Factors affecting tree regeneration following a severe wind disturbance in Coastal British Columbia

FRST 498 – BSc (Forest Sciences) thesis

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Abstract

In 2006 a severe wind disturbance damaged many of the forested areas in Stanley Park. Following the windstorm, windthrown areas were salvage logged to reduce the risk of fire. This study looks to determine how basal area, severity of disturbance, and site series affect the regeneration densities of coniferous and deciduous trees. Different types of analysis were used to determine how each of the different factors affects regeneration density. Results from this study show that as basal area increases, regeneration density for coniferous and deciduous trees increases. There is a higher regeneration density in areas of higher disturbance. As moisture and nutrient levels increase both coniferous and deciduous regeneration density increases. There is lots of opportunity for more research in trying to determine which factors most strongly affect regeneration densities.

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Introduction

On December 15th, 2006, a major windstorm struck southwest British Columbia (City of Vancouver, n.d.; Kheraj, 2007). In Stanley Park, winds reached speeds of 119 km/h knocking over more than 10 000 trees and destroying 41 hectares of forest in the park (City of Vancouver, n.d.). To help with the restoration effort $10 million dollars was donated by private individuals, corporations and governments to plant 15 000 trees and shrubs and remove approximately 10 000 damaged or fallen trees from the park, stabilize steep slopes and repair the seawall (City of Vancouver, n.d.). This is not the first time that large windstorms have caused damage in Stanley Park. Similar storms happened in 1934 and 1962 when thousands of trees were uprooted or broken and the Stanley park board made efforts to restore most of the damaged areas to a pre disturbance state (Kheraj, 2007).

History of Stanley Park

Stanley Park is a 400 ha park located just west of downtown Vancouver (City of Vancouver, n.d.). It was established in 1888. At that time it was an area that had been heavily logged but it was set aside from further logging or housing development to be a green space in the newly established city of Vancouver (City of Vancouver, n.d.).

Following a major windstorm in 1934 where thousands of trees were blown down, the park administrators adopted the management objective of making the forested areas of the park look like a natural forest with no major human influences or disturbances (Kheraj, 2007). The park board was successful in this goal and the public opinion was that Stanley Park looked like a natural forest with few human influences (Kheraj, 2007). In 1962 Stanley Park was struck by another large windstorm that knocked over more than 2000 trees (Kheraj, 2007). Following the storm the park board tried to recreate the undisturbed forest look again by removing many of the damaged and fallen trees and planting of

Douglas-fir in rows and at high densities. This was received with lots of confusion, as the public believed that in order for Stanley Park to be natural it should be left alone (Kheraj, 2007).

Context for this study

Following the December 15, 2006 wind storm, decisions were made regarding how to best manage Stanley Park. The priorities for the restoration plan were to create a new forest that would be more resistant to wildfire and wind disturbance, as well as protecting users of the park (Vancouver Park Board, 2007). This plan included removing logs and branch material as well as planting new trees and brushing at an estimated cost of $1 million (Vancouver Park Board, 2007).

In 2009, a forest management plan was approved by the Vancouver Park Board. This addressed the question of how to best manage Stanley Park into the future (*Stanley Park forest management plan,* 2009). The vision of the plan is to produce a healthy forest of native species that is resilient to future disturbances and safe for all users of Stanley Park and to protect the variety of plant and animal species within the park (*Stanley Park forest management plan,* 2009). The new forest management plan has three main strategies for managing the forest (*Stanley Park forest management plan* ,2009). The three strategies are maintenance, protection, and enhancement (*Stanley Park forest management plan,* 2009). The maintenance part of the plan includes removing dangerous trees and managing the woody debris (*Stanley Park forest management plan,* 2009). In the protection strategy, the plan is to avoid creating conditions that will allow for another disturbance to cause lots of damage to the forest (*Stanley Park forest management plan,* 2009). The final strategy is to enhance the forest by creating better conditions for animal species and forest health (*Stanley Park forest management plan,* 2009).

Understanding recovery following wind disturbances is very important in the management of forests in which wind is a dominant disturbance process (Everham III & Brokaw, 1996). With the current changing climate we may see wind playing a more important role in affecting forest structure and composition into the future (Peterson, 2000). In the next section of this thesis, I will review the state of knowledge on wind disturbance and regeneration.

In addition to fundamental questions concerning post-storm and post-salvage stand development, there are some unresolved questions regarding forest regeneration dynamics in Stanley Park that have practical implications for park managers. In this study I compare the abundance of planted and natural regeneration. I also evaluate the factors that make areas suitable for natural regeneration. The answers to these questions can help determine if planting was necessary in this ecosystem, and if so, where efforts should be concentrated if another storm happens with similar damage characteristics.

Stanley Park provides an interesting location for a study on regeneration. Because of its close proximity to Vancouver, management decisions are made with a lot of thought towards the safety and enjoyment of visitors to the park (Kheraj, 2007). This is balanced with the desire for a natural healthy looking forest that is resilient to future large disturbances (*Stanley Park forest management plan,* 2009). The result of this and the differences in disturbance patterns is that there is lots of variety in the way that the Stanley Park forest is managed, there are areas of forest that are nearly left alone, to areas that are heavily managed with brushing and planting (Buffo, 2011). This difference allows for a comparison between natural regeneration and planted regeneration in nearby plots and in some cases in the same plots.

Literature Review

Wind as a disturbance agent

Wind can play a major role in the species composition and structure of a forest (Everham III & Brokaw, 1996). Wind damage can be both minor so that only an individual tree is affected or it can be very major where an entire stand is affected (Everham III & Brokaw, 1996). Wind disturbances can kill or damage large trees, creating openings for younger trees to grow into the canopy or just create space for already present canopy trees to grow bigger (Wimberly & Spies, 2001). Wind disturbances are typically patchy in their damage patterns and can cause a wide variety of age classes and species to be present in a forest (Wimberly & Spies, 2001).

Wind effects in forests vary on a timescale of days to many years (Peterson, 2000). Wind affects environmental conditions such as temperature and moisture reaching the forest floor (Peterson, 2000). In the short term it can decrease the density of overstory trees, which may lead to higher or lower densities in the future (Peterson, 2000). Higher densities develop if more trees replace the trees that were removed, and lower densities develop if overstory trees fill in the gap so there is no space for new trees (Peterson, 2000). Wind can change the species composition by removing overstory trees that are more susceptible to wind, or by allowing more shade tolerant species to grow in the resulting gaps (Peterson, 2000). Wind disturbances can move succession forward by allowing established e cohorts of trees to begin to take dominance (Peterson, 2000).

Damage Characteristics

Wind disturbances are distinct from many other types of forest disturbances because they do not destroy any organic matter (Franklin et al., 2002). Wind disturbances will often leave the forest with greater variety in structure as there will be fallen logs, broken snags, some large trees, and the understory vegetation often remains relatively unaffected (Franklin et al., 2002). Wind also affects the forest floor by exposing mineral soil and creating variations in microsites (Peterson *et al.*, 1990).

There are several different types of damage that wind can do to a tree: wind can uproot a tree, snap the stem or branches, or just permanently bend the tree (Cooper-Ellis *et al.*, 1999). The type and severity of wind damage to a tree is determined by several factors including the species of tree, size of the tree, topography of the area, history of disturbances, spatial patterns of the forest and the health of the individual trees (Cooper-Ellis et al., 1999; Everham III & Brokaw, 1996; Wimberly & Spies, 2001). Wind usually knocks over trees that already have some sort of stem damage such as a fork or that are rotting (Wimberly & Spies, 2001), but can also affect healthy trees that have poor mechanical stability in dense stands, they are tall and have a small diameter (Wilson & Oliver, 2000). Wind damage occurs more often on hill slopes and areas with shallow soils (Wimberly & Spies, 2001). Trees in forests that have been recently thinned are also much more susceptible to being knocked over by wind (Wilson & Oliver, 2000).

Regeneration patterns

The frequency and severity of disturbances such as wind are major components affecting the regeneration patterns of a forest (Foster & Boose, 1992). The tree species present in the canopy that survive the wind disturbance can have a large effect on the tree species that grow in after the wind disturbance (Peterson et al., 1990). Already established vegetation affects new regeneration through the type of litter that falls, the effect of the canopy on how rain/moisture reaches the soil, the way the roots grow, and as a source of seeds or vegetative reproductions (Everham III & Brokaw, 1996; Franklin et al., 2002; Peterson et al., 1990). Everham III and Brokaw state that there are four different ways forests can react following a wind disturbance; “regrowth, recruitment, release, or repression” (Everham III & Brokaw, 1996). Regrowth is when the same trees are able to continue growing or the same tree species replace those that were knocked over during the wind storm (Everham III & Brokaw, 1996). Regrowth usually occurs when the wind disturbance is not too severe and the damaged tree is able to replace its broken branches and continue growing (Everham III & Brokaw, 1996). The canopy trees that can remain following a wind disturbance often contribute to the regeneration of the stand as they are a source of seeds and vegetative reproduction (Everham III & Brokaw, 1996; Franklin et al., 2002). Recruitment occurs following major disturbances when lots of space is opened up for new earlier successional species to grow (Everham III & Brokaw, 1996). Wind disturbances can make the soil more suitable for the recruitment of new plants (Peterson, 2000). The gaps created in the canopy allow more light and can increase the soil temperature so that soil microbes can be more active and increase soil nutrient levels (Peterson et al., 1990; Peterson, 2000). Release is when the understory trees that were present before the wind disturbance are able to take advantage of the canopy openings and grow into the overstory (Everham III & Brokaw, 1996). Wind disturbances do not usually affect understory vegetation so they allow advanced regeneration to move up into the canopy to replace the trees that were knocked over by the wind disturbance (Franklin et al., 2002). Repression occurs when new trees do not grow in the disturbed forest (Everham III & Brokaw, 1996). This could be because other types of plants suppress trees from growing or the litter and woody debris from the damaged trees prevent new trees from growing (Everham III & Brokaw, 1996).

Tree Regeneration

There are three important factors affecting the regeneration of trees in a forest, the seed bed, the seed source, and the environment of the site (Carter & Klinka, 1992; LePage *et al.*, 2000). Seed bed refers to the substrate the seed may grow on (mineral soil, organic material, etc.)(,(LePage et al., 2000). The seed source is where the seeds come from. Seed source is affected by how many parent trees there are, how far away they are, and the size of the seed crop (LePage et al., 2000). The environment refers to the amount of light reaching the seed as well as temperature, moisture and nutrient levels around the seed (Carter & Klinka, 1992). Variations in these three factors affect if and how well a seed will germinate and grow at a given location (LePage et al., 2000).

The ability of any tree to grow in an area depends on availability of key factors including moisture, nutrients, and light (Carter & Klinka, 1992). These factors affect growth rates, species composition and species abundance (Carter & Klinka, 1992). Light is probably the most important factor, when there is enough light for a certain species than the moisture and nutrient level become important (Drever & Lertzman, 2001). Overstory basal area and the abundance of pits created by uprooted trees can both be used to approximate the relative amount of light that is reaching the forest floor (Jenkins & Chambers, 1989; Peterson & Pickett, 1990).

Basal Area

Basal area of overstory trees has an effect on the species composition of seeds falling to the forest floor, the environment and seedbed conditions that the seeds have to grow; overstory basal area also affects the amount of light reaching the forest floor (Greene et al., 1999). Trees need to be dense enough that there is a large seed source but thin enough that sufficient light can make it through to the forest floor (Zeide, 1985). For some species, increased basal area is important as it is related to the amount vegetative reproduction (Greene et al., 1999). Basal area is a very good measure of stand density because it combines the number of trees, how close the trees are together, and the size of trees into one single easy to determine measurement (Jenkins & Chambers, 1989; Zeide, 1985). Basal area is also well correlated with canopy cover so that when the site has a low basal area it has a less dense canopy so more light filters through to the canopy (Jenkins & Chambers, 1989; Zeide, 1985).

Light

One of the most important factors that trees need to grow is light (Drever & Lertzman, 2001). It has been shown that basal area is related to amount of understory light (Jenkins & Chambers, 1989). Page *et al. s*howed that as basal area increases the germinant density increases because when basal area is high there is an increased seed source to allow for more regeneration (Page *et al.*, 2001).

However, when the new regeneration gets older, much of the regeneration starts to die because there is not enough light (Page et al., 2001). Different species react differently to the amount of available light depending on their shade tolerance level (Drever & Lertzman, 2001). The growth of *Pseudotsuga menziesii* (Mirb.) (Douglas-fir) trees increases with light, this relationship is very strong (Drever & Lertzman, 2001). *Thuja plicata (*Donn) (western red-cedar) growth increases with increased light up to about 20% of full sunlight, after that growth rate does not change very much with different light levels (Drever & Lertzman, 2001)

Pits and Mounds

Pits are created when a tree falls over with its roots attached; this leaves a hole where the roots were (Peterson & Pickett, 1990). The pulled up roots and associated soil also make a small mound. Pits are related to light levels because they occur where a tree has been knocked over allowing more light to pass through the canopy to the forest floor (Peterson & Pickett, 1990). Pits and mounds are also important microsite habitats that allow for more variation in regeneration occurring on a site (Peterson & Pickett, 1990). Depending on the species and location, mounds or pits may be better for germination (Peterson & Pickett, 1990; Ulanova, 2000).

Peterson and Pickett found that in north western Pennsylvania, regeneration in pits is often different from that on mounds in terms of species and density (Peterson & Pickett, 1990). Different studies have produced different results. In some cases, regeneration density is higher in pits and in some cases regeneration density is lower in pits (Peterson & Pickett, 1990; Peterson & Campbell, 1993). The argument for why pits are more favourable for regeneration is that pits have more moisture, the pits are more stable, and seeds are more likely to end up in pits (Peterson & Pickett, 1990). Pits may also decrease regeneration as seedlings that grow in pits are susceptible to damage or death from the pit flooding with water during a rain event or soil movement along the edge of the pit (Ulanova, 2000). Pits can also collect lots of litter which seeds are not able to germinate on (Peterson & Campbell, 1993). Pits and mounds do not affect the height growth of seedlings (Peterson & Pickett, 1990). The sizes of the pits and mounds also can have an effect on the type of regeneration (Peterson et al., 1990).

Site Series

Ecological site series are areas with a certain plant community and soil conditions, including moisture and nutrient regime (Pojar *et al.*, 1987). The quality of the site plays an important role in determining the growth rate of trees (Drever & Lertzman, 2001). Drever and Lertzman found that Douglas-fir seedlings have increased growth as the nutrients and moisture regime improved, but only when there was sufficient light (Drever & Lertzman, 2001).

Kranabetter *et al.* (2003) found that for some of the most common conifer species in the west coast of BC, *Tsuga heterophylla* (Raf.) (western hemlock), *Picea sitchensis* (Bong.) (Sitka spruce), and western red-cedar, growth was higher on well drained sites and lower on poorly drained sites (Kranabetter *et al.*, 2003).The distribution of soil nutrients plays an important role in determining where certain tree species are located (John et al., 2007). Trees on sites with higher nutrient levels grow better than trees on lower nutrient sites (Kranabetter et al., 2003).

Research Questions and Hypotheses

This study will evaluate the most important factors in predicting the density of coniferous and deciduous regeneration following a damaging wind storm and salvage harvesting. The questions that will be investigated are:

1) What effect does basal area of overstory trees have on the abundance of regeneration?

2) How does the amount of ground disturbance by wind affect the abundance of regeneration? (The level of wind disturbance will be based on the amount of tree fall pits in the study area)

3) How does Site Series affect regeneration? Soil moisture and soil nutrients will also be looked at separately.

Three hypotheses can be formulated in association with these questions:

1) If the basal area increases, then the abundance of natural regeneration of coniferous and deciduous trees will decrease.

2) If the level of windthrow disturbance increases, then the abundance of natural regeneration of coniferous and deciduous trees will increase,

3) In locations of higher nutrients and moisture, the abundance of natural regeneration of coniferous and deciduous trees will increase.

Methods

Study Area

This study was conducted in Stanley Park which is located just to the west of downtown Vancouver, BC. Stanley Park has about 256 ha of vegetated area with approximately 150 000 trees (Buffo, 2011; City of Vancouver, n.d.).

Stanley Park is located in the Coastal Western Hemlock Biogeoclimatic Zone, most of the park is in the dry maritime but the western edge borders on the xeric maritime subzone (Buffo, 2011). The terrain is fairly flat with various aspects and with most slopes under 10%. The elevation of Stanley Park ranges from sea level up to 70 m (Buffo, 2011). The forests are dominated by Douglas-fir, western red cedar, bigleaf maple, and red alder in young, mature and old age classes. There are also small amounts of other native and non-native tree species throughout the forests.

Data Collection

Data was collected during the summer or 2008 by Mike Buffo, MSc student and his field assistants. This was the second growing season following the wind storm (*Guidelines for data collection and analysis: Stanley Park 2008,* 2008). There are 130 temporary sample plots and 58 permanent sample plots. Plots were located by first making a grid with points 100 m apart, then, using Microsoft Excel, random intersections within the grid were chosen for plot locations (Fig. 1 shows location of Temporary and Permanent Sample plots) (*Guidelines for data collection and analysis: Stanley Park 2008,* 2008). Once locations were determined, a Garmin 60CSx GPS unit was used to find the locations of the centre of the plots.

Abundance of regeneration was measured in a 1.78 m fixed radius plot (10 m^2). Data was collected for each individual species. Seedlings that had been planted were also counted (*Guidelines for data collection and analysis: Stanley Park 2008,* 2008). A tree was counted as regeneration if it was less than 1.3 m tall and two or more years old (Buffo, 2011). Basal area was measured using a Cruisemaster Prism with a Basal Area Factor of 8(*Guidelines for data collection and analysis: Stanley Park 2008,* 2008). The site series was determined using the BCMoF Field Guide for Site Identification and Site Interpretation for Vancouver Forest Region (Green and Klinka, 1994), the biogeoclimatic zone is CWHdm (*Guidelines for data collection and analysis: Stanley Park 2008,* 2008). The moisture and nutrient regimes were classified using soils, slope position and vegetation according to the guide. To simplify the data analysis, locations were re-classified as ‘poor in nutrients’ if the site series was 1 and ‘rich in nutrients’ if the site series was 5, 7, or 12. Similarly, locations were re-classified as ‘fresh’ if the site series was 1 or 5, ‘moist’ if the site series was 7 and ‘wet’ if the site series was 12. No other site series classes were found in the study area. All of this collected data was imputed into Microsoft Excel.

Figure 1: A map showing the locations of the Temporary and Permanent Sample Plots (from Buffo 2010)

Data Analysis

For the purpose of this study, the temporary sample plots (TSP's) and permanent sample plots (PSP's) were combined to form one dataset. This single data set was analyzed using Statistical Analysis Software (SAS Institute inc., 2008) All of the coniferous trees (western hemlock, western redcedar, Douglas-fir, and Sitka spruce) were reclassified as 'conifers', all of the deciduous trees (*Acer macrophyllum* Pursh (bigleaf maple), *Alnus rubra Bong.* (red alder), and *Sorbus sitchensis* M.J. Roem. (Sitka mountain ash)) were reclassified as 'deciduous', and all of the trees that looked to be planted following the windstorm (Douglas-fir, western redcedar, and Sitka spruce) were reclassified as 'planted'. For some analyses, conifers, deciduous and planted trees were analyzed separately.

SAS was used to create box plot graphs for the regeneration based on basal area, pits, site series, soil moisture and soil nutrients to show the range of data as well as provide information about the mean and median and to see how the data was distributed. The means and standard errors were input into Excel to show trends in the data. This information was used to see if any of the predictor variables were able to help predict the density of regeneration.

SAS was used to do a Pearson Correlation Analysis to determine the degree of correlation between any of the factors affecting regeneration or any of the levels of regeneration. Pearson correlations show whether one variable has a linear relationship with another variable.

SAS was used to create contingency tables to examine whether classes of predictor variables caused the amount of seedlings to be above or below a threshold 'stocking' value. The threshold 'stocking' values that were used were 1000 stems/ha, 3000 stems/ha, 5000 stems/ha, and 8000 stems/ha. This stocking information is very useful for managing a forest because it shows what the percentage of plots have more than the desired number of seedlings, for a given predictor variable. Only the contingency tables that had significant Chi-square values ($p < 0.05$) are shown. Thresholds above 8000 stems/ha were not looked at because very few variables were significant with such a high stocking threshold. These thresholds were chosen to show differences in the results at different threshold values. Depending on the desired future forest as well as remaining trees different stocking values are appropriate for different forests.

Finally, SAS was used to conduct a forward stepwise regression to determine if multiple factors were involved in affecting the density of regeneration. A forward stepwise regression creates a model by starting out with no predictor variables and sequentially adding the variables that are most significant until there are no more significant variables to be added (Pearce & Ferrier, 2000). Variables were added to the model as long as the p-value remained under 0.5.

Sources of Error

After combining the data from the temporary sample plots and permanent sample plots, some plots did not contain enough data for analysis. Plots were deleted from the analytical dataset if they were not forested (they were in fields or along roads) or were not within forest boundaries. This left 179 plots in total.

For practical reasons, if there were more than 50 seedlings of one species in a plot the plot was classified as having 50 seedlings of that species, and this truncates the upper value of stems per hectare at 50,000 for each species. Many of the plots did not have any seedlings which created lots of 0 values in the data. These zeros also affected the distribution of the data. The sample plots may have been too small to represent the variability in ground conditions within a given PSP or TSP.

This study looked at all of the regeneration, not just what had started growing since the windstorm and salvage logging. The conditions before the windstorm probably have an important effect on the heights and densities of all the different types of regeneration.

Results

Descriptive Statistics

In the 179 plots that were analyzed, most of the germinants were coniferous, there were lots of deciduous and not very many planted trees found. Western hemlock was the most abundant type of regeneration (Table 1). Of the naturally regenerating trees red alder was tallest but both planted Sitka spruce and grand fir were taller (Table 1).

Table 1. Average number of stems/ha, range, and average height of regeneration by species in sample plots in Stanley Park in 2008.

	Species	Average number of Stems/ha	Range of plots(stems/ha)	Average Height (m)
Deciduous	Sitka mountain ash	8475	0 – 50 000	0.4
	bigleaf maple	564	0 – 50 000	0.98
	red alder	302	0 – 50 000	1.01
Coniferous	western hemlock	22642	0 – 50 000	0.37
	western redcedar	799	0 – 10 000	0.45
	Sitka spruce	39	0 – 3 000	0.6
	Douglas-fir	22	0 – 3 000	0.7
Planted	western redcedar	737	0 – 20 000	0.43
	Douglas-fir	369	0 -9 000	0.51
	grand fir	61	0 - 3000	1.05
	Sitka spruce	39	0 – 2 000	1.19

Abundance Analysis

Basal Area

Regeneration densities varied greatly between plots, even for similar overstory basal area levels. However, there are weak trends in mean natural regeneration density with increasing overstory basal area (Figure 2). Box plots showing the distribution of regeneration densities at different overstory basal areas indicate a non normal distribution (Appendix A, figures A1-A3). There is increasing mean coniferous regeneration density as the basal area increases. For deciduous trees, as basal area increases, the regeneration density also increases but the trend is not as prominent as it is for coniferous trees. Planted trees show the opposite trend. As basal area increases, the number of planted trees decreases (Figure 2).

For all the different basal area classes, the density of coniferous vegetation was greater than deciduous vegetation, and aside from plots with very sparse overstories (an overstory basal area of 5), deciduous species were more abundant than the planted regeneration.

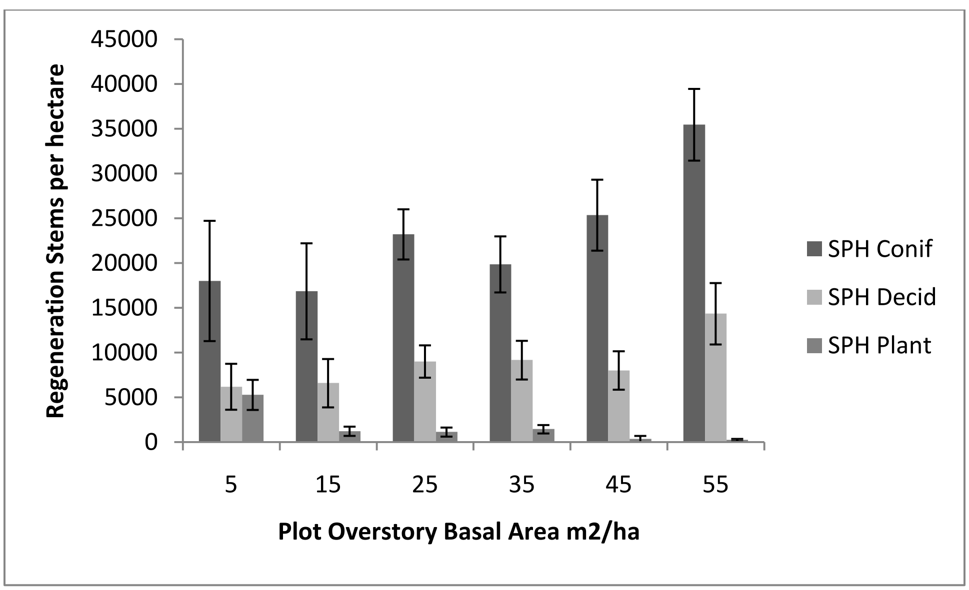

Figure 2: Seedling densities versus plot overstory basal area in Stanley Park. Error bars equal 1 standard error (n = 179).

Windthrow Pits

Of the 179 plots, 136 of them did not have any pits caused by uprooting trees. Thirty two of the sites had pits at a density of 1000 per hectare, 7 sites had pits at a density of 2000 per hectare, and 4 sites had a density of 3000 pits per hectare[1].

As the density of pits increases there is an increased amount of coniferous regeneration (Figure 3). The deciduous regeneration shows no change in density as the amount of pits increases except for when pits are at a density of 3000/ha, then there is lots of deciduous regeneration. Planted trees increase in density as the number of pits increases.

Aside from when pits are at a density of 3000/ha, there is always a fairly large difference between the coniferous, deciduous, and planted regeneration densities. At 3000 pits/ha the difference is not as large. The data for the number of pits versus regeneration density is not normally distributed, see Appendix A, figures A4-A6 which are box plots showing how the data is distributed.

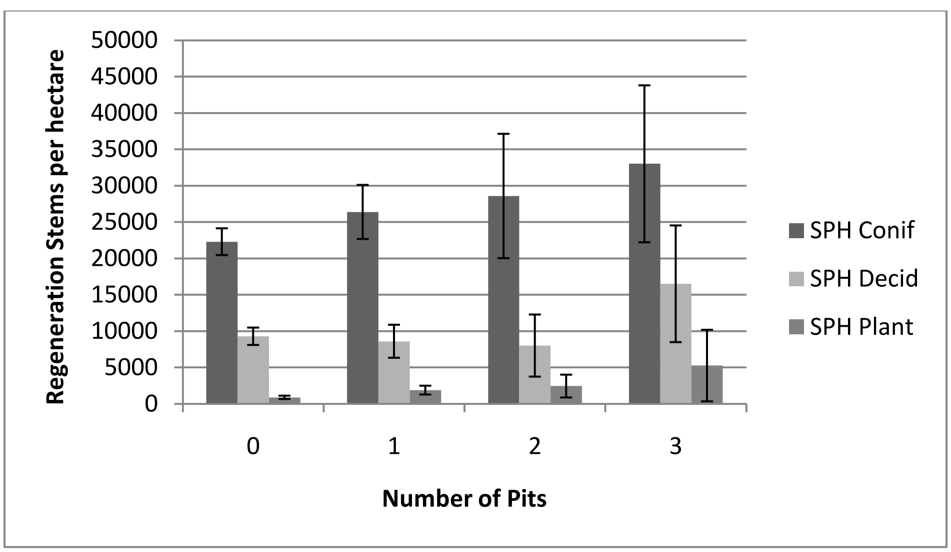

Figure 3: Seedling densities versus amount of pits in 2008 in Stanley Park. Error bars equal 1 standard error. For pits = 0 n = 136, pits = 1000 n = 32, pits = 2000 n = 7, pits = 3000 n = 4.

[1] Numbers of pits are not very realistic because of the small plot size, but they give an estimate of the level of disturbance.

Site Series

There were four different site series identified for all of the 179 sites. 10 sites were found to have a site series of 1, 96 sites had a site series of 5, 69 sites had a site series of 7 and 4 sites had a site series of 12. The data for site series versus regeneration density is not normally distributed, see Appendix A, figures A7-A9 which show how the data is distributed in box plots.

For both coniferous and deciduous tree regeneration there is a trend of an increase in regeneration at higher numeric values of the site series (Figure 4). This does not mean anything by itself because site series relates to a combination of soil moisture and soil nutrients (Pojar et al., 1987). However, soil moisture in site series 12 is higher than 7 and site series 7 has higher moisture than 1 and 5 (soil moisture 12>7>5=1). Also, nutrients levels in site series 1 is lower than 5, 7, and 12 (soil nutrients 5=7=12>1).

Coniferous trees regeneration shows an increasing trend in regeneration density as soil moisture increases and as soil nutrients increases (Figure 4). Deciduous trees show the same trend, as soil moisture and soil nutrients increase there is more regeneration (Figure 4). Figure 4 shows that there may be a slight decrease in planted trees as soil moisture and soil nutrients increase.

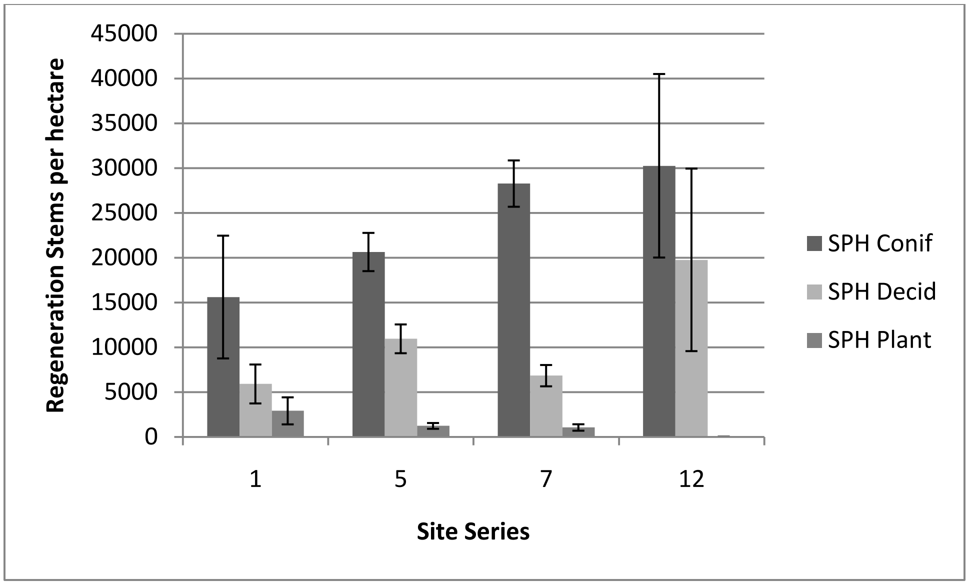

Figure 4: Seedling densities versus plot site series in 2008 in Stanley Park. Error bars equal 1 standard error. At site series 1 n = 10, site series 5 n=96, site series 7 n = 69, site series 12 n =4.

Site series is a combination of soil moisture and soil nutrients, see appendix B for box plots and bar graphs of moisture and nutrients relation to coniferous, deciduous, and planted seedling density.

Correlation Analysis

There are weak correlations between basal area and all of the different types of regeneration (Table 2). There are weak positive correlations between basal area and coniferous and deciduous regeneration densities. There is a negative relationship between basal area and planted seedling density.

The number of pits is weakly positively correlated with the density of planted regeneration but not the density of coniferous or deciduous regeneration (Table 2). Site series and moisture are both correlated with coniferous regeneration, while nutrients are not correlated with abundance of any class of regeneration.

One of the strongest correlations is between coniferous and deciduous regeneration.

Table 2: Pearson Correlation Analysis of 2008 data from Stanley Park. **Bold** numbers are significant (α < 0.05). (N = 179)

	Basal Area	Pits	Site Series	Moisture	Nutrient	Conifer Density	Deciduous Density	Planted Density
Basal Area	1							
Pits	**-0.17**	1						
Site Series	-0.121	**0.157**	1					
Moisture	**-0.172**	**0.19**	**0.833**	1				
Nutrient	0.009	-0.028	**0.657**	**0.194**	1			
Conifer Density	**0.264**	0.11	**0.175**	**0.186**	0.09	1		
Deciduous Density	**0.154**	0.03	0.022	-0.065	0.06	**0.32**	1	
Planted Density	**-0.24**	**0.231**	-0.127	-0.071	-0.129	-0.028	-0.006	1

Contingency tables

Figure 5 shows what percentage of plots are above a given threshold of coniferous regeneration by overstory basal area class. There is a general increase in stocked plots as overstory basal area increases. This is most pronounced for the highest stocking threshold (8000 sph).

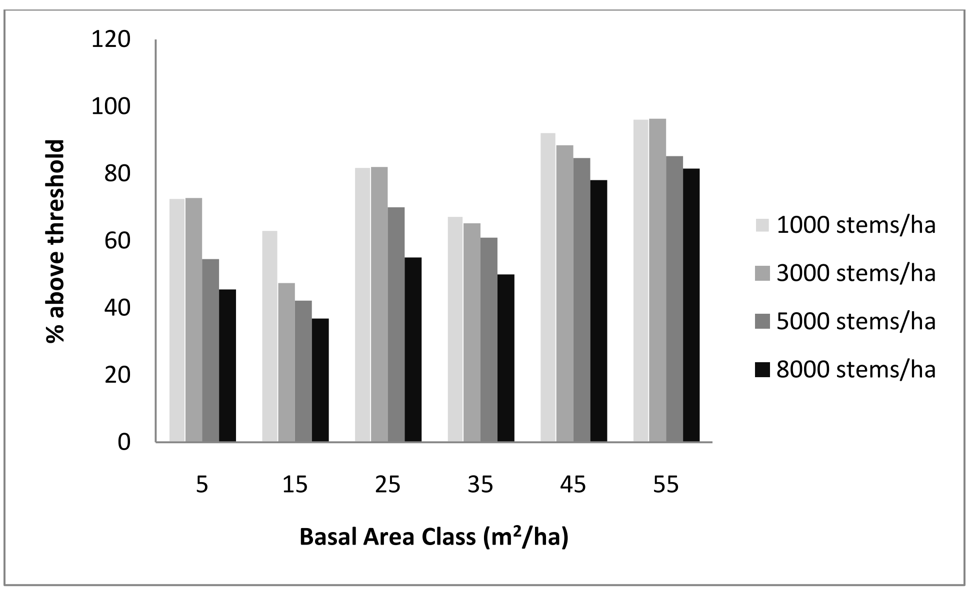

Figure 5: Summary of Contingency table showing what percentage of stands at a certain basal area were above thresholds of 1000, 3000, 5000, and 8000 coniferous stems/ha in 2008 in Stanley Park (n = 179).

For Site Series there was only significance at 8000 stems/ha. As the numeric value of site series increases, than the probability of a site having more than 8000 stems/ha increases. Because site series is a combination of moisture and nutrients there is more chance of a site having more than 8000 stems/ha in areas with high levels of moisture and high levels of nutrients. Locations with a site series of 12 are more than twice as likely to have more than 8000 stems/ha compared to locations with a site series of 1 (Figure 6).

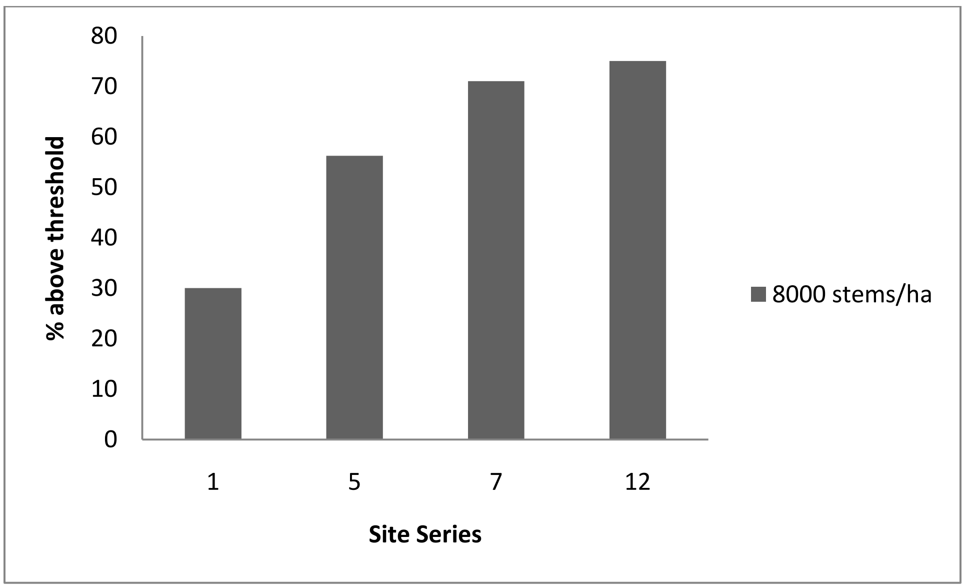

Figure 6: Summary of Contingency table showing what percentage of stands at different site series were above a threshold of 8000 coniferous stems/ha in 2008 in Stanley Park (n = 179).

For coniferous density 142 of the plots were above 1000 stems/ha and 37 plots were below 1000 stems/ha. At 3000 stems/ha 137 sites were above the threshold and 42 were below the threshold. At 5000 stems/ha 122 were above the threshold and 57 were below the threshold. At 8000 stems/ha 109 plots were above the threshold and 70 were below the threshold.

Site series and Basal area for coniferous trees are the only factors that produced significant contingency tables for any different stocking value.

Forward Stepwise Regression

For an alpha value of 0.05 the forward stepwise regression (Table 3) shows that a model which includes basal area and moisture is the best model for predicting the amount of coniferous regeneration. The R^2 value for this model is 0.1246. As more variables are included the p value shows that they are not significant and the R^2 value does not increase very much.

Table 3: Summary of results from a forward stepwise regression predicting coniferous regeneration density.

Step	variable added	R-squared	F value	p value
1	Basal Area	0.0695	13.22	0.0004
2	Moisture	0.1246	11.08	0.0011
3	Pits	0.139	2.93	0.0888
4	Nutrients	0.1415	0.5	0.4813

For the deciduous regeneration the model that best predicts the density of regeneration is a model that includes all of the different variables (Table 4), as this model produces the highest R^2 value and is significant (p value < 0.05). When the model had two to four variables included the result was never significant.

Table 4: Summary of results from a forward stepwise regression predicting deciduous regeneration density.

Step	variable added	R-squared	F value	p value
1	Basal Area	0.0237	4.29	0.0398
2	Nutrients	0.0271	0.63	0.429
3	Pits	0.0305	0.61	0.4352
4	Moisture	0.0345	0.71	0.4017

The forward stepwise regression for planted trees did not include moisture or nutrients as the p value of these two variables was higher than 0.5. The results of the forward stepwise regression for planted trees show that the model is the best when it only includes basal area (Table 5). When the pits variable was added the results got worse, the R-squared decreases.

Table 5: Summary of results from a forward stepwise regression predicting coniferous regeneration density.

Step	variable added	R-squared	F value	p value
1	Basal Area	0.0576	10.81	0.0012
2	Pits	0.0373	7.26	0.0077

See Appendix E for more detailed results of the Forward Stepwise Regression Analysis.

Discussion

On average, over all of the different plots, there was much more coniferous regeneration than deciduous regeneration. There was especially a lot of western hemlock regeneration. Even though there was more coniferous regeneration the average height of the deciduous regeneration was much taller. These results show that in the near future disturbed areas may be dominated by deciduous trees.

Coniferous and deciduous regeneration increased in abundance as the overstory basal area increased. The reason for this is probably because after two growing seasons the availability of seeds is more important to abundance of regeneration than the availability of light because the seedlings are still small enough that there is not very much competition and when the basal area is high there is probably fewer understory shrubs. The high basal area also indicates that the wind disturbance was not very severe in that area and there was less salvage logging, both of which would have damaged the natural regeneration. In the future, light will probably become a more important factor as competition increases and the opposite trend will be seen, in areas with more openings and more light there will be more new regeneration once competition becomes an important factor. The results also show that even at a high basal area the seed bed is sufficient to allow for lots of regeneration to occur.

Planted trees show the opposite trend to natural regeneration, with most planted trees occurring in areas with really low basal area. This is because planting was concentrated in areas where there was the most damage from the 2006 windstorm.

At all basal areas, coniferous regeneration was more abundant than deciduous regeneration. As the overstory basal area goes up, the difference becomes greater. These results show that following a major wind disturbance (basal area of $5m^2$/ha left) conifer trees are still more likely to regenerate but there is relatively higher deciduous regeneration. As the stand gets older it will continue to be dominated by coniferous regeneration but in stands that were more disturbed by the wind there will be a higher proportion of deciduous regeneration. The fallen debris probably made it difficult for deciduous trees to regenerate. When basal area was high and lots more coniferous regeneration was seen compared to deciduous regeneration it is probably explained by the fact that coniferous trees are in general more shade tolerant than deciduous trees in the area so they could grow in the places with high basal area and more shade.

As overstory basal area increases there is a higher likelihood that the number of regenerating stems/ha will be above a certain threshold value. These values are very important when it comes to deciding how important planting is. If a manager is trying to restock a forest following a windstorm and they know what the minimum amount of regeneration they desire is, they can determine what the likelihood of meeting that stocking is in the absence of planting. For example if a forest manager wants to have at least 5000 stems/ha of coniferous regeneration at a basal area of 5 m^2/ha only a 54.6% of sites will have enough regeneration. However, if the basal area is 55 then 85.2% of the sites will have 5000 stems/ha of regeneration. The results that were found in this study are similar to the results found by Page *et al.* in Southern Scotland, who found that there was a weak positive correlation between density of overstory trees and regeneration densities (Page *et al.*, 2001). Page *et al*. looked at Sitka spruce trees and found that only 18% of germinant density could be explained by the overstory density (Page *et al.,* 2001).

Basal area and pits were both used as a measurement of the severity of the 2006 windstorm. There is a weak negative correlation between basal area and pits, and this is what is expected. Since declining BA and increasing numbers of pits are signs of increased wind disturbance, it was expected that the correlation should be stronger. An explanation for this weak correlation could be that the plot size was not large enough. As the density of windthrow pits increases, the density of coniferous regeneration also increases. This is very likely because in areas with lots of pits there is lots of microsite variation and different soils (mineral soil, humus) allowing for more different types coniferous species to grow as well as some very suitable sites for growth. Pits do not seem to have very much of an effect of the amount of deciduous regeneration as it stays about constant for most densities except for at 3000 pits/hectare where there is a higher density of regeneration. The large increase could be related to the sample size, as only 4 sites had pits of this density. It could also represent a level of wind disturbance that was severe enough to open up enough space and allow enough light for lots of deciduous regeneration compared to when there were fewer pits. The density of planted trees increases as the density of pits increases. This is because wind knocks over trees and creates pits and areas that were more disturbed were preferentially planted.

At all of the different pit densities there was more coniferous regeneration than deciduous regeneration, however the difference was not significant at 3000 pits/hectare. This shows that coniferous trees are better able to regenerate following a wind disturbance no matter how severe it is, but at more severely disturbed areas conifer and deciduous regeneration is more similar than at lightly disturbed areas.

The distribution of densities for coniferous germinants on different site series indicates that as moisture or nutrients increase, regeneration abundance increases. For deciduous trees, moisture does not play a role in the density, but nutrients do.

There does not appear to be very much of a relationship between planted trees and site series except for more planting done on dry poor sites. There is probably no reason for this other than chance as planting was done at highly disturbed sites regardless of site series. This could possibly show that drier nutrient poorer sites were more susceptible to wind disturbance in the 2006 storm; however, a more in depth study on this factor would need to be completed to show this for sure. This is what is expected because these sites may not have as healthy trees because there is not very much moisture or nutrients. Dry sites also often occur on hill slopes where the water quickly runs off; hill slopes are often more susceptible to wind disturbances because the soil is shallower so the roots aren't as secure (Wimberly & Spies, 2001). In Stanley Park, one of the steeper areas of the park is also the most exposed to wind and suffered the most damage.

Natural and planted western redcedar regeneration both have very similar heights which shows that clearing around the planted western redcedar trees does not affect their growth rate very much. There is however not a very high density of western redcedar regeneration which shows that western redcedar should be planted but it might not necessary to brush around it. Douglas-fir seedlings did not seed in very much following the windstorm, this shows the importance of planting Douglas-fir seedlings after a wind disturbance if it is desired to have these trees in the stand in the future. The results show that naturally regenerating Douglas-fir grew slightly better than planted Douglas-fir, this could be caused because of the very small sample size of naturally regenerating Douglas-fir. Planted Sitka spruce grew nearly twice as tall as naturally regenerating Sitka spruce which shows how important brushing is to their growth. Western hemlock seeds in very abundantly so it was not planted.

Bigleaf maple and red alder both grew to about the same average height and were much taller than coniferous regeneration; however, big leaf maple was about twice as abundant as red alder. Neither of these species was very abundant and if it is desired for them to be important in the future forest it may be necessary to plant them, however, neither of these species was very abundant in the original stand. Both of these species have low shade tolerance (Appendix C) so they may not be very common because there were not very many areas where wind disturbance knocked over enough trees for them to germinate and grow well.

There was a weak positive correlation between coniferous and deciduous regeneration density. In plots with lots of one class of regeneration there was also typically lots of the other types of regeneration. This shows that in good areas for regeneration both coniferous and deciduous trees were able to grow, and that in poor regeneration sites neither trees were able to grow. This suggests that on windthrown and salvaged sites, mixed species stands are likely to develop.

When multiple variables were used to predict the amount of regeneration in the forward stepwise regression basal area was always the first variable to be used as it always best predicted the regeneration density. The next variable added to the model was different for each of the different regeneration types. For the coniferous regeneration densities the R^2 value increased when the second variable, moisture, was added which means that the model explained the variation in the results better. For deciduous and planted regeneration densities the R^2 value was lower when a second variable was added to the model. None of the models fit well enough to provide much predictive capacity.

The model for coniferous regeneration was best when it included overstory basal area and moisture. The R^2 value increased as more variables were added, however, they were not significant ($p>0.05$). This model shows that if trying to predict the density of coniferous regeneration on a site, of the variables looked at, using moisture and basal area produces the best result. However, even with combining these two variables there is still a lot of variation that is not explained. The variation might better be explained if other variables are added that better predict regeneration density such as light levels or soil type.

The forward stepwise regression showed that deciduous regeneration density is best explained when all of the different variables are included (basal area, nutrients, pits, and moisture). Even with all of these different variables included the model still explains very little of the variation in the results. Like coniferous regeneration, the results show that another variable, not looked at in this study, or combination of other variables, might better be able to explain the variation in the deciduous regeneration densities.

The results from the forward stepwise regression showed that, for the planted trees, basal area is the most important factor in predicting the regeneration density of planted trees and that as more variables are added the model does a poorer job in predicting regeneration densities.

Sources of Error

One source of error comes from the variation in the amount of seeds produced in any given year. Some years are good seed years for certain tree species and other years are poor seed years for some species. In poor seed years it is may be important to plant in most areas including areas that this study showed high regeneration densities or for species that were found very often in this study.

A main possible source of error coming from this study is that all tree species were combined into categories as either coniferous or deciduous. This creates a problem as not all coniferous or deciduous trees are affected in the same way by the same variables. For example, western hemlock are very shade tolerant so will probably show more regeneration in shade, while Douglas fir are not shade tolerant and will probably grow best in areas of high light.

There was a lot of variation that was not explained at all through the methods used in this study. This could show that these species looked at in this study have very stochastic regeneration densities or that it is hard to determine regeneration density when it has only been two years since a disturbance. This means that a lot of the differences in regeneration densities cannot be explained by any factors.

Further Research

The results of this study reveal that there are many options for future research in the area of regeneration densities following a wind disturbance. Comparisons of different species could be looked. Additional factors affecting regeneration and combinations of factors should be looked at. This study only looked at densities of regeneration and regeneration height; it would be possible to look at the growth rate or the regenerating seedlings as well.

This study combined all the different species of coniferous trees into one category and all the different species of deciduous trees into one category. Most of the coniferous trees were western hemlock and most of the deciduous trees were Sitka Mountain Ash. It would be very useful to only look at one species instead of a combination of all the species. This would help to learn more about species that were not found very often, like Douglas-fir (22 stems/ha of naturally regenerating individuals).

Only three main variables were looked at; basal area, pit density, and site series were looked at. None of these variables predicted regeneration density very well. It is very possible that there are other variables that may predict regeneration densities better. Variables that could be looked at include light levels, surrounding species, or soil type.

Another area that should be studied in the future is the affect of salvaging on windthrown areas. This could provide important information to forest managers about the effect of salvaging on regeneration densities and whether or not salvaging in necessary or beneficial. This could be done by determining what areas where salvaged and what areas where not salvaged and comparing them to each other to see if there is a difference.

A final area of further research could be to measure regeneration growth rather than density. If multiple measurements of the same individual can be made or take an average growth rate in a plot, it would enable us to look at the height growth of different trees and how this is affected by different predictor variables.

Conclusion

This research focused on three questions regarding how different factors affect the abundance of regeneration following a windstorm.

1) What affect does basal area have on the abundance of regeneration?
2) How does the amount of wind disturbance affect the abundance of regeneration?
3) Does Site Series affect regeneration?

It was found that as the overstory basal area increases, the amount of natural regeneration also increases. The answer to this question shows that when trying to regrow a forest after a major wind disturbance it is more necessary to plant in areas with low basal area, particularly where conifers such as Douglas-fir are desirable.

In areas where there are lots of pits created by trees being knocked over there is more regeneration than areas where few pits were created. As the density of pits increases the density of both coniferous and deciduous regeneration also increases. This supports the hypothesis that where microsite disturbances are more severe than there will be more regeneration, and suggests that windthrow followed by salvage promotes mixed species stands of conifers and deciduous trees.

The answer to the final question relating to site series shows that as either moisture or nutrient level increases than the density of both coniferous and deciduous regeneration increases. This supports the hypothesis that at higher moisture or nutrient levels, density of regeneration will be higher after two years.

The forward stepwise regression model showed that there is lots of variability in regeneration densities not explained by any of the factors looked at in this study, other variables not looked at could play an important role in affecting regeneration densities. This study was completed using only data from the second growing seasons following a major wind disturbance and salvage operation. There is lots to be learned from continuing the study and monitoring the regeneration trends into the future.

References

Buffo, M. (2011). *Chapter 3: Stanley park vegetation dynamics and prescriptions (draft).* MSc thesis. The University of British Columbia.

Carter, R. E., & Klinka, K. 1992. Variation in shade tolerance of douglas fir, western hemlock, and western red cedar in coastal british columbia. *Forest Ecology and Management, 55*, 87-105.

City of Vancouver. (n.d.). *Welcome to stanley park.* Retrieved 03/20, 2011, from http://vancouver.ca/parks/parks/stanley/

Cooper-Ellis, S., Foster, D. R., Carlton, G., & Lezberg, A. 1999. Forest response to catastrophic wind: Results from an experimental hurricane. *Ecology, 80*, 2683-2696.

Drever, C. R., & Lertzman, K. P. 2001. Light-growth responses of coastal douglas-fir and western redcedar saplings under different regimes of soil moisture and nutrients. *Canadian Journal of Forest Research, 31*, 2124-2133.

Everham III, E. M., & Brokaw, N. V. L. 1996. Forest damage and recovery from catastrophic wind. *The Botanical Review, 62*, 113-185.

Foster, D. R., & Boose, E. R. 1992. Patterns of forest damage resulting from catastrophic wind in central new england, USA. *Journal of Ecology, 80*, pp. 79-98.

Franklin, J. F., Spies, T. A., Pelt, R. V., Carey, A. B., Thornburgh, D. A., Berg, D. R., *et al*. 2002. Disturbances and structural development of natural forest ecosystems with silvicultural implications, using douglas-fir forests as an example. *Forest Ecology and Management, 155*, 399-423.

Green, R.N. & Klinka, K. 1994. A field guide for site identification and interpretation for the Vancouver forest region. *Province of British Columbia Ministry of Forests.*

Greene, D. F., Zasada, J. C., Sirois, L., Kneeshaw, D., Morin, H., Charron, I., *et al*. 1999. A review of the regeneration dynamics of north american boreal forest tree species. *Canadian Journal of Forest Research, 29*, 824-839.

Guidelines for data collection and analysis: Stanley park 2008. 2008.

Jenkins, M. W., & Chambers, J. L. 1989. Understory light levels in mature hardwood stands after partial oversotry removal. *Forest Ecology and Management, 26*, 247-256.

John, R., Dalling, J. W., Harms, K. E., Yavitt, J. B., Stallard, R. F., Mirabello, M., *et al*. 2007. Soil nutrients influence spatial distributions of tropical tree species. *Proceedings of the National Academy of Sciences, 104*, 864-869.

Kheraj, S. 2007. Restoring nature: Ecology, memory, and the storm history of vancouver's stanley park. *Canadian Historical Review, 88*, 577-612.

Kranabetter, J. M., Banner, A., & Shaw, J. 2003. Growth and nutrition of three conifer species across site gradients of north coastal british columbia. *Canadian Journal of Forest Research, 32*, 313-324.

LePage, P. T., Canham, C. D., Coates, K. D., & Bartemucci, P. 2000. Seed abundance versus substrate limitation of seedling recruitment in northern temperate forests of british columbia. *Canadian Journal of Forest Research, 30*, 415-427.

Page, L. M., Cameron, A. D., & Clarke, G. C. 2001. Influence of overstorey basal area on density and growth of advance regeneration of sitka spruce in variably thinned stands. *Forest Ecology and Management, 151*, 25-35.

Pearce, J., & Ferrier, S. 2000. An evaluation of alternative algorithms for fitting species distribution models using logistic regression. *Ecological Modelling, 128*, 127-147.

Peterson, C. J. 2000. Catastrophic wind damage to north american forests and the potential impact of climate change. *Science of the Total Environment, 262*, 287-311.

Peterson, C. J., & Campbell, J. E. 1993. Microsite differences and temporal change in plant communities of treefall pits and mounds in an old-growth forest. *Bulletin of the Torrey Botanical Club, 120*, pp. 451-460.

Peterson, C. J., Carson, W. P., McCarthy, B. C., & Pickett, S. T. A. 1990. Microsite variation and soil dynamics within newly created treefall pits and mounds. *Oikos, 58*, pp. 39-46.

Peterson, C. J., & Pickett, S. T. A. 1990. Microsite and elevational influences on early forest regeneration after catastrophic windthrow. *Journal of Vegetation Science, 1*, 657-662.

Pojar, J., Klinka, K., & Meidinger, D. V. 1987. Biogeoclimatic ecosystem classification in british columbia. *Forest Ecology and Management, 22*, 119-154.

SAS Institute inc. 2008. *SAS 9.2*

Stanley park forest management plan. 2009.

Ulanova, N. G. 2000. The effects of windthrow on forests at different spatial scales: A review. *Forest Ecology and Management, 135*1-3, 155-167.

Vancouver Park Board. 2007. *Stanley park restoration recommended plan*. Vancouver, B.C.

Wilson, J. S., & Oliver, C. D. 2000. Stability and density management in douglas-fir plantations. *Canadian Journal of Forest Research, 30*, 910-920.

Wimberly, M. C., & Spies, T. A. 2001. Influences of environment and disturbance on forest patterns in coastal oregon watersheds. *Ecology, 82*, pp. 1443-1459.

Zeide, B. 1985. How much space does a seedling need? *Forest Ecology and Management, 11*, 225-229.

Appendix A

Box plots showing distribution or regeneration, see Appendix D for explanation of Box plot diagrams

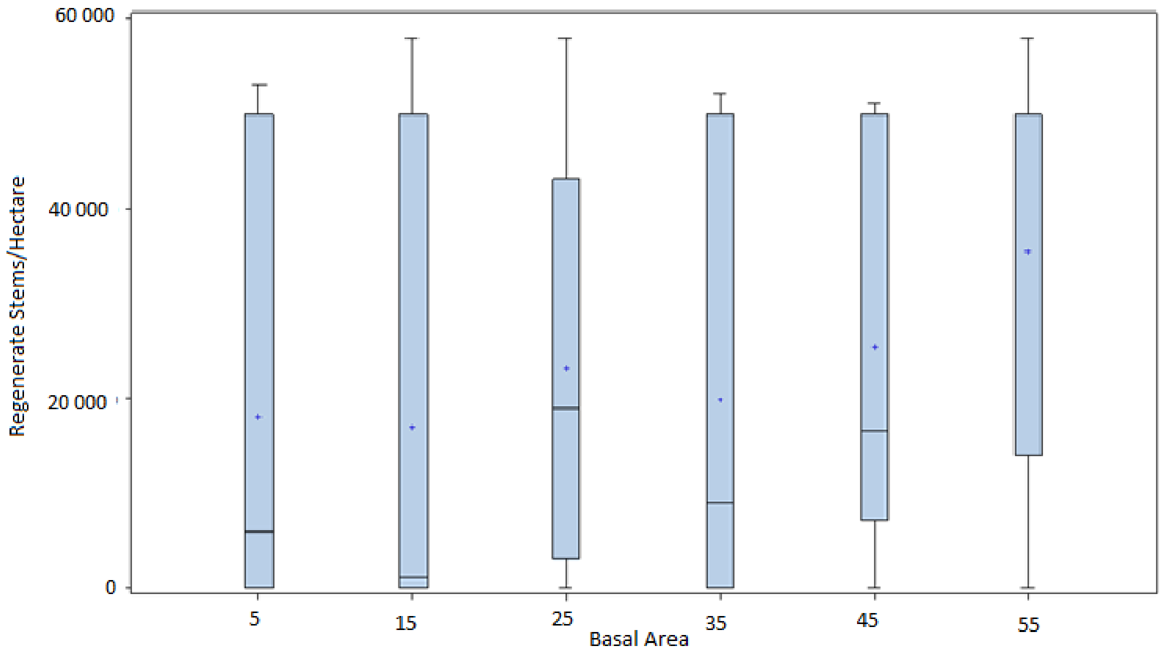

Figure A1: Coniferous tree regeneration densities versus Basal area class in 2008 in Stanley Park. Showing the sample minimum, 25% quartile, median, mean, 75% quartile and sample maximum (n = 179).

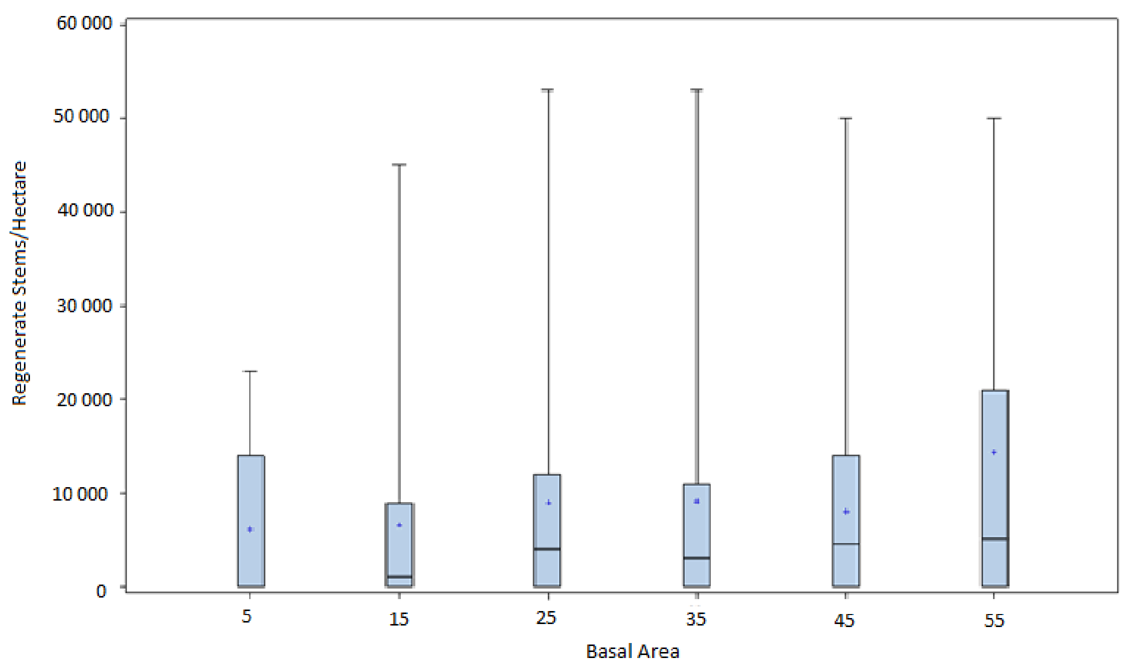

Figure A2: Deciduous tree regeneration densities versus Basal area class in 2008 in Stanley Park. Showing the sample minimum, 25% quartile, median, mean, 75% quartile and sample maximum (n = 179).

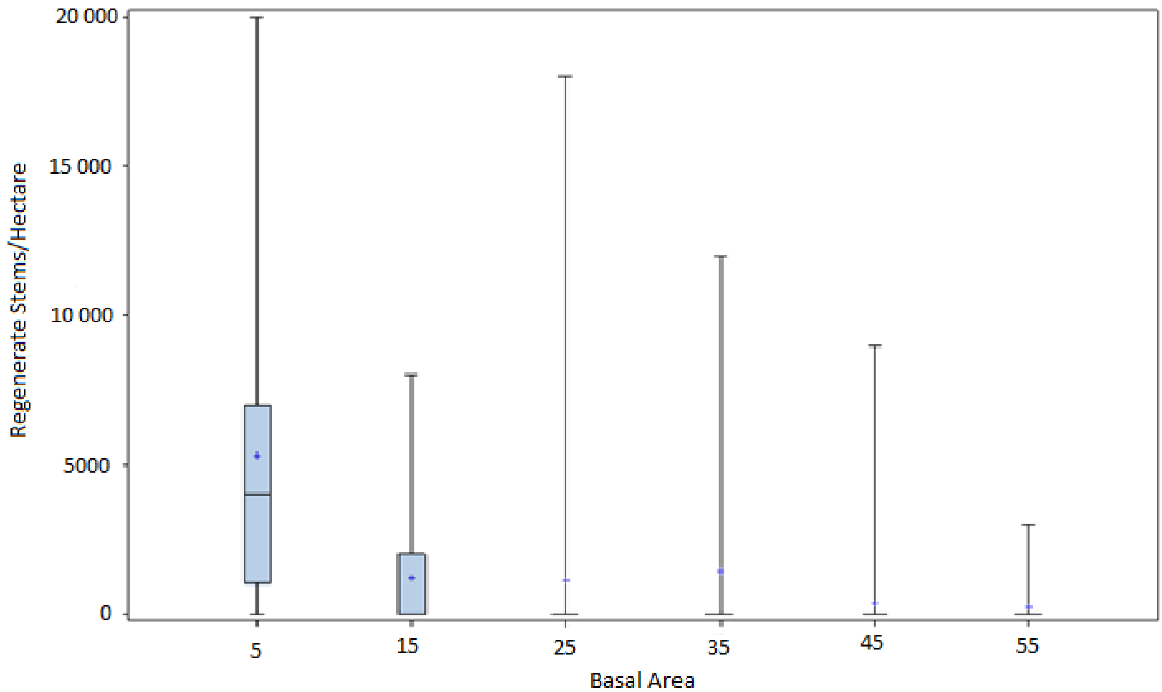

Figure A3: Planted tree densities versus Basal area class in 2008 in Stanley Park. Showing the sample minimum, 25% quartile, median, mean, 75% quartile and sample maximum (n = 179).

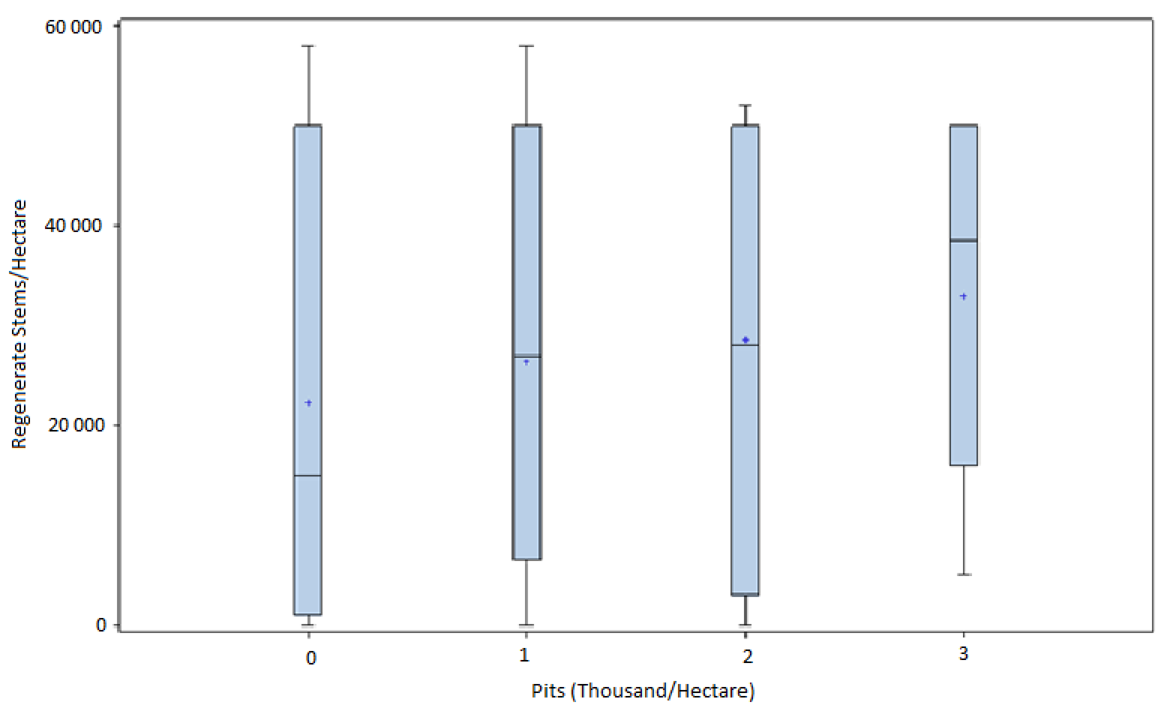

Figure A4: Coniferous tree regeneration densities versus amount of pits in 2008 in Stanley Park. Showing the sample minimum, 25% quartile, median, mean, 75% quartile and sample maximum. For pits = 0 n = 136, pits = 1000 n = 32, pits = 2000 n = 7, pits = 3000 n = 4.

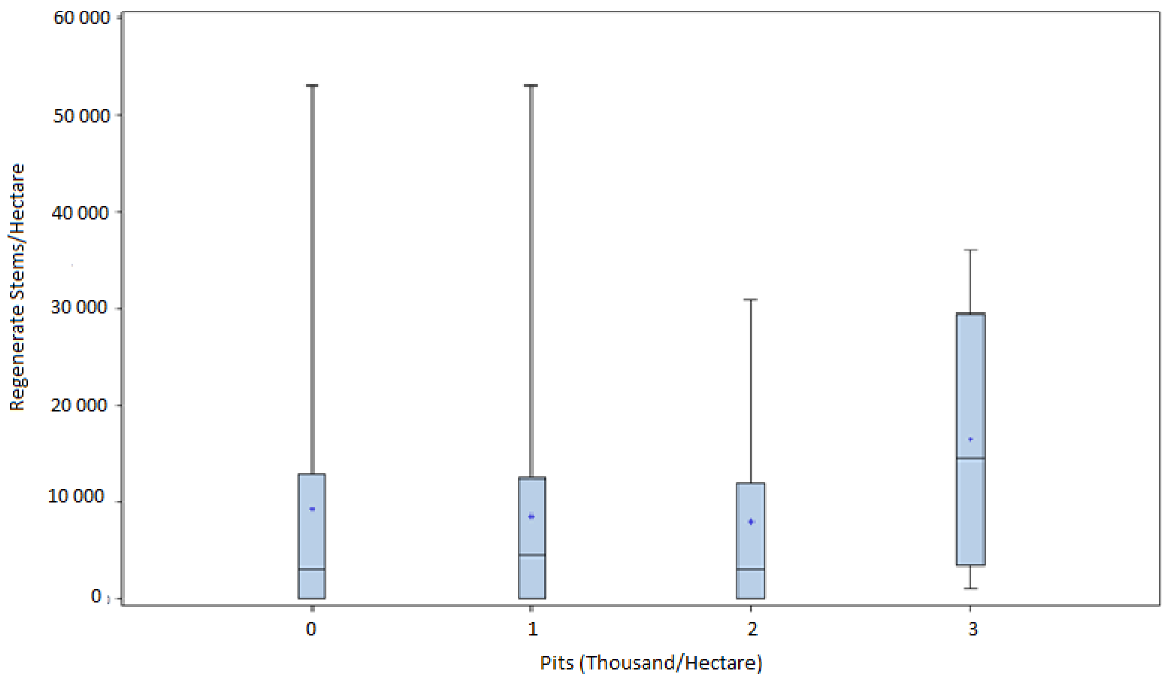

Figure A5: Deciduous tree regeneration densities versus amount of pits in 2008 in Stanley Park. Showing the sample minimum, 25% quartile, median, mean, 75% quartile and sample maximum. For pits = 0 n = 136, pits = 1000 n = 32, pits = 2000 n = 7, pits = 3000 n = 4.

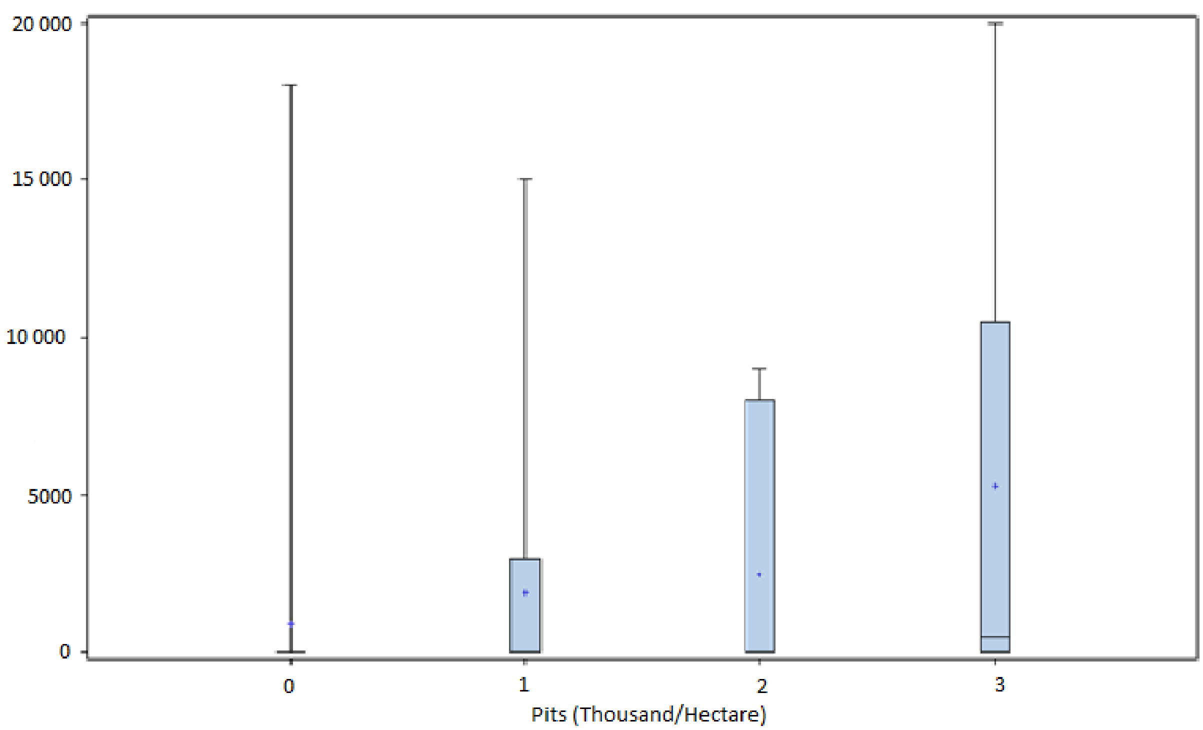

Figure A6: Planted tree densities versus amount of pits in 2008 in Stanley Park. Showing the sample minimum, 25% quartile, median, mean, 75% quartile and sample maximum. For pits = 0 n = 136, pits = 1000 n = 32, pits = 2000 n = 7, pits = 3000 n = 4.

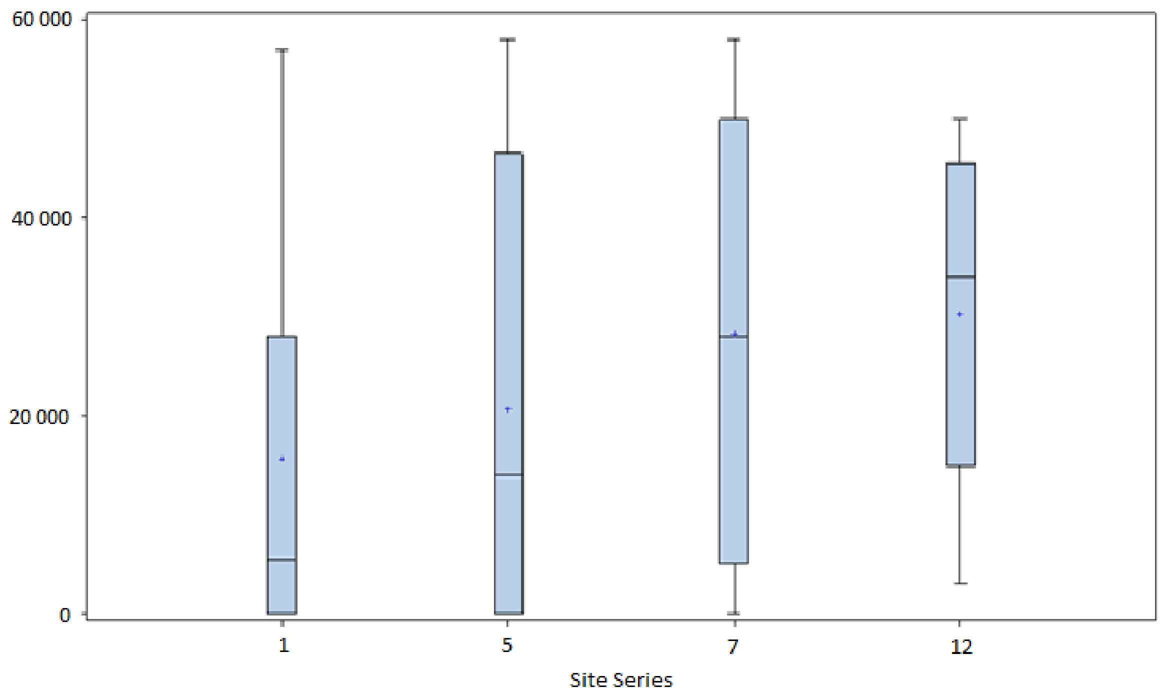

Figure A7: Coniferous tree regeneration densities versus plot site series in 2008 in Stanley Park. Showing the sample minimum, 25% quartile, median, mean, 75% quartile and sample maximum. At site series 1 n = 10, site series 5 n=96, site series 7 n = 69, site series 12 n =4.

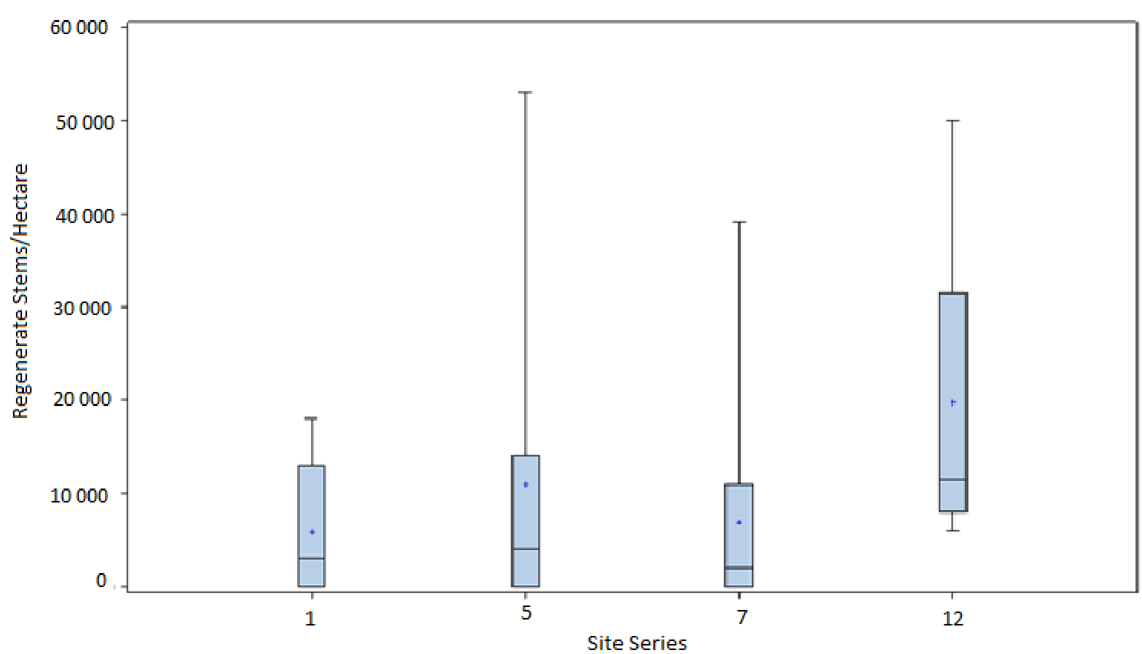

Figure A8: Deciduous tree regeneration densities versus plot site series in 2008 in Stanley Park. Showing the sample minimum, 25% quartile, median, mean, 75% quartile and sample maximum. At site series 1 n = 10, site series 5 n=96, site series 7 n = 69, site series 12 n =4.

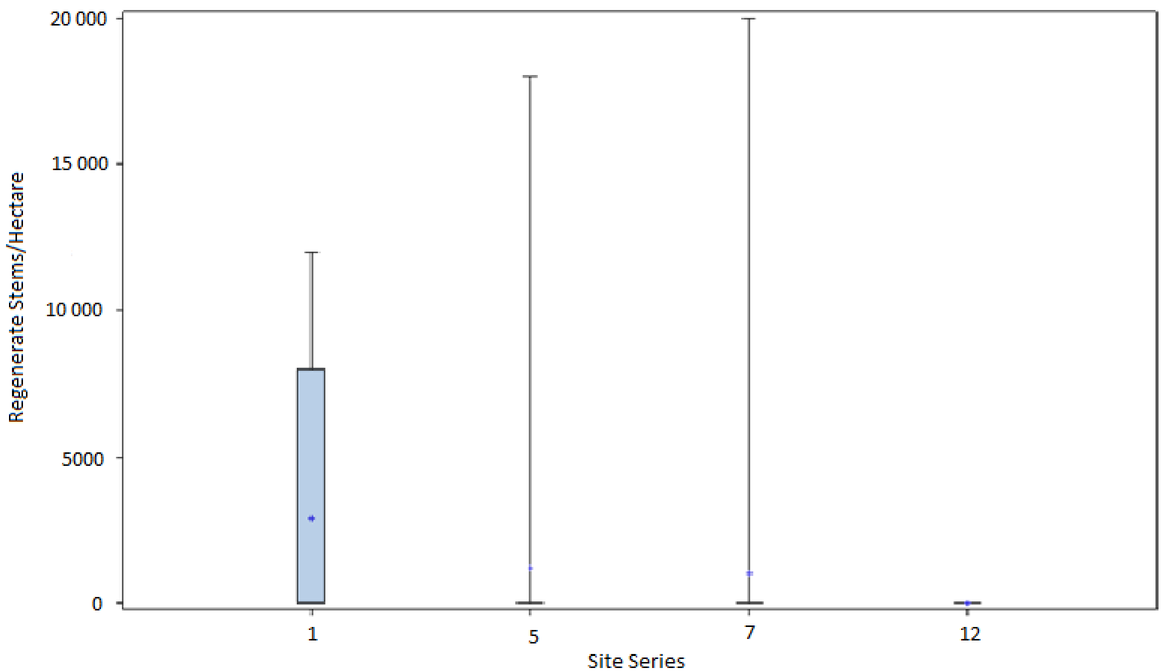

Figure A9: Planted seedling densities versus plot site series in 2008 in Stanley Park. Showing the sample minimum, 25% quartile, median, mean, 75% quartile and sample maximum. At site series 1 n = 10, site series 5 n=96, site series 7 n = 69, site series 12 n =4.

Appendix B

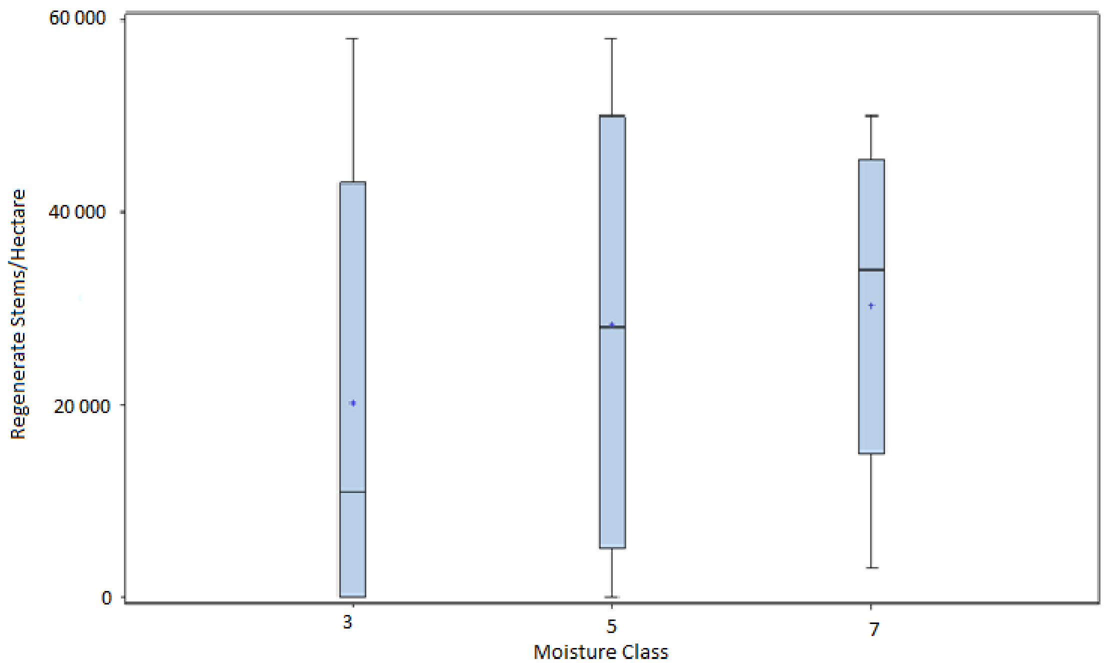

Figure B1: Coniferous tree regeneration densities versus plot moisture class in 2008 in Stanley Park. Showing the sample minimum, 25% quartile, median, mean, 75% quartile and sample maximum. At moisture class 2 n = 106, moisture class 5 n=69, moisture class 7 n = 4.

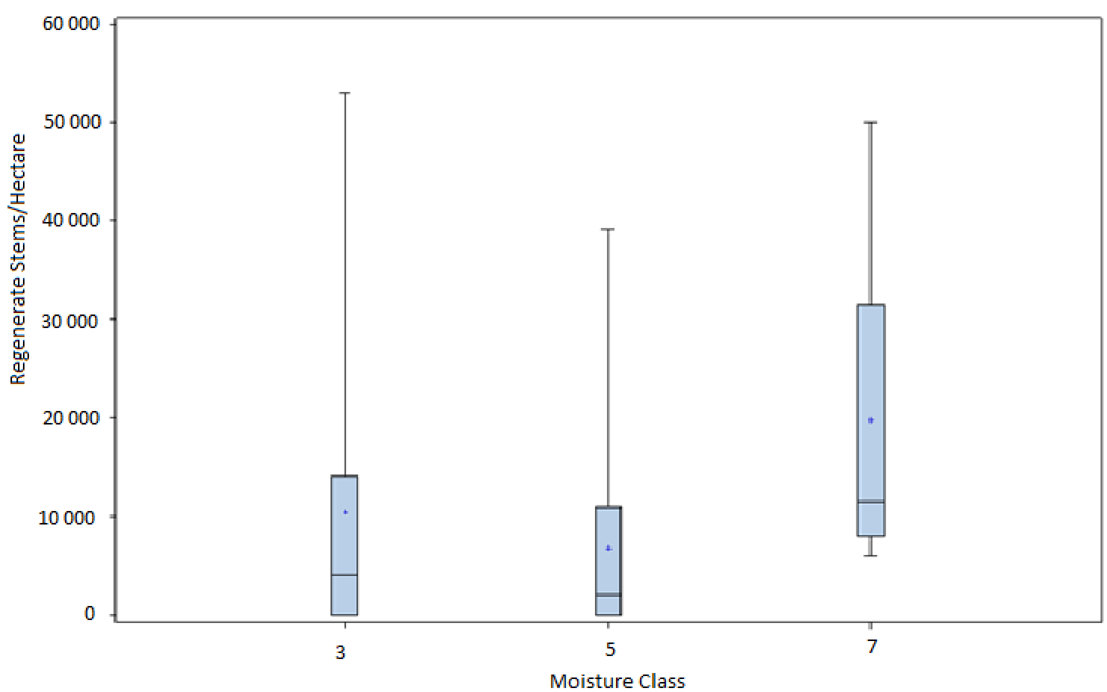

Figure B2: Deciduous tree regeneration densities versus plot moisture class in 2008 in Stanley Park. Showing the sample minimum, 25% quartile, median, mean, 75% quartile and sample maximum. At moisture class 2 n = 106, moisture class 5 n=69, moisture class 7 n = 4.

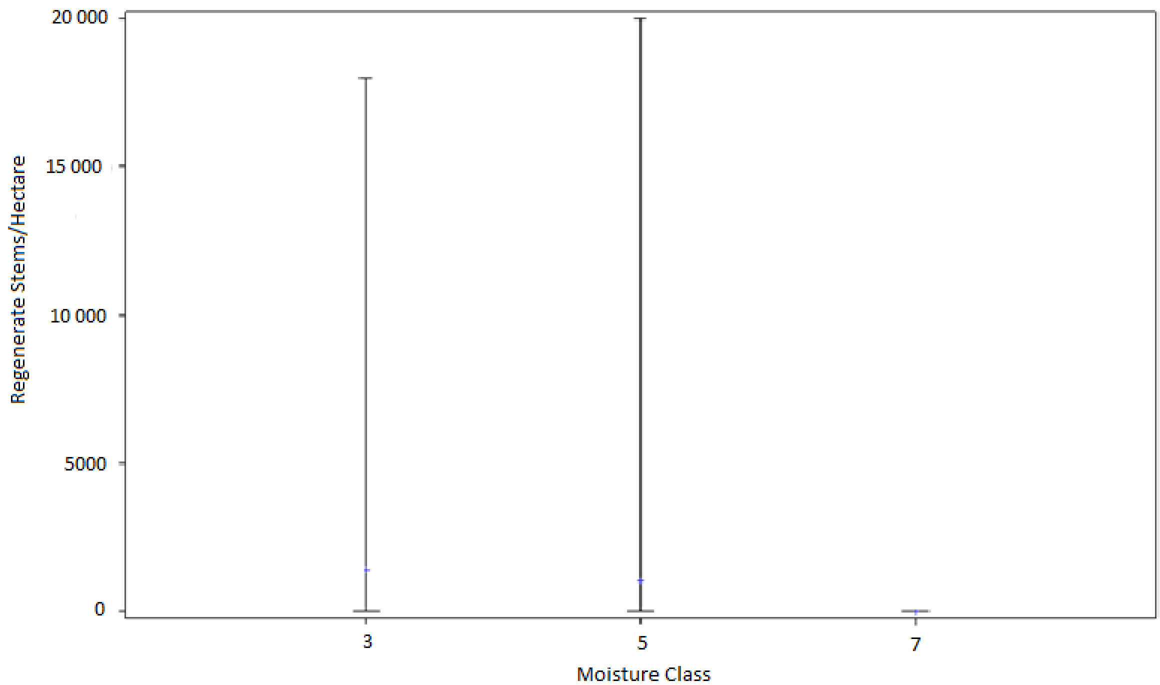

Figure B3: Planted tree densities versus plot moisture class in 2008 in Stanley Park. Showing the sample minimum, 25% quartile, median, mean, 75% quartile and sample maximum. At moisture class 2 n = 106, moisture class 5 n=69, moisture class 7 n = 4.

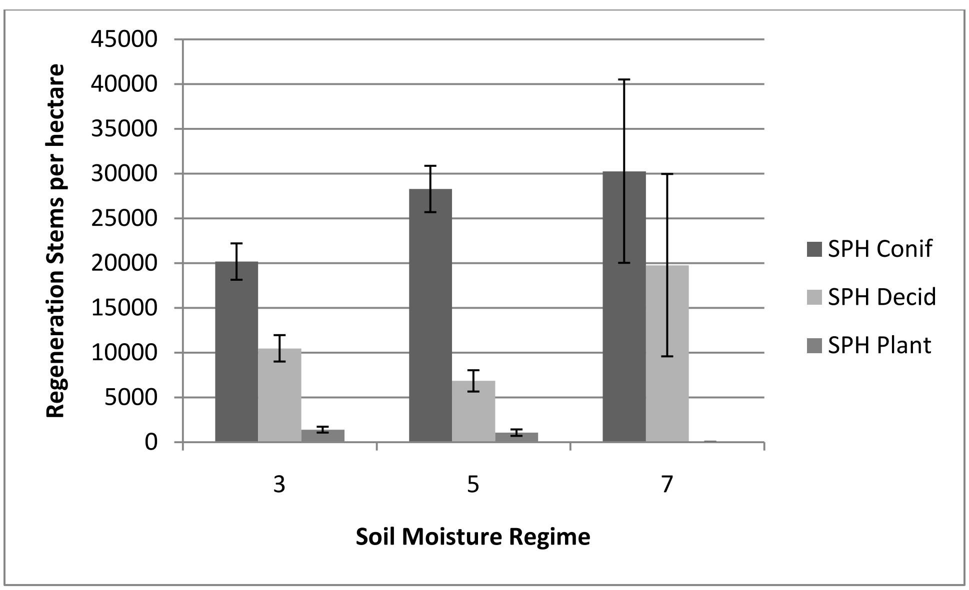

Figure B4: Seedling densities versus plot site series in 2008 in Stanley Park. Error bars equal 1 standard error. At moisture class 2 n = 106, moisture class 5 n=69, moisture class 7 n = 4.

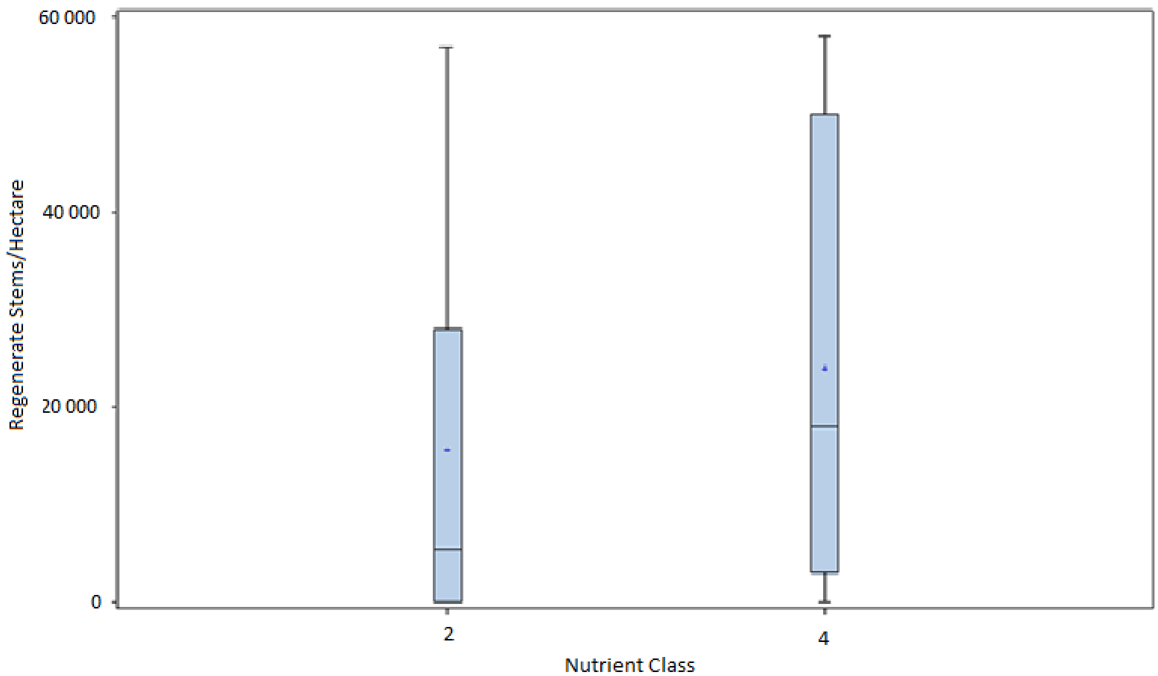

Figure B5: Coniferous tree regeneration densities versus plot nutrient class in 2008 in Stanley Park. Showing the sample minimum, 25% quartile, median, mean, 75% quartile and sample maximum. At nutrient class 2 n = 10, nutrient class 4 n=169.

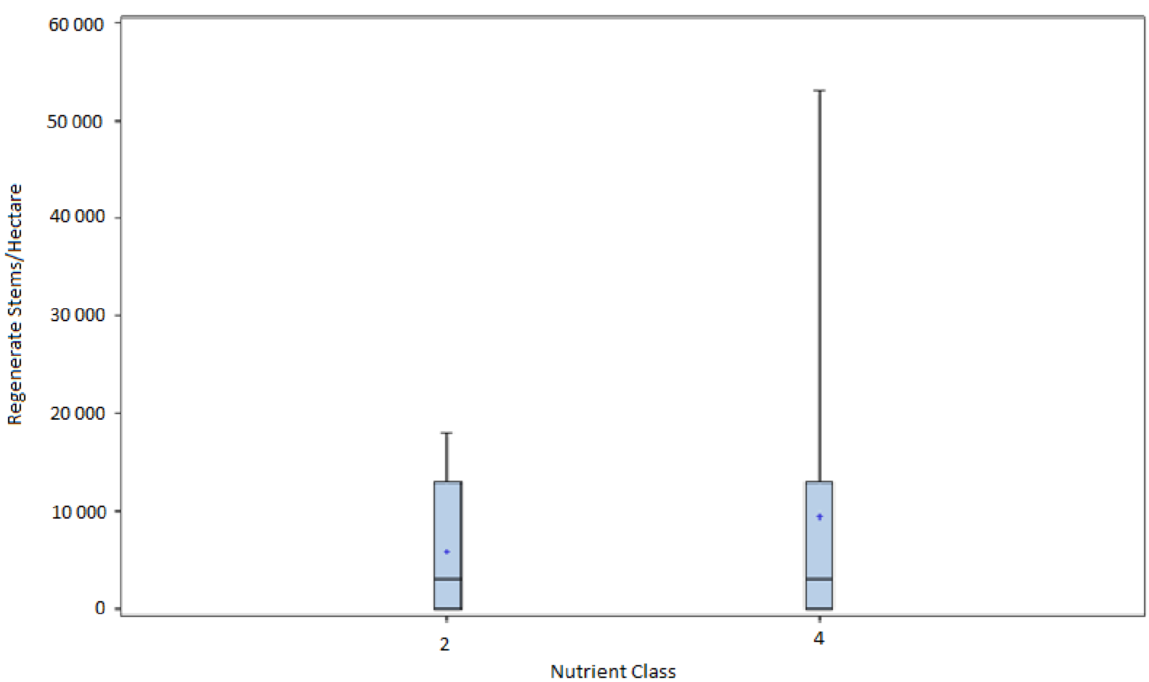

Figure B6: Deciduous tree regeneration densities versus plot nutrient class in 2008 in Stanley Park. Showing the sample minimum, 25% quartile, median, mean, 75% quartile and sample maximum. At nutrient class 2 n = 10, nutrient class 4 n=169.

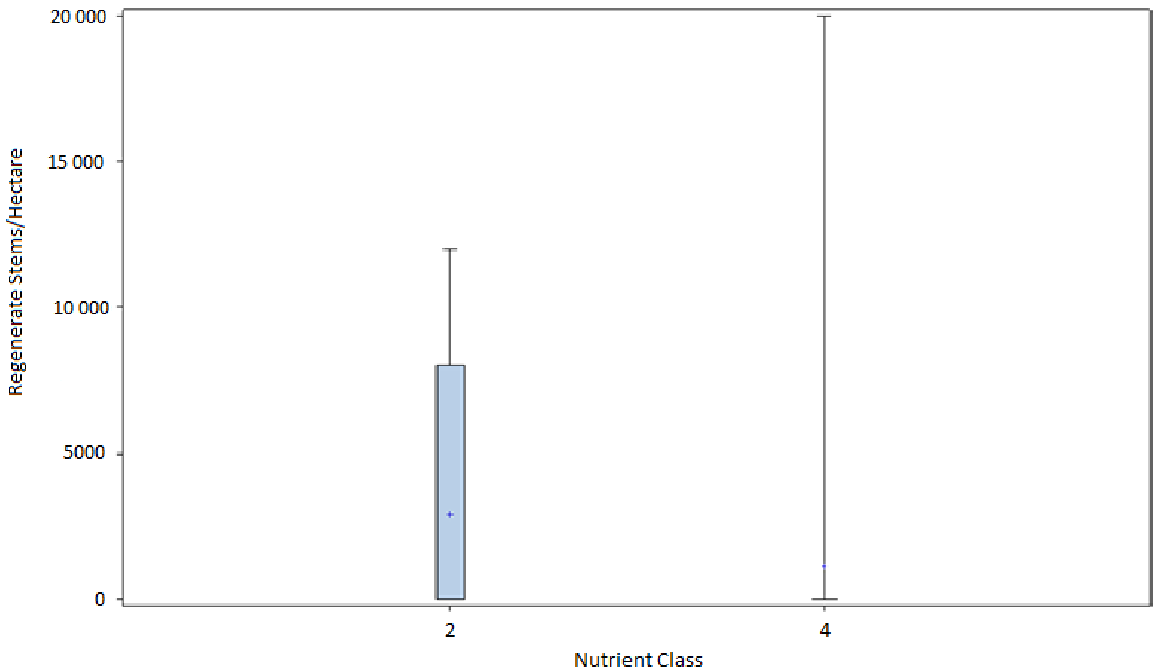

Figure B7: Planted tree densities versus plot nutrient class in 2008 in Stanley Park. Showing the sample minimum, 25% quartile, median, mean, 75% quartile and sample maximum. At nutrient class 2 n = 10, nutrient class 4 n=169.

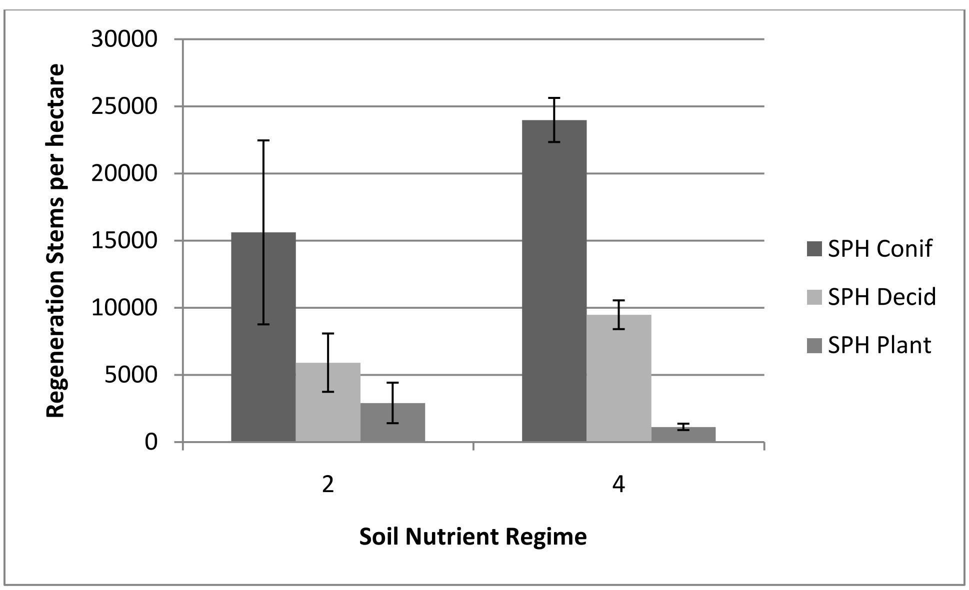

Figure B8: Seedling densities versus plot site series in 2008 in Stanley Park. Error bars equal 1 standard error. At nutrient class 2 n = 10, nutrient class 4 n=169.

Appendix C

Table C1: Regeneration requirements for the individual species looked at during this study

	Moisture regime	Nutrient regime	Climate	Shade tolerance
Douglas-fir	moderately dry - slightly dry	medium - rich	cool and warm temperate - cool mesothermal	low - high
western redcedar	slightly dry - wet	poor - very rich	cool mesothermal	high
western hemlock	fresh - very moist	very poor - medium	cool temperate - cool mesothermal	high
Sitka spruce	fresh - very moist	rich - very rich	wet cool mesothermal	medium
grand fir	slightly dry - very moist	rich - very rich	cool temperate - dry cool mesothermal	low - medium
bigleaf maple	fresh - moist	rich - very rich	cool and warm mesothermal	low
red alder	wet	rich - very rich	cool mesothermal	low

Appendix D

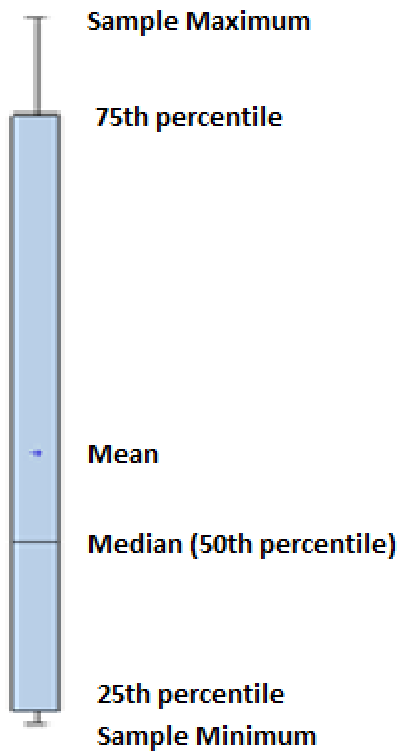

Figure D1: The meaning of different marks on a box plot diagram as used by SAS in this study.

Appendix E

Table E1: Analysis of Variance table for the forward stepwise regression predicting coniferous regeneration density.

		DF	sum of squares	mean square	F value	Pr > F	Predictors
1	Model	1	5665137898	5665137898	13.22	0.0004	Basal Area
	Error	177	75851610706	428540173			
	Corrected Total	178	81516748603				
2	Model	2	10155843705	5077924852	12.52	<0.0001	Basal Area, Moisture
	Error	176	71360904899	405459687			
	Corrected Total	178	81516748603				
3	Model	3	11330457386	3776819129	9.42	<0.0001	Basal Area, Moisture, Pits
	Error	175	70186291218	401064521			
	Corrected Total	178	81516748603				
4	Model	4	11530787451	2882696863	7.17	<0.0001	Basal Area, Moisture, Pits, Nutrient
	Error	174	69985961152	402218168			
	Corrected Total	178	81516748603				
5	Model	5	11764635033	2352927007	5.84	<0.0001	Basal Area, Moisture, Pits, Nutrient, Site Series
	Error	173	69752113571	403191408			
	Corrected Total	178	81516748603				

Table E2: Analysis of Variance table for the forward stepwise regression predicting deciduous regeneration density.

		DF	sum of squares	mean square	F value	Pr > F	Predictors
1	Model	1	783457375	783457375	4.29	0.0398	Basal Area
	Error	177	32319671116	182597012			
	Corrected Total	178	33103128492				
2	Model	2	898441923	449220962	2.46	0.0888	Basal Area, Nutrient
	Error	176	32204686569	182981174			
	Corrected Total	178	33103128492				
3	Model	3	1010631611	336877204	1.84	0.1422	Basal Area, Nutrient, Pits
	Error	175	32092496880	183385696			
	Corrected Total	178	33103128492				
4	Model	4	1140457847	285114462	1.55	0.1893	Basal Area, Nutrient, Pits, Moisture
	Error	174	3196270644	183693509			
	Corrected Total	178	33103128492				
5	Model	5	1963080569	392616114	2.18	0.0584	
	Error	173	31140047923	180000277			
	Corrected Total	178	33103128492				

Table E3: Analysis of Variance table for the forward stepwise regression predicting planted regeneration density.

		DF	sum of squares	mean square	F value	Pr > F	Predictors
1	Model	1	104094661	104094661	10.81	0.0012	Basal Area
	Error	177	1704408132	9629424			
	Corrected Total	178	1808502793				
2	Model	2	171614499	85807250	9.23	0.0002	Basal Area, Pits
	Error	176	1636888294	9300502			
	Corrected Total	178	1808502793				
3	Model	3	233938195	77979398	8.67	<0.0001	Basal Area, Pits, Site Series
	Error	175	1574564598	8997512			
	Corrected Total	178	1808502793				