gentle to moderate, with an average slope of 27% (range: 4-52%). The largest height above stream sampled was 8.34m. Only Douglas-fir and red alder were encountered. There appeared to be a positive curvilinear relationship between height above stream and percent basal area in Douglas-fir (Figure 4.4). At least one live tree was captured at each sample point.

Douglas-fir was the most abundant species, as measured in basal area and tree density (Table 4.12). The diameter distribution for Douglas-fir was skewed to the right, with a diameter range from 20-90cm. The QMD for Douglas-fir was 44.3cm. The diameter distribution for red alder was also skewed to the right, with a diameter range from 20-70cm. The QMD for red alder was 36.6cm. More conifer snags than hardwood snags were tallied. Most snags were small (<40cm). However, conifer snags up to 175cm were tallied. The dominant Douglas-fir trees cored at this site were 41-48 years old.

The majority of trees had DM=0.00 (Figure 4.10). However, some trees had higher mingling. Values for the TD and TH indices were low overall. Most Douglas-fir trees had DM index values of 0.00, although some trees had values of 0.50. DM index values for red alder were evenly distributed from 0.00-0.75. The majority of both Douglas-fir and red alder trees had “small” diameter differentiation, and all Douglas-fir and red alder trees had “small” height differentiation. The U index for

Douglas-fir was fairly evenly distributed, indicating that Douglas-fir trees sampled occupied a range of canopy positions within the site. The U index for red alder was bell-shaped across a range from 0.00 to 0.50.

Sword fern and salmonberry were the most abundant low shrub species. Vine maple, California hazelnut, casacara, thimbleberry, evergreen blackberry and huckleberry were present as minor species (Table 4.13). Bitter cherry and elderberry were noted, but did not have low cover values significantly different from 0. While vine maple, California hazelnut, sword fern, cascara, salmonberry and huckleberry were present as high cover, no species had high cover values significantly different from 0.

The forb cover distribution was skewed to the right and centered on Class 2 (5-25% cover; Figure 4.6). Approximately half of all quadrats had no one species identifiable as most abundant. Redwood-sorrel was frequently the most abundant species, while wild cucumber, wild ginger, piggyback plant, inside-out flower and fringe cup were locally most abundant. Palmate coltsfoot was also noted. Among fern species encountered, sword fern was found at 94% of all sample points, while bracken fern was noted at 11%, lady fern was noted at 39%, and deer fern was noted at 22% of all sample points, respectively.

We found an average of 725 m<sup>3</sup>/ha (95% CI: 12-1437 m<sup>3</sup>/ha) and 280 pieces/ha (95% CI: 96-464 pieces/ha) of coarse woody debris  $\geq 10$ cm in diameter. Most pieces found were fresh as a result of relatively recent commercial thinning activity.

## ***RK2***

The terrain adjoining this stream was gentle to rugged, with an average slope of 32% (1-79%). The largest height above stream sampled was 16.62m. Three species were encountered: Douglas-fir, red alder and a minor amount of western hemlock. Many sample points contained conifer species only, and there seemed to be little relationship between conifer dominance and height above stream (Figure 4.4). Five

sample points were dominated by red alder. Two sample points failed to capture any trees.

Douglas-fir was most abundant, as measured in basal area and tree density (Table 4.14). The diameter distribution for Douglas-fir was broadly bell-shaped and skewed to the right, with a diameter range from 5-90cm. The QMD for Douglas-fir was 39.1cm. The diameter distribution for red alder was narrowly bell-shaped, with a diameter range from 20-60cm. The QMD for red alder was 38.9 cm. A small amount of western hemlock in the 15cm diameter class was sampled. Only one conifer tree in the 55cm diameter class was tallied. The Douglas-fir trees cored were 51-58 years old. The red alder trees cored were 30-54 years old.

The DM index for all species was fairly evenly distributed, with the majority of trees having  $DM \geq 0.25$  (Figure 4.11). The majority of trees had “average” diameter differentiation and “small” height differentiation. Douglas-fir and red alder had similar mingling patterns. All western hemlock trees sampled had  $DM=1.00$ . Both Douglas-fir and red alder had trees evenly split between “small” and “average” diameter differentiation, while western hemlock trees were evenly split between “average” and “big” diameter differentiation. Douglas-fir and red alder trees all had “small” height differentiation, while western hemlock trees were split between “small” and “average” height differentiation. U index values were fairly evenly split for both Douglas-fir and red alder, although red alder had more trees with  $U=1.00$ . All western hemlock trees had  $U=1.00$ .

Sword fern and salmonberry were the most abundant low shrub species (Table 4.15). Minor low shrub species were vine maple, fool’s huckleberry, thimbleberry and huckleberry. Dwarf Oregon-grape, devil’s club, wild rose and evergreen blackberry were noted but did not have low cover values significantly different from 0. Vine maple and salmonberry were present as high cover. Fool’s huckleberry, devil’s club,

thimbleberry and huckleberry were noted but did not have high cover values differing significantly from 0.

The forb cover distribution was bell-shaped and centered on Class 3 (25-50% cover; Figure 4.6). Redwood-sorrel was the most abundant species on almost all quadrats, but foamflower was locally abundant. Inside-out flower, bleeding heart, twinflower and star-flowered false Solomon's-seal were also noted. Among fern species encountered, sword fern was found at 95% of all sample points, while bracken fern was noted at 14%, lady fern was noted at 27%, deer fern was noted at 50%, spiny wood fern was noted at 4.5% and maidenhair fern was noted at 14% of all sample points, respectively.

We found an average of 488 m<sup>3</sup>/ha (95% CI: 139-838 m<sup>3</sup>/ha) and 636 pieces/ha (95% CI: 310-962 pieces/ha) of coarse woody debris  $\geq 10$ cm in diameter. Most pieces found were moderately decayed.

### ***RK3***

The terrain adjoining this stream was gentle to rugged, with an average slope of 28% (range: 4-88%). The largest height above stream sampled was 13.65m. Three species were encountered: Douglas-fir, red alder and a minor amount of western redcedar. There appeared to be a positive curvilinear relationship between height above stream and percent basal area in Douglas-fir (Figure 4.4). At least one live tree was captured at each sample point.

Douglas-fir was most abundant, as measured in basal area and tree density (Table 4.16). The diameter distribution for Douglas-fir was broadly bell-shaped and skewed to the right, with a diameter range from 10-120cm. The QMD for Douglas-fir was 43.3cm. The diameter distribution for red alder was narrower, with a diameter range from 10-80cm, but also skewed to the right. The QMD for red alder was 38.8cm. A small amount of western redcedar in the 15cm diameter class was sampled. A large number of conifer snags, and a smaller number of hardwood snags, were

tallied in the 13-40cm diameter classes. The Douglas-fir trees cored were 49-57 years old, while the red alder trees cored were 37-43 years old.

Most trees had low values of the DM and TH indices (Figure 4.12). The trees were almost evenly split between “small” and “average” diameter differentiation. Most Douglas-fir trees had DM=0.00. DM index values for red alder trees were fairly evenly distributed, and all western redcedar trees had DM=1.00. Douglas-fir and red alder trees were evenly, or almost evenly, split between “small” and “big” diameter differentiation. All western redcedar trees had “big” diameter differentiation. Most Douglas-fir trees, and all red alder trees, had “small” height differentiation. All western redcedar trees had “big” height differentiation. Both Douglas-fir and red alder had an even distribution of U index values. All western redcedar trees had U=0.00.

The most abundant low shrub species present was sword fern, with salmonberry, thimbleberry, evergreen blackberry and huckleberry present in lesser amounts (Table 4.17). Vine maple, fool’s huckleberry, devil’s club, cascara, wild rose, elderberry and snowberry were noted but did not have high values differing significantly from 0. Vine maple and salmonberry were present as high cover, while fool’s huckleberry, devil’s club, cascara, thimbleberry, salmonberry and huckleberry were noted but did not have high cover values differing significantly from 0.

The majority of quadrats contained 25-50% forb cover (Figure 4.6). Redwood-sorrel was the most abundant species on most quadrats, but star-flowered false Solomon’s-seal, inside-out flower and wild ginger were locally abundant. Bleeding heart, western trillium, twinflower and fringe-cup were also noted. Among fern species encountered, sword fern was found at 92% of all sample points, while bracken fern was noted at 33%, lady fern was noted at 29% and deer fern was noted at 17% of all sample points, respectively.

We found an average of 339 m<sup>3</sup>/ha (95% CI: 5-673 m<sup>3</sup>/ha) and 618 pieces/ha (95% CI: 234-1002 pieces/ha) of coarse woody debris  $\geq 10$ cm in diameter. Most pieces found were fresh as a result of relatively recent commercial thinning activity.

### ***UM3***

The terrain adjoining this stream was gentle to moderate, with an average slope of 45% (range: 6-70%). The largest height above stream sampled was 17.25m. Three species were encountered: Douglas-fir, red alder and western hemlock. Most sites were dominated by Douglas-fir (Figure 4.4), although two sites were dominated by red alder.

The diameter distribution for Douglas-fir was broadly bell-shaped and skewed to the right, with a diameter range from 5-90cm (Table 4.18). The QMD for Douglas-fir was 43.4cm. The diameter distribution for red alder and western hemlock was narrow, with most trees in the 10-50cm range. Some red alder trees were present in the 75cm diameter class. The QMD for red alder was 32.8cm, and the QMD for western hemlock was 30.6cm. Most conifer and hardwood snags tallied were in the 13-30cm diameter range. However, a smaller number of snags were found in the 55cm diameter class. The Douglas-fir trees cored were 46-57 years old, while the red alder trees cored were 44-49 years old.

Most trees had DM=0.00 (Figure 4.13). The TD index had a bell-shaped distribution that was centered on the “average” differentiation category. Most trees had “small” height differentiation. Most Douglas-fir trees had DM=0.00, while the majority of red alder trees had DM=0.75. Both Douglas-fir and red alder trees had a bell-shaped TD distribution centered on “average” diameter differentiation. The majority of Douglas-fir trees, and all red alder trees, had “small” height differentiation. The U index for Douglas-fir was fairly evenly spread across all classes, while the majority of red alder trees had U=1.00.

The most abundant low shrub species present was sword fern, with vine maple, devil's club, huckleberry and evergreen blackberry present in lesser amounts (Table 4.19). Dwarf Oregon-grape, salal, fool's huckleberry, devil's club, wild rose, thimbleberry, salmonberry and snowberry were noted but did not have high cover values differing significantly from 0. Vine maple was present as high cover, while fool's huckleberry, thimbleberry, salmonberry and huckleberry were noted but did not have high cover values differing significantly from 0.

The forb cover distribution was slightly skewed to the right, with the majority of observations in Class 2 (5-25% cover; Figure 4.6). Redwood-sorrel was most often the most abundant forb species, but star-flowered false Solomon's-seal and inside-out flower were locally abundant. Skunk cabbage, western trillium and inside-out flower were also noted. Among fern species encountered, sword fern was found at 87% of all sample points, while bracken fern was noted at 17%, lady fern was noted at 26% and deer fern was noted at 22% of all sample points, respectively.

We found an average of 253 m<sup>3</sup>/ha (95% CI: 97-410 m<sup>3</sup>/ha) and 323 pieces/ha (95% CI: 99-547 pieces/ha) of coarse woody debris  $\geq 10$ cm in diameter. Most pieces found were moderately decayed.

## **Discussion**

### ***Forest structure and composition in the Trask Watershed***

Results from this study provide a window into the history of structural development in the Trask Watershed. The dominant trees on most sites were 40-60 years old. The dominant red alder trees seemed to be generally younger than the dominant Douglas-fir trees, although the tree coring protocol was not rigorous enough to permit statistical comparison of tree ages by species. Although it is not known whether the Trask Watershed was part of any reforestation program, the age range of



dominant trees does roughly coincide with the 1948-1973 range of the active planting program on the Tillamook State Forest, which includes the Pothole Creek area. Reforestation efforts could have also occurred in the Gus Creek, Upper Mainstem and Rock Creek watersheds, which are currently owned by Weyerhaeuser Co.

If the Trask Watershed was impacted by an active planting program for Douglas-fir, it did not keep red alder from regenerating successfully across much of the riparian forest. Although height above stream was a strong predictor of relative conifer abundance, sites differed in relative conifer abundance in ways that could not be fully predicted by height above stream. This heterogeneity probably results from variation in topography, flooding-related disturbance, and post-fire seed sources. The conifer species mix also changed by site. Western hemlock was present as a minor species only in sites GS3, RK2 and UM3, while western redcedar was present as a minor species only in site RK3. Interestingly, noble fir was found only in site GS3, where it was present both in the very large (60-100cm) and very small (5-20cm) size classes. In a study of riparian stand dynamics in the central Oregon Coast Range, Nierenberg and Hibbs (2000) gave lack of seed source as a likely explanation for the paucity of western hemlock and western redcedar regeneration they observed, and availability of seed source is probably a limiting factor for regeneration of these species in the Trask Watershed as well. The size of many of the noble fir trees tallied in site GS3 indicates that the species was either planted or was able to colonize the area relatively soon after the fire, which would have required a local seed source.

While high cut stumps seemed to be ubiquitous throughout the Trask Watershed, very large (>100cm) snags occurred only in sites PH2 and PH4. Since both of these sites are managed by the Oregon Department of Forestry, it is possible that large trees were not logged out of the Pothole Creek drainage as intensively as they were logged out of the surrounding private drainages. Then again, the snags could have been created prior to the logging. All large snags tallied were highly decayed.

Among shrub species, salmonberry has been much discussed as a strong competitor and inhibitor of tree regeneration in lower-order riparian forests of the Coast Range (Nierenberg and Hibbs 2000; Pabst and Spies 1999; Hibbs and Giordano 1996). However, it was found in substantial amounts only in sites GS1, PH4, RK2 and RK3, and did not seem to be a particularly strong competitor in most of the study area. In some locations vine maple was present in impenetrable thickets in which it would be very difficult for tree seedlings to survive. However, the biggest element limiting seedling regeneration seemed to be a lack of light as a result of dense cover of overstory conifers.

The distributions of the neighborhood-based indices were somewhat helpful in completing this picture of stand development. At site GS1, species mingling, diameter differentiation and height differentiation values for Douglas-fir and red alder reference trees were very low. This presents a picture of an even-aged forest where Douglas-fir and red alder, though certainly coexisting at many sites, tended to be present in discrete clumps. This pattern was also evident with Douglas-fir at site PH3, and probably would have also been noted for red alder if reference trees of that species had been sampled at that site. However, a higher degree of mingling occurred in most other sites where both Douglas-fir and red alder were sampled as reference trees. For sites GS3, RK2 and RK3, some Douglas-fir reference trees had a high degree of species mingling. Species mingling index values for red alder were fairly evenly spread for sites PH4, RK2, RK3 and UM3.

Minor conifer species, when sampled as reference trees, had high species mingling values. Western hemlock and western redcedar, when encountered as reference trees, always had the highest mingling value. This could be expected of tree species that were always observed occurring sporadically below the main canopy. Noble fir reference trees in site GS3 had high mingling values, indicating that, while

they could be dominant in the main canopy, they were heavily intermingled with Douglas-fir or red alder.

Diameter and height differentiation values were generally quite low for Douglas fir and red alder, although exceptions did occur. Shade-tolerant conifer species always had relatively high diameter and height differentiation values. This could be expected, since they tended to be much smaller than the trees surrounding them. All noble fir trees sampled as reference trees in site GS3 had very low diameter and height differentiation values.

While most of the area we surveyed seems to have been essentially unmanaged, aside from possible regeneration efforts, after the Tillamook Burn, there were two exceptions. The Oregon Department of Forestry implemented a thinning prescription in the Pothole Creek area in 1998 (TRWS 2006, p22). Cut stumps of the appropriate diameter were rarely observed in sites PH2 and PH3, but were observed quite often in PH4, indicating that this area was substantially changed from its pre-thinning condition. The site RK3 was also commercially thinned in 1996, although cut stumps were not encountered as often as they were in PH4. Given the tendency of red alder to regenerate in clumps with low species mingling, and the tendency of most commercial thinning operations to increase the uniformity of tree spacing, it is possible that these thinning operations served to increase the mingling of red alder. One clear effect of the commercial thinning activity was the production of a larger quantity of coarse woody debris than was found in other sites.

### ***Performance of different measures of forest structure in the Trask Watershed***

The overstory structure of headwater riparian forest within a given watershed in western Oregon may be highly variable, as a result of fine-scale disturbance processes (Pabst and Spies 1999; Nierenberg and Hibbs 2000). This can make inventory and monitoring of these forests difficult, particularly when the objective of the inventory process is to capture change over an environmental gradient, such as the

latitudinal gradient from stream-bank to ridgetop. One manifestation of this difficulty can be seen in the selection of an appropriate plot size.

In an inventory project where the objective is to construct a precise point estimate (such as of stocking, basal area, or merchantable volume) for a given stand, the optimal plot size, regardless of the sampling system used, is a result of the trade-off between the desire to capture as much variation as possible within a given plot (which will decrease plot-to-plot variation and provide more precise estimates) and the desire to avoid measuring or counting too many trees at one plot (which can be burdensome and incur a risk of missing or double-counting trees). For example, Bell and Dilworth (2007, p211) recommend that variable radius “count” plots for basal area estimation contain an average of 4-8 trees.

If the primary objective for surveying a riparian stand is to compile one or more point estimates of the stand as a whole, such as with the simulation studies of Chapters 2 and 3, similar principles can be applied. However, if the objective is to provide an estimate of change across a gradient within the stand, the situation must be considered differently. A sampling protocol for this purpose should capture as little riparian-to-upland variation within a given plot as possible. A plot that is too large will run the risk of capturing too much fine-scale variation in species abundance or other characteristics, thereby obscuring the nature of the gradient (D. Hibbs, pers. comm. 5/09). This risk will be greater in a steep draw, where a given plot size will capture a large amount of variation in height above stream, than in a shallow floodplain, where a given plot size will capture much less variation in height above stream (Figure 4.14). However, it is also important to capture as much longitudinal (along the stream) variation as possible. Too small a plot can result in a highly variable estimate of composition and structure at any given distance away from the stream. In addition, there may be an excessive number of “zero-tree” plots, which do not provide much

information about the plot except that it landed at least a certain distance away from any tree.

One way to deal with these constraints is to use a rectangular plot shape, with the long end oriented parallel to the general direction of streamflow. This approach has often been taken for studies of riparian forest composition in western Oregon (Hibbs and Bower 2001; Hibbs and Giordano 1996; Nierenberg and Hibbs 2000; Sarr and Hibbs 2007). Such plots capture a maximum of longitudinal variation at a given position along the gradient but a minimum of latitudinal variation between two positions on the gradient. However, for a given plot area, they are more time-intensive to establish than circular plots, and therefore their use outside of research is limited.

When circular plots are used, we do not have the luxury of optimizing the degree of longitudinal and latitudinal area covered, and the previously-described trade-off is inherent in the selection of the appropriate plot size. This is true whether the sampling is considered with fixed or variable plots. Variable plot sampling could be criticized on the basis that it is possible to capture a very large-diametered tree that is far from the sample point, and therefore the ecological scale at which trees are captured is unclear. However, it is an appropriate sampling system when basal area is the metric used for quantifying species abundance at a given height above stream. It is axiomatic that larger trees generally have an ecological impact (in terms of shading and water and nutrient usage) over a wider area than do smaller trees. While larger trees may be captured at a distance under variable plot sampling, this is justified by the wider ecological impact that larger trees have. However, the height of trees may be a better indicator of their site occupancy than their basal area. In this case, vertical line sampling, which samples trees with probability proportional to their height (Husch et al. 2003, p285), may be more appropriate. This is likely to be the case in many riparian forest settings, where the ability of a tree to cast shade over the stream channel and to directly supply wood to the stream is strongly related to its height, and

the application of this method to riparian forest sampling should be explored further. In any case, a larger variable plot BAF, a smaller fixed plot radius, and a larger angle in vertical line sampling will all have the same effect: fewer trees will be captured on average, and those trees that are captured will tend to be nearer to the sample point.

Experiences in the Trask Watershed illustrate some of the challenges of attempting to apply a single sampling protocol to a diverse array of topographic settings. The sampling protocol we used called for the second sample point on a transect to be, at most, ~20m from the primary stream. For some sites, such as GS1, the topography was such that the area that was exposed to seasonal inundation extended far beyond 20m, and the sampling protocol was generally not sufficient to capture the entire riparian-upslope gradient. Other sites, such as PH2, were characterized by steep canyons, and the second sample point on a transect was sometimes located over 20m in height above the stream. In addition, the terrain in the Trask Watershed was often broken, so that a sample point 20m from a primary stream could be located over a slight rise and into an adjacent draw. Rather than measure position above stream as a quantitative variable, previous authors have focused on categorization of landform surface (Villarin et al. 2009) or a combination of landform and vegetation indicators (Nierenberg and Hibbs 2000). While the quantitative approach I used was defensible, objective and easy to understand, it was not as flexible for sampling in a variety of topographic settings as another, more categorical approach would have been.

In my experience, the percentage of basal area in conifer species was a more descriptive measure of composition at a given height above stream than was the basal area in conifer or hardwood species alone. As with basal area itself, this metric combined two individual metrics, and the result was a more informative point measure of relative abundance than either of the individual metrics alone. These two examples

of the added utility of combined measures may be indicative of a broader trend in forest sampling.

More discussion on the performance of neighborhood-based indices in the Trask Watershed is warranted. These measures did not convey as much information on forest structure as I had hoped. Diameter and height differentiation index values were very low in the vast majority of cases. Since the typical height-diameter relationship varies between species, I had expected the height differentiation index to be a more sensitive measure of size differentiation, but it was universally less sensitive than the diameter differentiation index. This poor performance may arise, in part, from the fact that only the height-diameter equations for Douglas-fir were based on height measurements in the Trask Watershed, while I had to resort to the literature for equation coefficients for the other species. In general, size differentiation in the Trask Watershed was quite limited. This could have been expected, since the structure is essentially that of an even-aged forest.

The species mingling index was slightly more descriptive, and showed that Douglas-fir and red alder seemed to be more highly mingled at some sites than others. The neighborhood-based indices are, in general, probably better suited to characterizing structure of older, more structurally diverse forests. If succession is allowed to continue uninterrupted in sites GS3, RK2, RK3 and UM3, these forests will probably become more structurally diverse over time as more shade-tolerant conifer species become established in the understory. No seed source for shade-tolerant conifer species was observed in sites GS1, PH2, PH3 or PH4, indicating that these sites may develop along a different trajectory.

While the dominance index is interesting, it was difficult to interpret within the context of the study design, where neighborhood-based information was collected for the nearest tree to a given sample point. Because these trees are not necessarily

representative of the population of the species at large, interpretation was made difficult, and I did not take the results of this index too seriously.

It is important to note that I did not include trees smaller than 13cm DBH in calculation of the neighborhood-based indices. My results would have been different had smaller trees been included in the sampling frame. Particularly in the case of conifers, these scattered small trees were often intermingled with substantially larger trees. The consideration of these trees as neighbors would have generally increased computed diameter and height differentiation. In many cases, the small trees were members of a minor tree species such as western hemlock, and their inclusion would have increased my computed species mingling values as well.

A final difficulty with neighborhood-based indices is that they only consider trees. While this focus may be acceptable for some ecosystems, it does not seem appropriate for the Trask Watershed. Woody species such as western hazelnut and vine maple were observed to contribute significantly to structural diversity and foliage layering whenever they became tall enough to reach the mid-canopy. The quantification of forest structure where only traditional “tree” species were included painted a more impoverished picture of structural diversity than actually exists in the Trask Watershed. While abundance of vine maple, in particular, can be difficult to quantify using the traditional inventory metrics of density and basal area due to its “shrubby” growth habit, any fully functional system for quantifying structural diversity in this forest type must incorporate some woody species that are not typically recognized as tree species.

### **Conclusion**

While not perfect, the sampling protocol developed was reasonably well-suited for quantifying forest structure in the Trask Watershed. The system of having two sample points per transect was efficient and permitted the establishment of sample



points at a wide variety of distances from stream (although this did not necessarily lead to a wide variety of heights above stream being sampled at a given site). The nested plot design worked well for capturing changing species composition along the height-above-stream gradient while also allowing the estimation of precise stand tables.

The neighborhood-based indices were not as descriptive as hoped, and using the nearest-tree selection method for this purpose, even if it is not biased, led to complications in interpretation. The prejudice against shrub species in this application lead to an inaccurate picture of structural diversity in the Trask Watershed. Neighborhood-based indices are not recommended for incorporation into riparian inventory programs until more theoretical work is done to address their shortcomings in sampling and interpretation.

The sampling effort summarized in this chapter provided important baseline information regarding the overstory and understory species composition, diameter distribution, coarse woody debris presence and structural diversity of 8 selected sites in the Trask Watershed. While not designed to specifically evaluate the effects of any future harvest, my sampling program will help to inform studies of post-harvest condition by highlighting the extent to which forest composition and structure varied between sites.

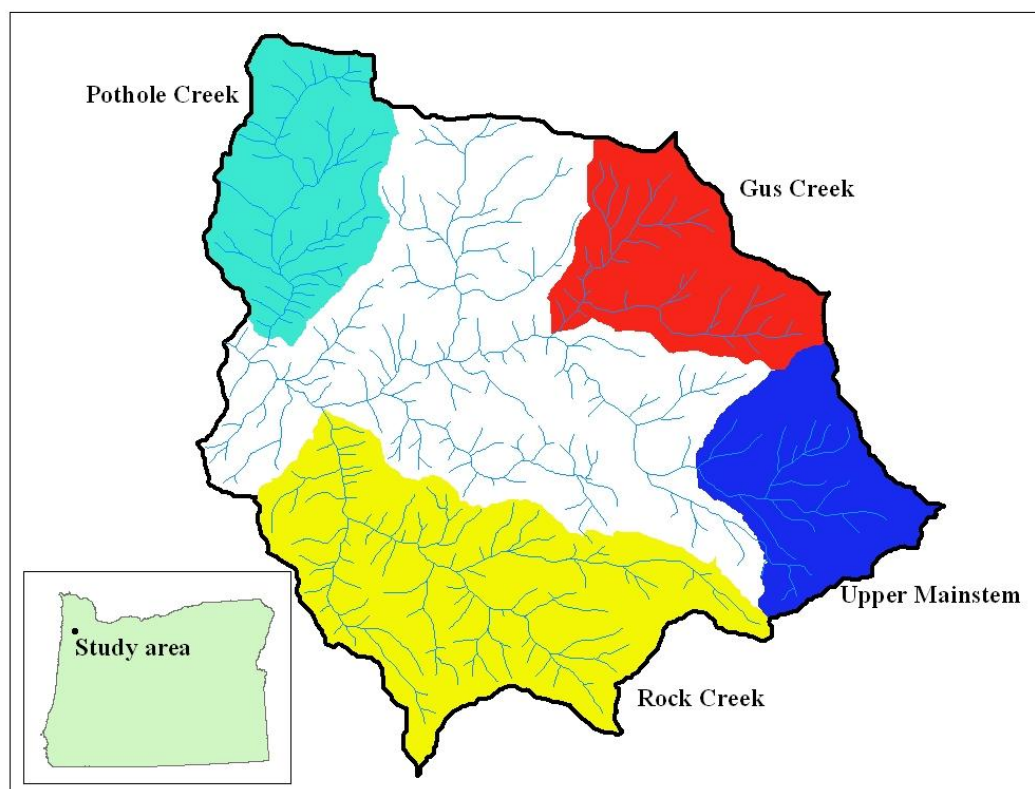


Figure 4.1. The Trask Watershed.

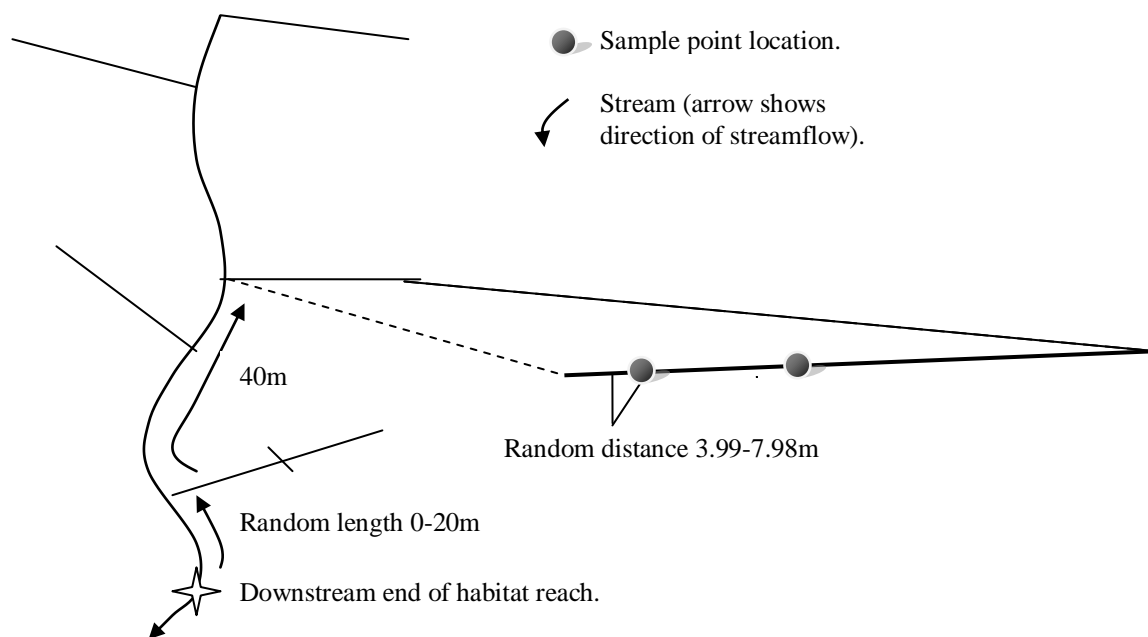


Figure 4.2. An example of how transects and sample points were typically laid out.

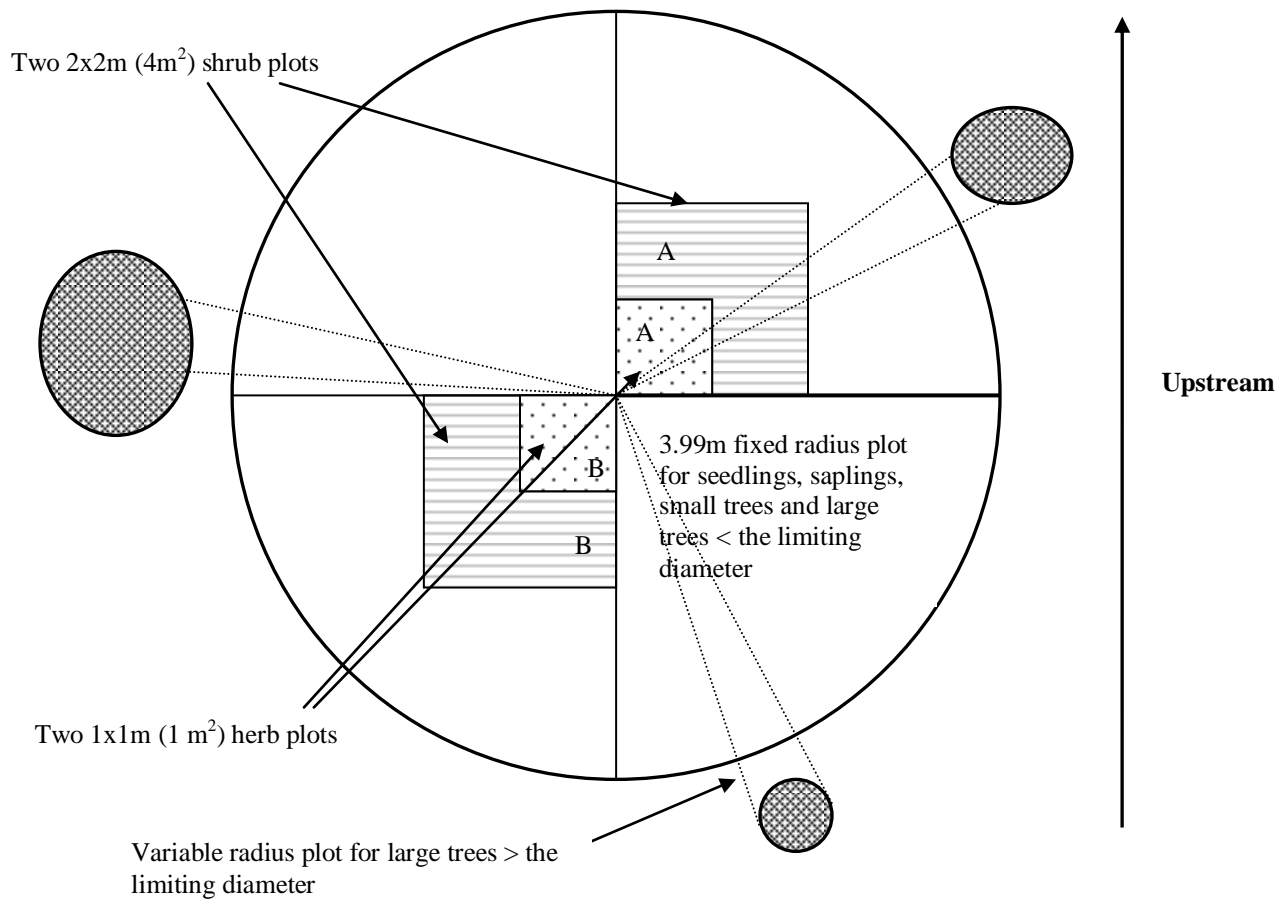


Figure 4.3. Diagram showing data collection layout at each sample point.

Table 4.1. BAF and limiting DBH at 3.99m by site.

| Site | BAF   | Limiting DBH at 3.99m |
|------|-------|-----------------------|
| GS1  | 9     | 23.9                  |
| GS3  | 12.25 | 27.9                  |
| PH2  | 9     | 23.9                  |
| PH3  | 9     | 23.9                  |
| PH4  | 4     | 15.9                  |
| RK2  | 12.25 | 27.9                  |
| RK3  | 9     | 23.9                  |
| UM3  | 12.25 | 27.9                  |

Table 4.2. Range and midpoint of Daubenmire cover classes.

| Class | Range  | Midpoint |
|-------|--------|----------|
| 0     | 0      | 0        |
| 1     | 0-5    | 2.5      |
| 2     | 5-25   | 15       |
| 3     | 25-50  | 37.5     |
| 4     | 50-75  | 62.5     |
| 5     | 75-95  | 85       |
| 6     | 95-100 | 97.5     |

Table 4.3. Number of Douglas-fir height trees ( $n$ ), coefficients, and root mean square error (RMSE; in feet) of height estimation by site.

| Site | $n$ | A          | B            | c           | RMSE       |
|------|-----|------------|--------------|-------------|------------|
| GS1  | 15  | 8.76363242 | -6.66656695  | -0.15224941 | 2.67912853 |
| GS3  | 35  | 5.46985387 | -6.71834111  | -0.71184407 | 3.12193749 |
| PH2  | 36  | 4.80137282 | -92.96367943 | -2.37510941 | 3.02446432 |
| PH4  | 33  | 4.84233473 | -17.61277607 | -1.60048957 | 3.17922258 |
| RK2  | 38  | 5.24783423 | -6.10943762  | -0.83057967 | 2.79011622 |
| RK3  | 37  | 5.11691562 | -9.32610254  | -1.10580695 | 2.25845792 |
| UM3  | 35  | 5.00175710 | -12.46935170 | -1.20185008 | 2.91280601 |

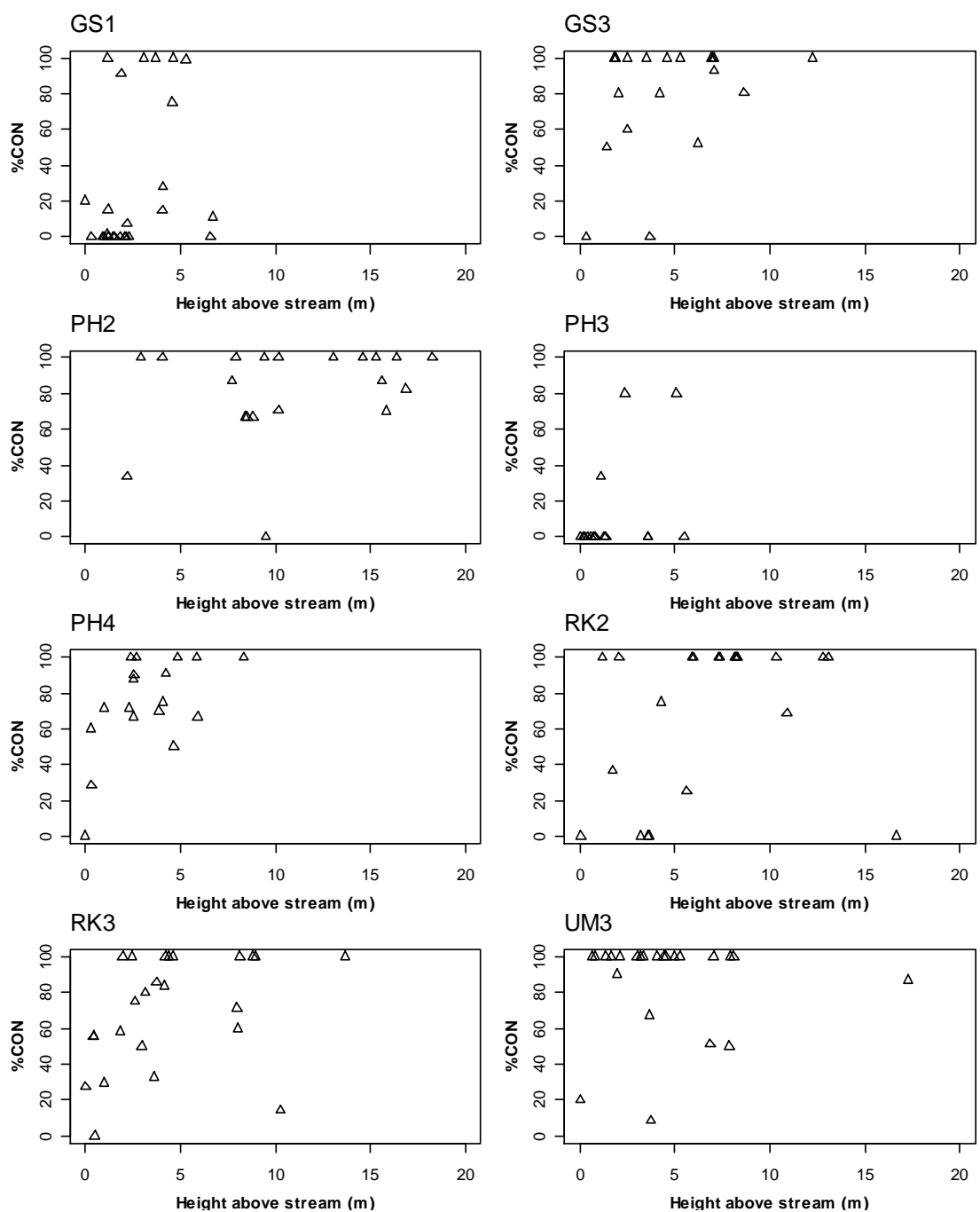


Figure 4.4. Percent of basal area in conifer species plotted against height above stream for all sites. Only sample points that contained at least one live tree are plotted.



Table 4.4. Stem density and basal area of live trees, and stem density of snags, by 10cm diameter class (expressed at the midpoint), for site GS1. N – trees/ha; G – basal area/ha.

| Diameter<br>class | Live trees  |       |           |       | Snags    |           |
|-------------------|-------------|-------|-----------|-------|----------|-----------|
|                   | Douglas-fir |       | red alder |       | conifers | hardwoods |
|                   | N           | G     | N         | G     | N        | N         |
| 5                 | 15.40       | -     | 7.70      | -     | -        | -         |
| 15                | 23.10       | 0.40  | 15.40     | 0.40  | 23.10    | 7.70      |
| 25                | 21.40       | 1.00  | 93.60     | 5.50  | 7.50     | -         |
| 35                | 37.30       | 3.50  | 122.60    | 11.80 | -        | -         |
| 45                | 15.60       | 2.40  | 54.50     | 8.30  | -        | -         |
| 55                | 11.60       | 2.80  | 12.30     | 2.80  | 1.80     | -         |
| 65                | 6.40        | 2.10  | 4.40      | 1.40  | -        | -         |
| 75                | 0.70        | 0.30  | -         | -     | -        | -         |
| 85+               | -           | -     | -         | -     | -        | -         |
| Total             | 131.50      | 12.50 | 310.60    | 30.10 | 32.40    | 7.70      |

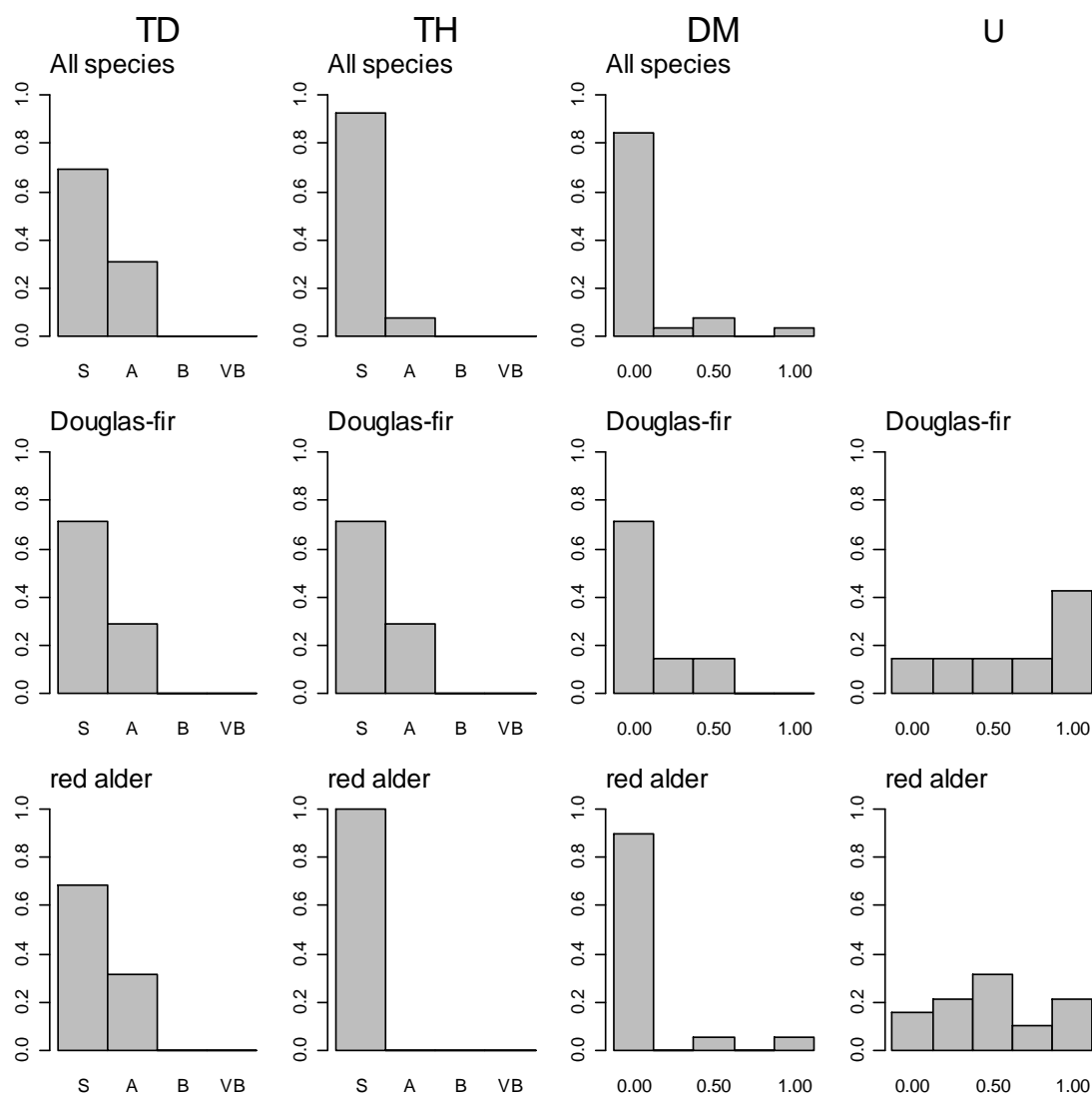


Figure 4.5. Relative frequency distribution of neighborhood-based indices for all species combined and individual species at site GS1. TD and TH index categories are: S – small differentiation (0-0.3); A – average differentiation (0.3-0.5); B – big differentiation (0.5-0.7); VB – very big differentiation (0.7-1.0).

Table 4.5. 95% confidence intervals for low (<1.37m) and high (>1.37m, <2m) shrub cover in site GS1, in the form (*low, high*). \* indicates 95% confidence intervals that included zero, indicating that the values are not significantly different from zero; - indicates that the species was not present in that cover class.

| Species              | Low cover (%) | High cover (%) |
|----------------------|---------------|----------------|
| vine maple           | (0.0, 3.0)*   | (0.0, 2.1)*    |
| dwarf Oregon-grape   | -             | -              |
| California hazelnut  | -             | -              |
| Salal                | -             | -              |
| oceanspray           | -             | -              |
| fool's huckleberry   | (0.0, 0.1)*   | -              |
| Indian-plum          | -             | -              |
| devil's club         | -             | -              |
| sword fern           | (34.6, 48.7)  | (0.0, 0.4)*    |
| bitter cherry        | -             | -              |
| cascara              | (0.0, 0.1)*   | -              |
| wild rose            | (0.0, 1.9)*   | (0.0, 0.2)*    |
| thimbleberry         | (0.0, 0.1)*   | -              |
| salmonberry          | (3.6, 17.6)   | (0.0, 2.6)*    |
| evergreen blackberry | (1.0, 5.0)    | -              |
| elderberry           | -             | -              |
| snowberry            | (0, 0.5)      | -              |
| huckleberry          | (0.2, 1.5)    | (0.0, 0.3)*    |

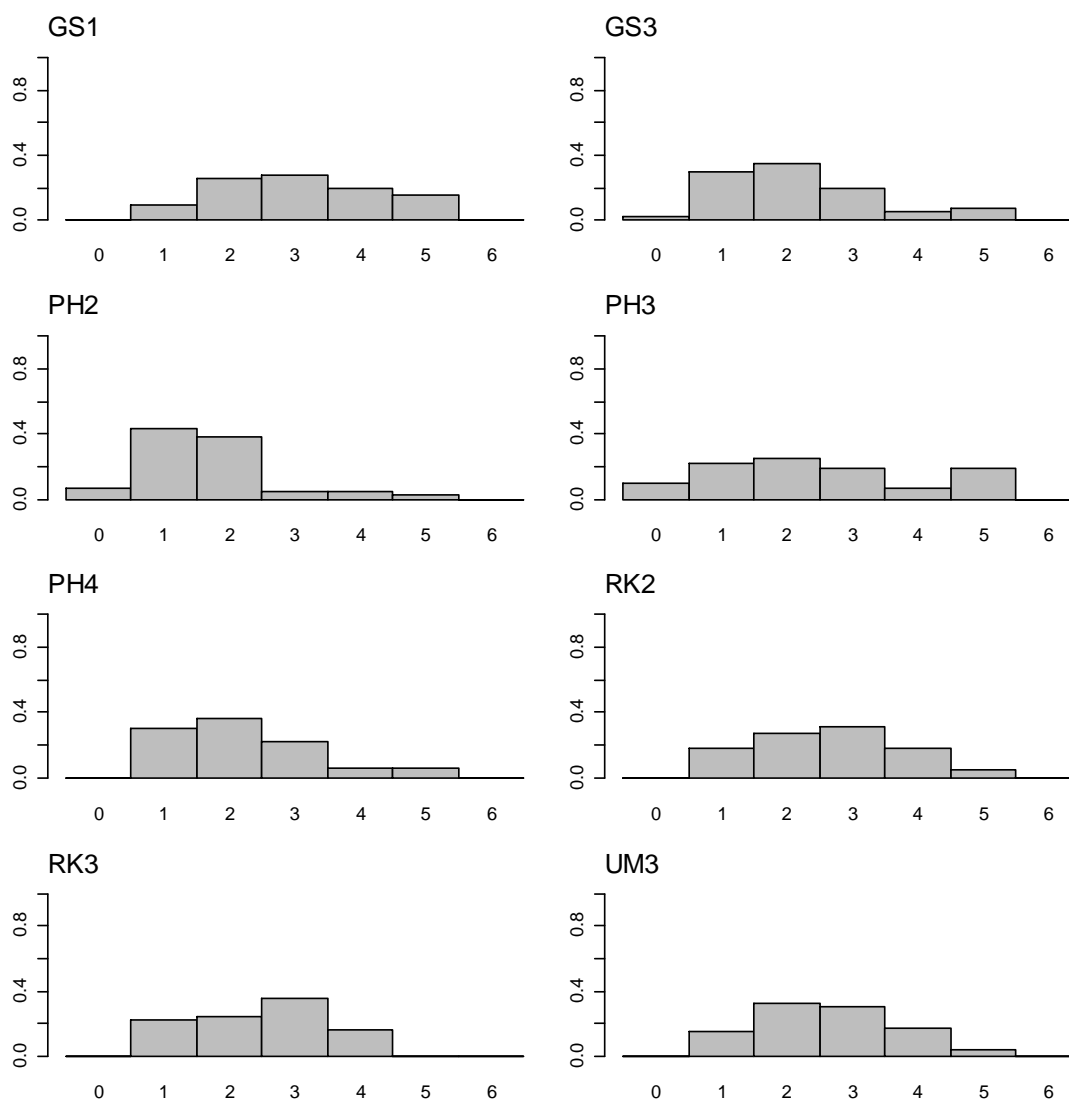


Figure 4.6. Relative frequency distribution of forb cover classes for each site.

Table 4.6. Stem density and basal area of live trees, and stem density of snags, by 10cm diameter class (expressed at the midpoint), for site GS3. N – trees/ha; G – basal area/ha.

| Live trees  |           |           | Snags           |
|-------------|-----------|-----------|-----------------|
| Douglas-fir | noble fir | red alder | western hemlock |

| Diameter<br>class | N     | G    | N    | G   | N    | G   | N    | G   | N    |
|-------------------|-------|------|------|-----|------|-----|------|-----|------|
| 5                 | 20.0  | 0.1  | 10.0 | 0.1 | -    | -   | -    | -   | -    |
| 15                | -     | -    | 20.0 | 0.5 | -    | -   | 10.0 | 0.1 | 10.0 |
| 25                | 25.7  | 1.4  | -    | -   | 10.0 | 0.4 | -    | -   | 9.7  |
| 35                | 44.1  | 4.3  | -    | -   | 14.9 | 1.2 | 4.9  | 0.6 | -    |
| 45                | 20.1  | 3.1  | -    | -   | 10.8 | 1.8 | -    | -   | 13.6 |
| 55                | 32.5  | 7.8  | -    | -   | 2.8  | 0.6 | -    | -   | 2.7  |
| 65                | 25.1  | 8.1  | 3.6  | 1.2 | -    | -   | -    | -   | -    |
| 75                | 14.1  | 6.1  | 3.1  | 1.2 | -    | -   | -    | -   | -    |
| 85                | 8.8   | 4.7  | 1.2  | 0.6 | -    | -   | -    | -   | -    |
| 95                | 0.8   | 0.6  | 1.8  | 1.2 | -    | -   | -    | -   | -    |
| 105+              | -     | -    | -    | -   | -    | -   | -    | -   | -    |
| Total             | 191.2 | 36.2 | 39.8 | 4.9 | 38.4 | 4.1 | 14.9 | 0.7 | 36.0 |

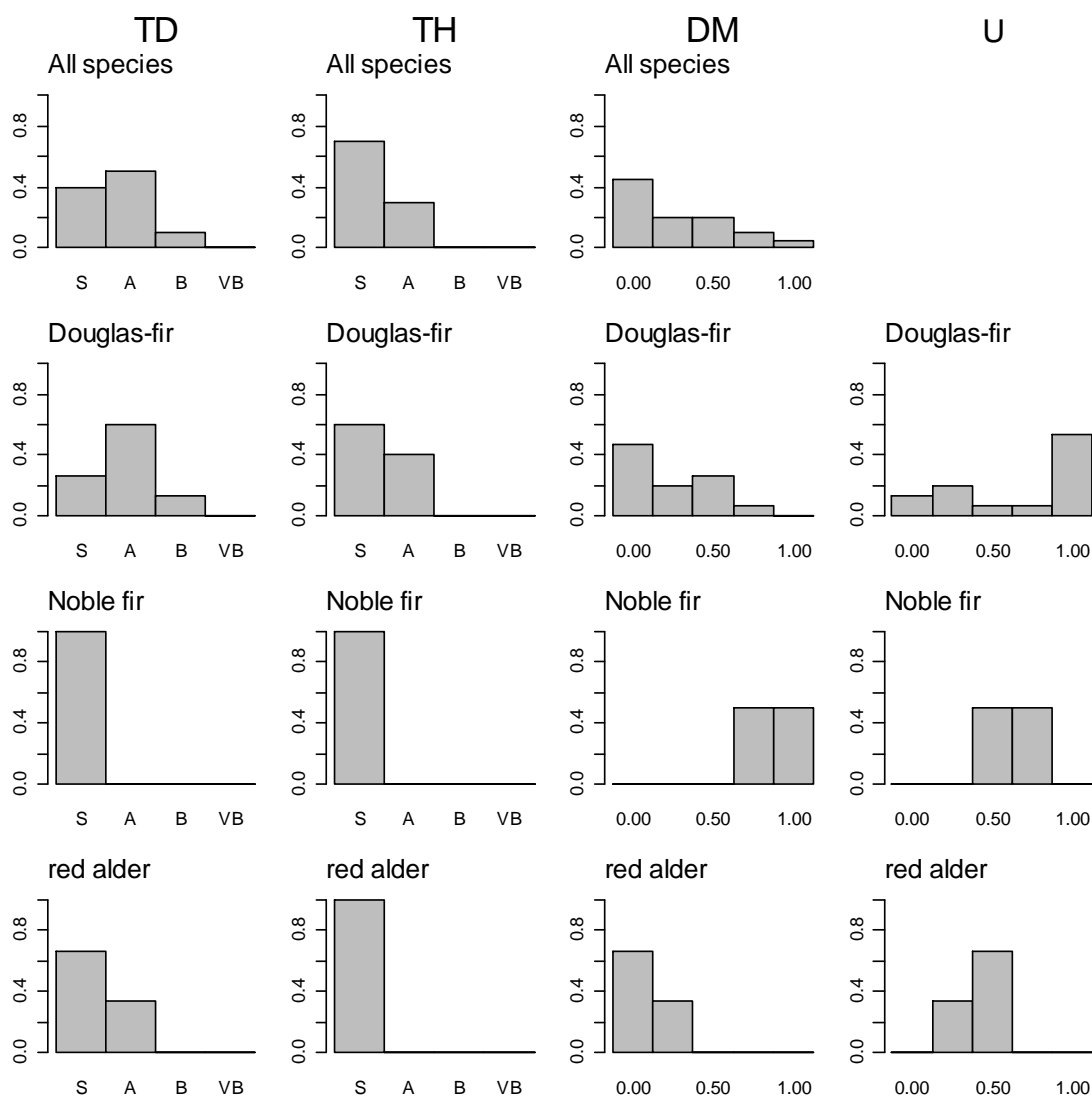


Figure 4.7. Relative frequency distribution of neighborhood-based indices for all species combined and individual species at site GS3. TD and TH index categories are: S – small differentiation (0-0.3); A – average differentiation (0.3-0.5); B – big differentiation (0.5-0.7); VB – very big differentiation (0.7-1.0).

Table 4.7. 95% confidence intervals for low (<1.37m) and high (>1.37m, <2m) shrub cover in site GS3, in the form (*low, high*). \* indicates 95% confidence intervals that included zero, indicating that the values are not significantly different from zero; - indicates that the species was not present in that cover class.

| Species             | Low cover (%) | High cover (%) |
|---------------------|---------------|----------------|
| vine maple          | (1.5, 6.4)    | (1.0, 8.0)     |
| dwarf Oregon-grape  | (0.0, 6.0)*   | -              |
| California hazelnut | -             | -              |
| Salal               | (0.0, 0.2)*   | -              |
| oceanspray          | -             | -              |
| fool's huckleberry  | (0.0, 0.3)*   | (0.0, 0.2)*    |
| Indian-plum         | -             | -              |
| devil's club        | (0, 2.1)      | -              |
| sword fern          | (13.6, 28)    | -              |
| bitter cherry       | -             | -              |
| cascara             | -             | -              |
| wild rose           | (0.0, 1.3)*   | -              |
| thimbleberry        | -             | -              |
| salmonberry         | (0.2, 3.9)    | (0.0, 1.6)*    |
| evergreen           |               |                |
| blackberry          | (0.2, 1.1)    | -              |
| elderberry          | -             | -              |
| snowberry           | -             | -              |
| huckleberry         | (6.6, 16.1)   | (1.7, 9.2)     |

Table 4.8. Stem density and basal area of live trees, and stem density of snags, by 10cm diameter class (expressed at the midpoint), for site PH2. N – trees/ha; G – basal area/ha.

| Diameter class | Live trees    |     |             |      |           |     | Snags |
|----------------|---------------|-----|-------------|------|-----------|-----|-------|
|                | bigleaf maple |     | Douglas-fir |      | red alder |     | N     |
|                | N             | G   | N           | G    | N         | G   |       |
| 5              | -             | -   | -           | -    | -         | -   | -     |
| 15             | -             | -   | 47.6        | 1.2  | -         | -   | 9.5   |
| 25             | -             | -   | 86.2        | 4.1  | -         | -   | 8.2   |
| 35             | -             | -   | 62.2        | 6.0  | -         | -   | -     |
| 45             | 3.4           | 0.4 | 65.5        | 10.7 | -         | -   | -     |
| 55             | -             | -   | 51.0        | 11.6 | 7.3       | 1.7 | -     |
| 65             | -             | -   | 17.4        | 5.6  | -         | -   | -     |
| 75             | -             | -   | 1.1         | 0.4  | -         | -   | 0.9   |
| 85             | -             | -   | -           | -    | -         | -   | -     |
| 95             | -             | -   | -           | -    | -         | -   | -     |
| 105            | -             | -   | -           | -    | -         | -   | 0.5   |
| 115            | -             | -   | -           | -    | -         | -   | 1.2   |
| 125            | -             | -   | -           | -    | -         | -   | 0.7   |
| 135            | -             | -   | -           | -    | -         | -   | 0.6   |
| 145+           | -             | -   | -           | -    | -         | -   | -     |
| Total          | 3.4           | 0.4 | 331.0       | 39.6 | 7.3       | 1.7 | 21.6  |



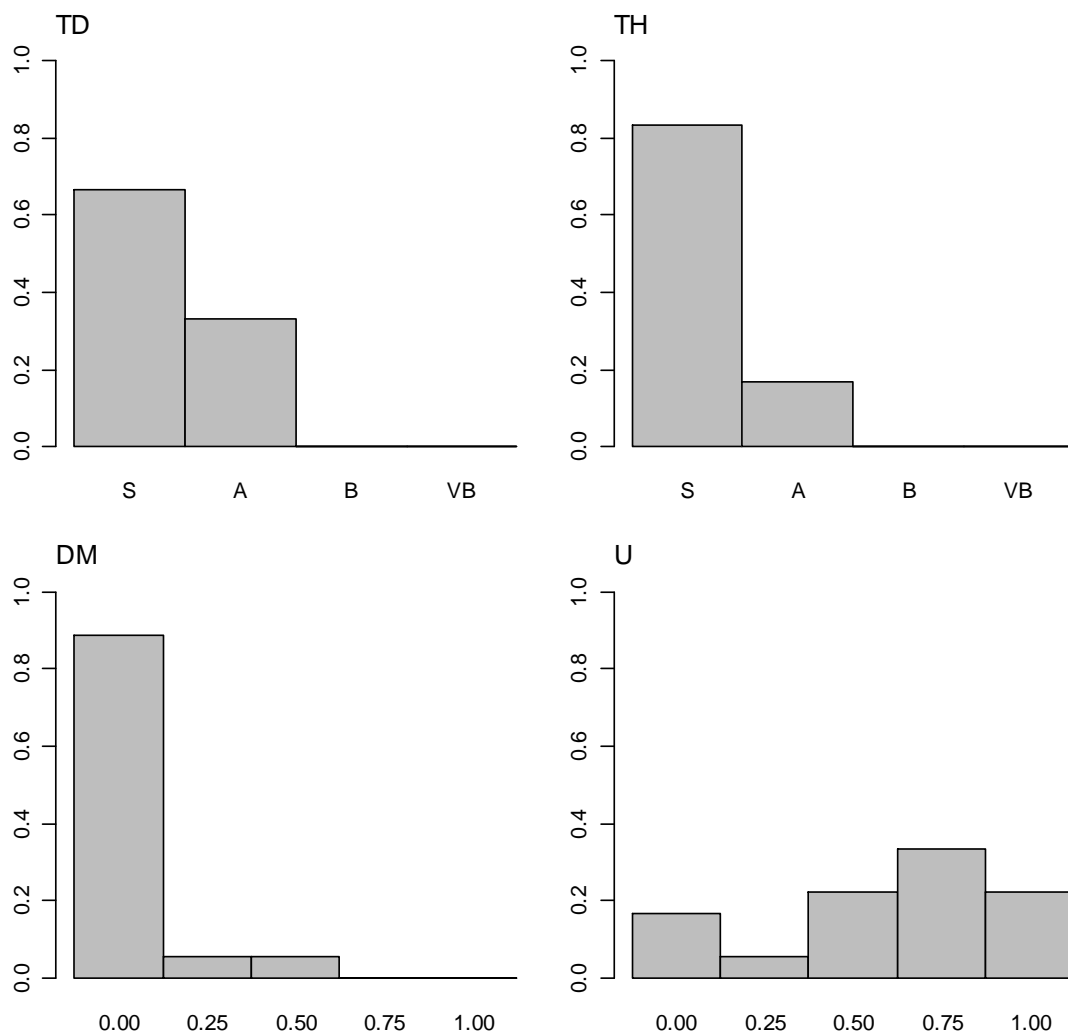


Figure 4.8. Relative frequency distribution of neighborhood-based indices for Douglas-fir at site PH2. TD and TH index categories are: S – small differentiation (0-0.3); A – average differentiation (0.3-0.5); B – big differentiation (0.5-0.7); VB – very big differentiation (0.7-1.0).

Table 4.9. 95% confidence intervals for low (<1.37m) and high (>1.37m, <2m) shrub cover in site PH2, in the form (*low, high*). \* indicates 95% confidence intervals that included zero, indicating that the values are not significantly different from zero; - indicates that the species was not present in that cover class.

| Species             | Low cover (%) | High cover (%) |
|---------------------|---------------|----------------|
| vine maple          | (0.0, 12.3)*  | (0.0, 12.6)*   |
| dwarf Oregon-grape  | (0.2, 10.9)   | -              |
| California hazelnut | (0.0, 1.2)*   | (0.0, 5.7)*    |
| salal               | (0.0, 1.1)*   | -              |
| oceanspray          | (0.0, 2.3)    | (0.0, 1.6)*    |
| fool's huckleberry  | (0.0, 1.3)*   | (0.0, 0.2)*    |
| Indian-plum         | (0.0, 0.1)*   | (0.0, 0.2)*    |
| devil's club        | -             | -              |
| sword fern          | (27.9, 44.6)  | -              |
| bitter cherry       | -             | -              |
| cascara             | -             | -              |
| wild rose           | (0.0, 0.6)    | -              |
| thimbleberry        | (0.1, 0.8)    | -              |
| salmonberry         | -             | -              |
| evergreen           |               |                |
| blackberry          | (2.2, 6.1)    | -              |
| elderberry          | -             | -              |
| snowberry           | (0.0, 1.7)*   | -              |
| huckleberry         | (0.4, 1.4)    | (0.0, 0.4)*    |

Table 4.10. Stem density and basal area by 10cm diameter class (expressed at the midpoint) for site PH3. N – trees/ha; G – basal area/ha.

| Diameter<br>class | Douglas-fir |     | red alder |      |
|-------------------|-------------|-----|-----------|------|
|                   | N           | G   | N         | G    |
| 5                 | -           | -   | -         | -    |
| 15                | -           | -   | 12.5      | 0.3  |
| 25                | -           | -   | 17.9      | 1.1  |
| 35                | 4.6         | 0.6 | 51.9      | 5.6  |
| 45                | 7.3         | 1.1 | 49.5      | 7.9  |
| 55                | 2.7         | 0.6 | 19.0      | 4.5  |
| 65                | 10.2        | 3.4 | 8.5       | 2.8  |
| 75                | -           | -   | 3.9       | 1.7  |
| 85                | -           | -   | -         | -    |
| 95                | -           | -   | -         | -    |
| 105               | -           | -   | 0.7       | 0.6  |
| 115               | -           | -   | -         | -    |
| Total             | 24.8        | 5.6 | 163.8     | 24.5 |

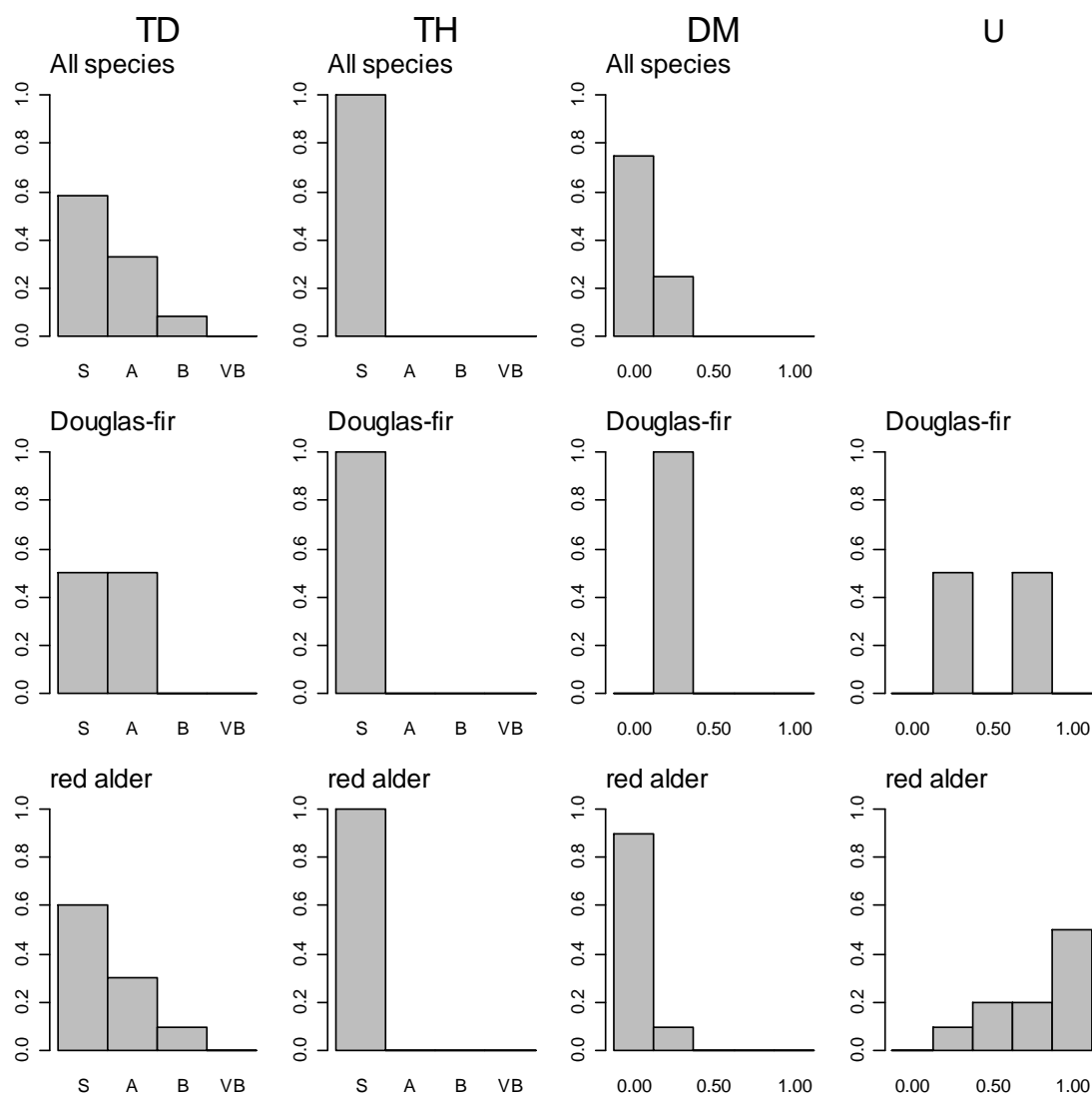


Figure 4.9. Relative frequency distribution of neighborhood-based indices for all species combined and individual species at site PH3. TD and TH index categories are: S – small differentiation (0-0.3); A – average differentiation (0.3-0.5); B – big differentiation (0.5-0.7); VB – very big differentiation (0.7-1.0).

Table 4.11. 95% confidence intervals for low (<1.37m) and high (>1.37m, <2m) shrub cover in site PH3, in the form (*low, high*). \* indicates 95% confidence intervals that included zero, indicating that the values are not significantly different from zero; - indicates that the species was not present in that cover class.

| Species             | Low cover (%) | High cover (%) |
|---------------------|---------------|----------------|
| vine maple          | (5.3, 25.2)   | (2.8, 21.3)    |
| dwarf Oregon-grape  | -             | -              |
| California hazelnut | (0.0, 2.7)    | (0.0, 2.3)*    |
| salal               | -             | -              |
| oceanspray          | -             | -              |
| fool's huckleberry  | -             | -              |
| Indian-plum         | (0.0, 0.2)*   | -              |
| devil's club        | -             | -              |
| sword fern          | (5.7, 26.3)   | (0.0, 0.5)*    |
| bitter cherry       | -             | -              |
| cascara             | (0.0, 0.2)*   | (0.0, 0.2)*    |
| wild rose           | -             | -              |
| thimbleberry        | (0.0, 0.2)*   | -              |
| salmonberry         | (0.0, 8.2)*   | (0.0, 9.6)*    |
| evergreen           |               |                |
| blackberry          | (0.2, 1.3)    | -              |
| elderberry          | -             | -              |
| snowberry           | -             | -              |
| huckleberry         | (0.0, 0.2)*   | -              |

Table 4.12. Stem density and basal area of live trees, and stem density of snags, by 10cm diameter class (expressed at the midpoint), for site PH4. N – trees/ha; G – basal area/ha.

| Diameter<br>class | Live trees  |      |           |     | Snags    |           |
|-------------------|-------------|------|-----------|-----|----------|-----------|
|                   | Douglas-fir |      | red alder |     | conifers | hardwoods |
|                   | N           | G    | N         | G   | N        | N         |
| 5                 | -           | -    | -         | -   | -        | -         |
| 15                | -           | -    | -         | -   | 8.5      | -         |
| 25                | 27.5        | 1.1  | 20.2      | 1.1 | -        | -         |
| 35                | 46.2        | 4.7  | 26.0      | 2.7 | -        | 2.7       |
| 45                | 37.4        | 6.2  | 7.3       | 1.1 | -        | -         |
| 55                | 15.4        | 3.6  | 5.0       | 1.1 | -        | -         |
| 65                | 11.8        | 4.0  | 0.7       | 0.2 | -        | -         |
| 75                | 3.5         | 1.6  | -         | -   | -        | -         |
| 85                | 2.0         | 1.1  | -         | -   | -        | -         |
| 95                | -           | -    | -         | -   | -        | -         |
| 105               | -           | -    | -         | -   | -        | -         |
| 115               | -           | -    | -         | -   | -        | -         |
| 125               | -           | -    | -         | -   | -        | -         |
| 135               | -           | -    | -         | -   | -        | -         |
| 145               | -           | -    | -         | -   | -        | -         |
| 155               | -           | -    | -         | -   | -        | -         |
| 165               | -           | -    | -         | -   | 0.2      | -         |
| 175               | -           | -    | -         | -   | 0.1      | -         |
| 185+              | -           | -    | -         | -   | -        | -         |
| Total             | 144.0       | 22.2 | 59.2      | 6.2 | 8.8      | 2.7       |

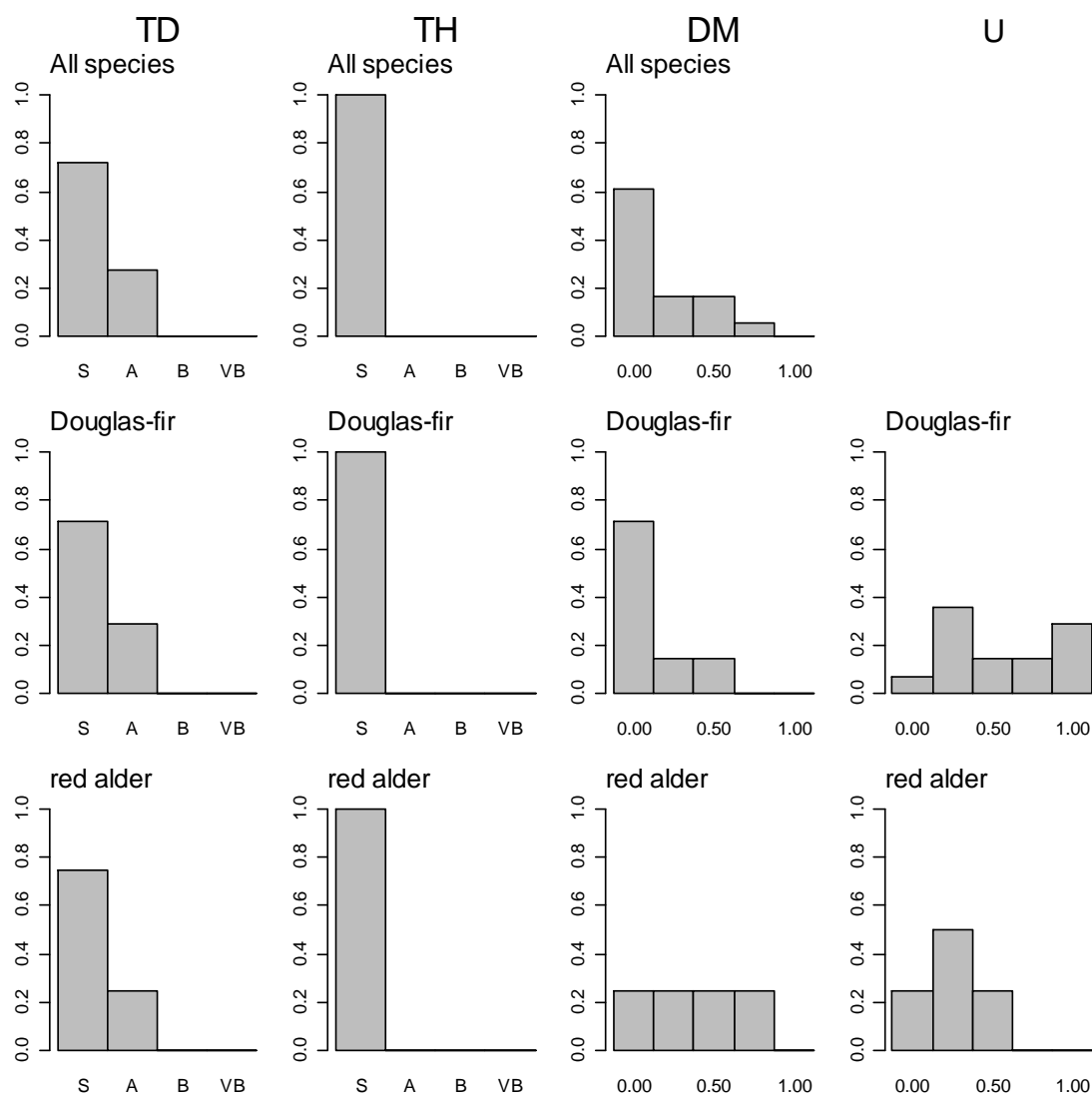


Figure 4.10. Relative frequency distribution of neighborhood-based indices for all species combined and individual species at site PH4. TD and TH index categories are: S – small differentiation (0-0.3); A – average differentiation (0.3-0.5); B – big differentiation (0.5-0.7); VB – very big differentiation (0.7-1.0).

Table 4.13. 95% confidence intervals for low (<1.37m) and high (>1.37m, <2m) shrub cover in site PH4, in the form (*low, high*). \* indicates 95% confidence intervals that included zero, indicating that the values are not significantly different from zero; - indicates that the species was not present in that cover class.

| Species             | Low cover (%) | High cover (%) |
|---------------------|---------------|----------------|
| vine maple          | (0.2, 5.7)    | (0.0, 3.4)*    |
| dwarf Oregon-grape  | -             | -              |
| California hazelnut | (0.2, 3.0)    | (0.0, 0.6)*    |
| salal               | -             | -              |
| oceanspray          | -             | -              |
| fool's huckleberry  | -             | -              |
| Indian-plum         | -             | -              |
| devil's club        | -             | -              |
| sword fern          | (20.4, 41.1)  | (0.0, 0.5)*    |
| bitter cherry       | (0.0, 0.2)*   | -              |
| cascara             | (0, 2.1)      | (0.0, 0.3)*    |
| wild rose           | -             | -              |
| thimbleberry        | (0.1, 0.7)    | -              |
| salmonberry         | (1.0, 12.5)   | (0.0, 7.5)*    |
| evergreen           |               |                |
| blackberry          | (0.8, 4.6)    | -              |
| elderberry          | (0.0, 1.3)*   | -              |
| snowberry           | -             | -              |
| huckleberry         | (0, 0.5)      | (0.0, 0.2)*    |



Table 4.14. Stem density and basal area of live trees, and stem density of snags, by 10cm diameter class (expressed at the midpoint), for site RK2. N – trees/ha; G – basal area/ha.

| Diameter class | Live trees  |      |           |     |                 |     | Snags |
|----------------|-------------|------|-----------|-----|-----------------|-----|-------|
|                | Douglas-fir |      | red alder |     | western hemlock |     | N     |
|                | N           | G    | N         | G   | N               | G   | N     |
| 5              | 18.2        | 0.1  | -         | -   | -               | -   | -     |
| 15             | 36.4        | 0.4  | -         | -   | 18.2            | 0.5 | -     |
| 25             | 44.4        | 2.4  | 9.1       | 0.4 | -               | -   | -     |
| 35             | 42.5        | 3.9  | 19.1      | 2.2 | -               | -   | -     |
| 45             | 28.0        | 4.5  | 15.2      | 2.2 | -               | -   | -     |
| 55             | 13.3        | 3.3  | 2.2       | 0.6 | -               | -   | 2.2   |
| 65             | 19.1        | 6.7  | -         | -   | -               | -   | -     |
| 75             | 7.5         | 3.3  | -         | -   | -               | -   | -     |
| 85             | 1.0         | 0.6  | -         | -   | -               | -   | -     |
| 95+            | -           | -    | -         | -   | -               | -   | -     |
| Total          | 210.3       | 25.2 | 45.6      | 5.4 | 18.2            | 0.5 | 2.2   |

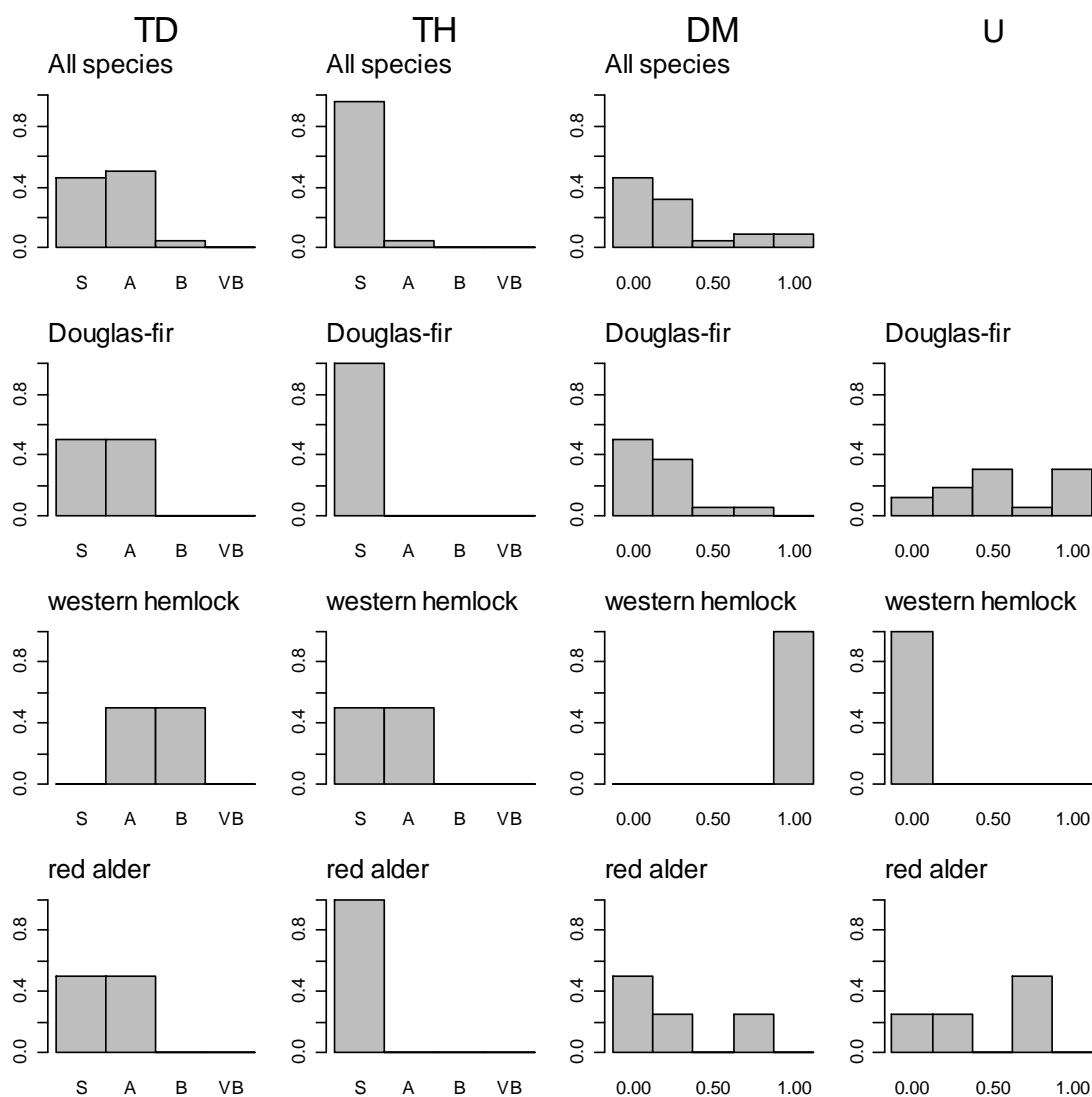


Figure 4.11. Relative frequency distribution of neighborhood-based indices for all species combined and individual species at site RK2. TD and TH index categories are: S – small differentiation (0-0.3); A – average differentiation (0.3-0.5); B – big differentiation (0.5-0.7); VB – very big differentiation (0.7-1.0).

Table 4.15. 95% confidence intervals for low (<1.37m) and high (>1.37m, <2m) shrub cover in site RK2, in the form (*low, high*). \* indicates 95% confidence intervals that included zero, indicating that the values are not significantly different from zero; - indicates that the species was not present in that cover class.

| Species              | Low cover (%) | High cover (%) |
|----------------------|---------------|----------------|
| vine maple           | (1.3, 4.8)    | (0.6, 5.2)     |
| dwarf Oregon-grape   | (0.0, 3.6)*   | -              |
| California hazelnut  | -             | -              |
| salal                | -             | -              |
| oceanspray           | -             | -              |
| fool's huckleberry   | (0.5, 1.9)    | (0.0, 1.6)*    |
| Indian-plum          | -             | -              |
| devil's club         | (0.0, 4.1)*   | (0.0, 0.2)*    |
| sword fern           | (17.7, 29.1)  | -              |
| bitter cherry        | -             | -              |
| cascara              | -             | -              |
| wild rose            | (0.0, 1.7)*   | -              |
| thimbleberry         | (0.2, 0.9)    | (0.0, 0.2)*    |
| salmonberry          | (4.5, 15.2)   | (0.3, 4.3)     |
| evergreen blackberry | (0.0, 0.6)*   | -              |
| elderberry           | -             | -              |
| snowberry            | -             | -              |
| huckleberry          | (0.9, 2.7)    | (0.0, 2.9)*    |

Table 4.16. Stem density and basal area of live trees, and stem density of snags, by 10cm diameter class (expressed at the midpoint), for site RK3. N – trees/ha; G – basal area/ha.

| Diameter<br>class | Live trees  |      |           |      |                     |     | Snags    |           |
|-------------------|-------------|------|-----------|------|---------------------|-----|----------|-----------|
|                   | Douglas-fir |      | red alder |      | western<br>redcedar |     | conifers | hardwoods |
|                   | N           | G    | N         | G    | N                   | G   | N        | N         |
| 5                 | -           | -    | -         | -    | -                   | -   | -        | -         |
| 15                | 33.3        | 0.6  | 8.3       | 0.2  | 8.3                 | 0.3 | 41.7     | -         |
| 25                | 47.1        | 2.6  | 6.1       | 0.4  | -                   | -   | -        | -         |
| 35                | 37.3        | 3.8  | 52.4      | 5.3  | -                   | -   | 16.5     | 5.1       |
| 45                | 51.0        | 7.5  | 18.5      | 3.0  | -                   | -   | -        | -         |
| 55                | 18.8        | 4.1  | 6.5       | 1.5  | -                   | -   | -        | -         |
| 65                | 10.6        | 3.4  | 1.2       | 0.4  | -                   | -   | -        | -         |
| 75                | 6.7         | 3.0  | 0.9       | 0.4  | -                   | -   | -        | -         |
| 85                | 5.7         | 3.0  | -         | -    | -                   | -   | -        | -         |
| 95                | 3.9         | 2.6  | -         | -    | -                   | -   | -        | -         |
| 105               | 0.4         | 0.4  | -         | -    | -                   | -   | -        | -         |
| 115               | 0.8         | 0.8  | -         | -    | -                   | -   | -        | -         |
| Total             | 215.6       | 31.8 | 93.9      | 11.1 | 8.3                 | 0.3 | 58.2     | 5.1       |

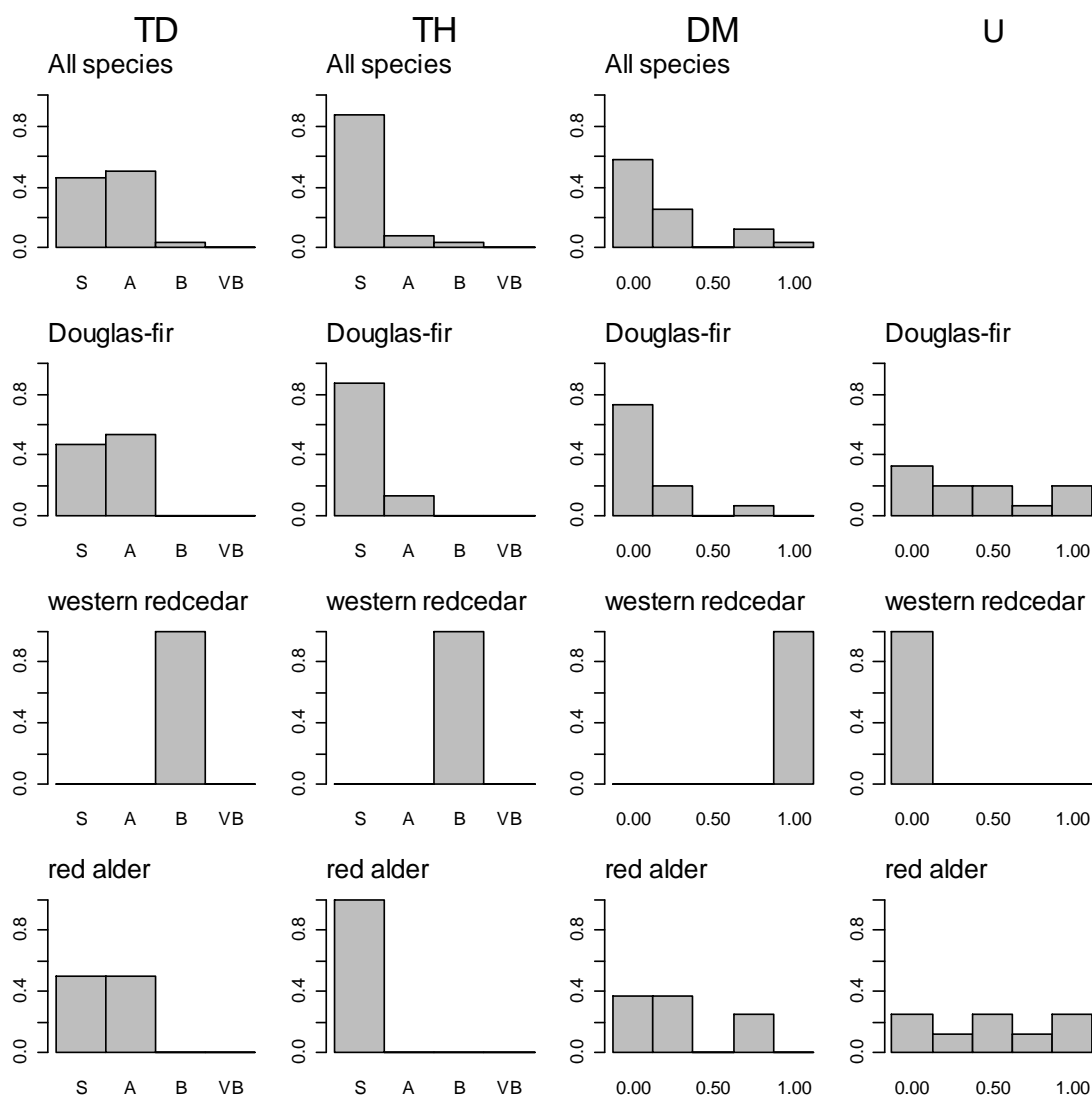


Figure 4.12. Relative frequency distribution of neighborhood-based indices for all species combined and individual species at site RK3. TD and TH index categories are: S – small differentiation (0-0.3); A – average differentiation (0.3-0.5); B – big differentiation (0.5-0.7); VB – very big differentiation (0.7-1.0).

Table 4.17. 95% confidence intervals for low (<1.37m) and high (>1.37m, <2m) shrub cover in site RK3, in the form (*low, high*). \* indicates 95% confidence intervals that included zero, indicating that the values are not significantly different from zero; - indicates that the species was not present in that cover class.

| Species             | Low cover (%) | High cover (%) |
|---------------------|---------------|----------------|
| vine maple          | (0.0, 1.2)*   | (0.0, 0.6)     |
| dwarf Oregon-grape  | -             | -              |
| California hazelnut | -             | -              |
| Salal               | -             | -              |
| oceanspray          | -             | -              |
| fool's huckleberry  | (0.0, 0.3)*   | (0.0, 0.2)*    |
| Indian-plum         | -             | -              |
| devil's club        | (0.0, 3.9)*   | (0.0, 3)*      |
| sword fern          | (33.9, 49.5)  | -              |
| bitter cherry       | -             | -              |
| cascara             | (0.0, 0.2)*   | (0.0, 0.2)*    |
| wild rose           | (0.0, 0.2)*   | -              |
| thimbleberry        | (0.1, 1.6)    | (0.0, 0.2)*    |
| salmonberry         | (3.5, 10.2)   | (0.4, 3.7)     |
| evergreen           |               |                |
| blackberry          | (0.4, 1.2)    | -              |
| elderberry          | (0.0, 0.3)*   | -              |
| snowberry           | -             | -              |
| huckleberry         | (0.3, 1.7)    | (0.0, 0.4)*    |

Table 4.18. Stem density and basal area of live trees, and stem density of snags, by 10cm diameter class (expressed at the midpoint), for site UM3. N – trees/ha; G – basal area/ha.

| Diameter<br>class | Live trees  |      |           |     |                    |     | Snags    |           |
|-------------------|-------------|------|-----------|-----|--------------------|-----|----------|-----------|
|                   | Douglas-fir |      | red alder |     | western<br>hemlock |     | conifers | hardwoods |
|                   | N           | G    | N         | G   | N                  | G   | N        | N         |
| 5                 | 17.4        | 0.1  | -         | -   | -                  | -   | -        | -         |
| 15                | 26.1        | 0.4  | 17.4      | 0.4 | 8.7                | 0.3 | 8.7      | 8.7       |
| 25                | 67.0        | 3.4  | 17.2      | 1.0 | -                  | -   | -        | 8.7       |
| 35                | 39.3        | 3.7  | 34.8      | 3.2 | 6.0                | 0.5 | -        | -         |
| 45                | 49.5        | 7.5  | 10.0      | 1.6 | 3.6                | 0.5 | -        | -         |
| 55                | 44.9        | 10.7 | -         | -   | -                  | -   | 2.4      | -         |
| 65                | 27.2        | 9.1  | -         | -   | -                  | -   | -        | -         |
| 75                | 17.6        | 7.5  | 1.2       | 0.5 | -                  | -   | -        | -         |
| 85                | 1.0         | 0.5  | -         | -   | -                  | -   | -        | -         |
| 95                | -           | -    | -         | -   | -                  | -   | -        | -         |
| 105               | -           | -    | -         | -   | -                  | -   | -        | -         |
| 115               | -           | -    | -         | -   | -                  | -   | -        | -         |
| Total             | 290.1       | 42.8 | 80.5      | 6.8 | 18.3               | 1.3 | 11.1     | 17.4      |

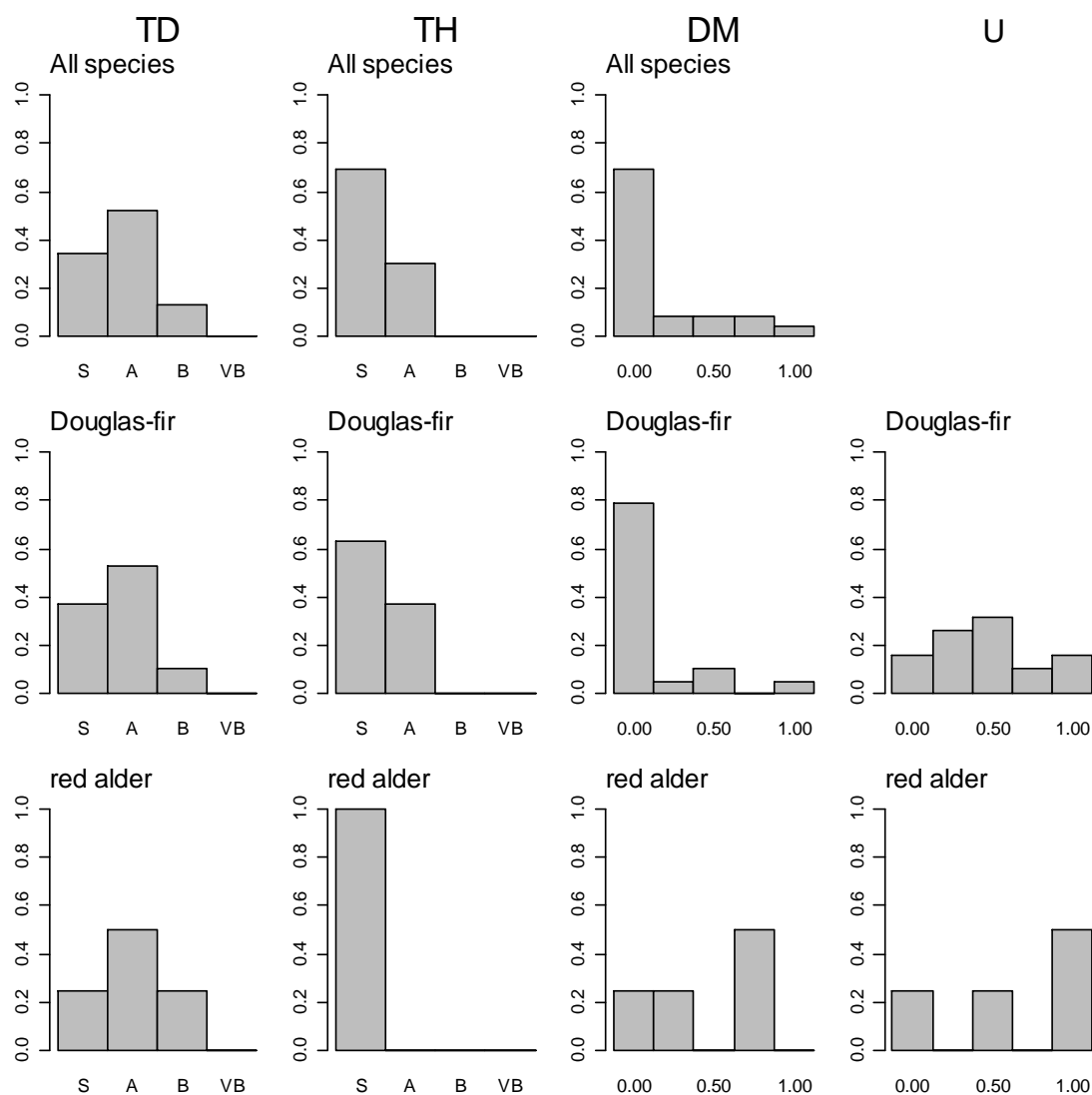


Figure 4.13. Relative frequency distribution of neighborhood-based indices for all species combined and individual species at site UM3. TD and TH index categories are: S – small differentiation (0-0.3); A – average differentiation (0.3-0.5); B – big differentiation (0.5-0.7); VB – very big differentiation (0.7-1.0).



Table 4.19. 95% confidence intervals for low (<1.37m) and high (>1.37m, <2m) shrub cover in site UM3, in the form (*low, high*). \* indicates 95% confidence intervals that included zero, indicating that the values are not significantly different from zero; - indicates that the species was not present in that cover class.

| Species              | Low cover (%) | High cover (%) |
|----------------------|---------------|----------------|
| vine maple           | 2, 7          | 0, 5           |
| dwarf Oregon-grape   | 0, 0*         | -              |
| California hazelnut  | -             | -              |
| Salal                | 0, 0*         | -              |
| oceanspray           | -             | -              |
| fool's huckleberry   | 0, 5*         | 0, 2*          |
| Indian-plum          | -             | -              |
| devil's club         | 0, 0          | -              |
| sword fern           | 18, 38        | -              |
| bitter cherry        | -             | -              |
| cascara              | -             | -              |
| wild rose            | 0, 1*         | -              |
| thimbleberry         | 0, 1*         | 0, 0*          |
| salmonberry          | 0, 4*         | 0, 0*          |
| evergreen blackberry | 1, 3          | -              |
| elderberry           | -             | -              |
| snowberry            | 0, 0*         | -              |
| huckleberry          | 2, 6          | 0, 4*          |

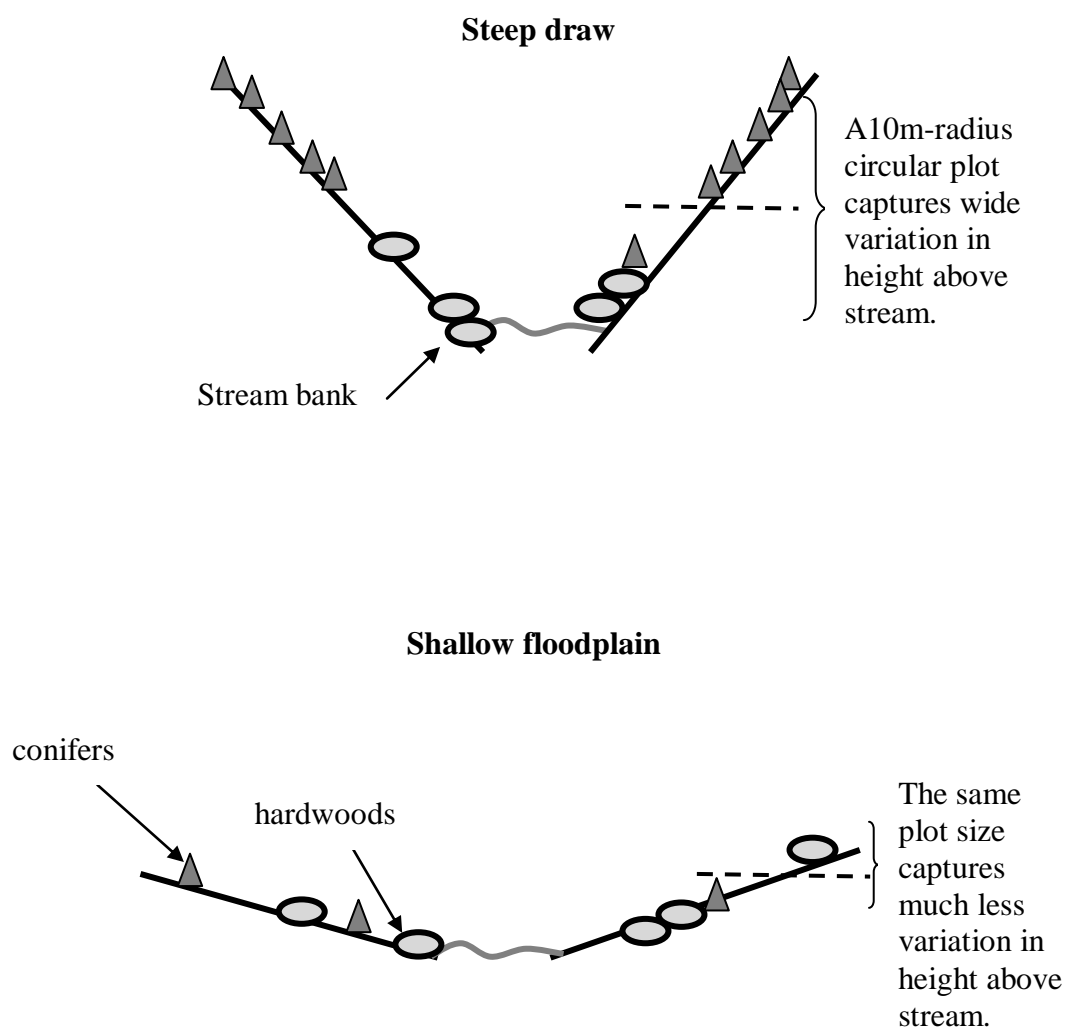


Figure 4.14. Illustration showing the difference in height-above-stream variation captured by the same plot size in two hypothetical but frequently encountered situations in riparian forest sampling.

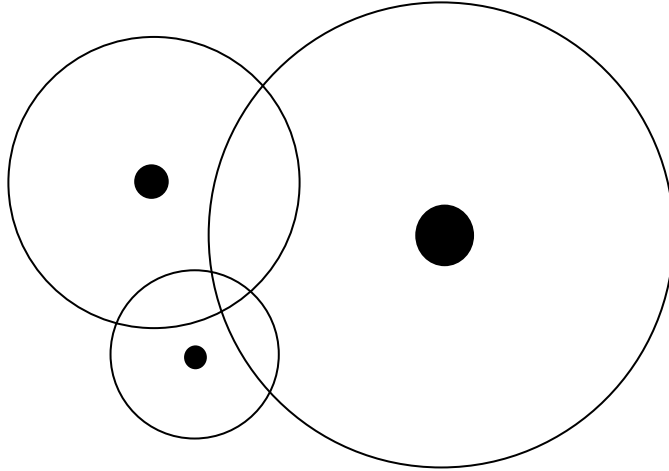


Figure 4.15. An illustration of the “tree-centered” approach for conceptualizing variable plot sampling. The “tree circle” of a tree is proportional to its basal area. Trees are counted in a variable plot sample if a randomly-placed sample point lands inside this tree circle. A sample point located in the area where all three circles overlap would capture all three trees.

## CHAPTER FIVE

### CONCLUSION

The objective of this thesis was to describe and evaluate several innovative approaches for quantifying riparian forest structure in western Oregon. In Chapter 2, I introduced and evaluated n-tree distance sampling, an uncommon forest sampling method, for density and basal area estimation. Chapter 3 introduced neighborhood-based indices and evaluated the performance of several sampling methods for estimating them. Chapter 4 set the scene for the analysis in Chapter 5 by determining the best plot type and metric for characterizing change in species composition across the height-above-stream gradient. Chapter 5 utilized the results of the previous chapters to offer a full characterization of eight study sites in the Trask Watershed.

As the interest of the general public in the nontimber values provided by forests continues to expand, and as forest managers continue to be challenged to manage for a full suite of goods and services from forests, the importance of developing sound, efficient, and effective protocols for quantifying forest structure will continue to increase.

Unfortunately, unlike more traditional mensurational concepts such as timber volume, forest structure is difficult to define and, therefore, difficult to measure. Many researchers have expended considerable energy on the development of composite measures of structural diversity (e.g. an “old growth index”; see McElhinny et al. 2005). However, it seems that such narrowly defined metrics will always be limited in application. As McElhinny et al. (2005) point out, vertical foliage diversity is one of the most commonly-used attributes for the description of structural diversity. This approach can be traced to the work of MacArthur and MacArthur (1961), who found that bird species diversity was positively correlated with a metric of foliage height diversity in some deciduous forests.

Many of the things we measure in our desire to quantify forest structure can be considered crude stand-ins for either foliage height diversity or leaf area. For example, the diameter distribution of a single-species stand can give a rough indication of the evenness of leaf area throughout the canopy. Similarly, basal area or volume of a given species, perhaps in proportion to the total, can be a rough measure of the leaf area occupied by that species. The neighborhood-based indices can be seen as a more direct attempt to quantify foliage diversity at the single-tree level.

There is nothing wrong with measuring trees in lieu of measuring foliage. Leaf area index, a unitless index of the area of leaves over an equivalent area of ground surface, is difficult to measure directly (Marshall and Waring 1986). The foliage height diversity index used by MacArthur and MacArthur (1961) is also very time-consuming to estimate. If it is easier to measure trees than go to all this trouble, so be it. However, we must not lose sight of the end goal. Although for some specialized applications the quantification of wildlife habitat or other nontimber resources may require information about sizes and abundance of trees themselves, much of the demand for knowledge in forest ecosystem sampling relates more directly to the measurement of leaf area, and the tree boles that we love to count and measure are merely the bearers of this leaf area. It is easy to forget this.

Unfortunately, tree leaf area tends to be more highly correlated with sapwood basal area than total basal area, and therefore many of the standard techniques for estimating total basal have limited application in this context. If there is a reasonable, however imperfect, correlation between sapwood basal area and total basal area for a individual species, a subsampling method used in conjunction with variable plot sampling may be effective for estimating total basal area (and, hence, total leaf area) of a given species on a certain site. However, precise estimation of sapwood basal area is currently very difficult operationally (Tappeiner et al. 2007, p155).

The size differentiation (TD and TH) indices hold some promise for inexpensive estimation of foliage height diversity. However, these indices could only

be applied under the implicit assumption that the crown ratio for a given tree species is always a certain percentage of the tree's height. While this assumption may not ever be strictly true, it may provide reasonable results in practice. Any correlation between the size differentiation indices and any metric of foliage height diversity has yet to be tested. However, it would seem that any correlation would have at least partially failed in the Trask Watershed, given the contribution of tall shrub species such as western hazelnut and vine maple towards foliage height diversity in that system. There may be opportunities for inexpensively-measured measures of forest structure that correlate well with what we are after: the abundance, type and spatial arrangement of leaf area.

In conclusion, while most measures of forest structure have focused on the abundance, size and spatial arrangement of tree boles, I believe that what we are really interested in, particularly insofar as wildlife habitat is concerned, has far more to do with quantifying leaf area. As such, many of the future challenges in sampling forest structure in the Pacific Northwest will revolve around the development of operationally efficient protocols for sampling leaf area. Protocols that will allow us little humans, scurrying around the forest floor, to paint a picture, tentative and incomplete as it may be, of the vast expanse of vertical space that is filled by some of the tallest plants on earth.

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APPENDIX A



### IMPORTANT INFORMATION ABOUT SIAFOR

SIAFOR calculates the DM and TD indices for all species combined, and separately for each species. The program also calculates two different types of buffers. For the DM index, the buffer is equal to “the greatest observed distance between a tree within the buffer and its  $n$ th nearest neighbor ( $n$  depending on the calculated index)” (Kint 2004). This is also true for the TD index when all species are considered at once. However, the calculations for the species-specific TD index only includes nearest neighbors of the particular species under consideration. Therefore, the buffer width for this calculation is set equal to the greatest observed difference between a tree within the buffer and the  $n$ th neighbor that is of the same species (V. Kint Pers. Comm. 3/14/2010). This sometimes resulted in a calculated buffer width that was  $>20\text{m}$ .

Because I was not interested in the TD index when calculated in this way, I ignored the calculated buffer width for the species-specific TD index and used the buffer width that was calculated for the overall DM and TD indices.

