EVALUATING FARM HEDGEROWS FOR THEIR CLIMATE CHANGE MITIGATION POTENTIAL IN THE LOWER FRASER RIVER DELTA OF BRITISH COLUMBIA

by

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ABSTRACT

Hedgerows have potential to help mitigate greenhouse gas emissions from agricultural activities by sequestrating carbon in woody biomass and in soil. In the Fraser Valley of British Columbia, a hedgerow stewardship program supports farmers to plant hedgerows to create habitat for biodiversity conservation and to improve ecosystem services, but it is unclear how much hedgerows contribute to climate change mitigation.

This study evaluated components of the mitigation potential of two types of hedgerows, those planted by the stewardship program, and those that are remnant in the region. We quantified the carbon stored in woody biomass and soil, and greenhouse gas emissions of these two hedgerow types relative to neighbouring production fields used for cultivation of annual crops. There was no significant difference in the biomass carbon in the two hedgerow types despite age differences. Woody vegetation species diversity was significantly greater in planted hedgerows than remnant hedgerows for richness, Shannon, and Simpson measures. Planted hedgerows stored greater soil carbon than remnant hedgerows to 1.2 t m^{-2} standard soil mass. Soil carbon was significantly correlated with the Shannon, and Simpson diversity of the hedgerow shrubs and trees indicating that planting a diversity of woody species likely has a positive effect on the mitigation potential of hedgerows on farmland.

Carbon dioxide, nitrous oxide, and methane effluxes from soil, measured bi-monthly for one year indicate that the mitigation potential is not straightforward. For the 6-month production and non-production seasons, carbon dioxide was significantly greater in hedgerows than production fields. Relative emissions, emissions from hedgerows relative to their neighbouring production fields, from planted hedgerows were significantly greater than remnant hedgerows. For the 6-month production season, nitrous oxide emissions were significantly lower in hedgerows than productions fields, while no difference were observed in the non-production season or between hedgerow types. No significant differences were observed between seasons or hedgerow types for methane fluxes.

These findings suggest that planting hedgerows may be an important management option to store carbon on agricultural land in the Fraser River delta relative to remnant hedgerows, but their net impact on climate change mitigation is still unclear.

PREFACE

Chapter 2 was co-authored by Dr. Sean Smukler, Dr. Maja Krzic, Dr. Sarah Gergel, and Christine Terpsma for publication submission.

Bryanna Thiel, thesis author, was responsible for managing the field trial set-up, sampling, data collection, and data analysis.

Dr. Sean Smukler, research supervisor, and Christine Terpsma, Delta Farmland & Wildlife Trust, initiated the research project. Dr. Sean Smukler, Dr. Maja Krzic, and Dr. Sarah Gergel provided guidance in overall experimental design, trial set-up, statistical analyses, data interpretation, and preparation of the manuscript.

Dr. Andy Black, Rachpal Jassal, and Iain Hawthorne advised on the sampling design and data analysis methodology for soil greenhouse gas measurements using static non-through-flow chambers. Iain Hawthorne and Rick Ketler provided direction on where to source materials for static non-through-flow chambers. Iain Hawthorne provided training and analysis services for measuring greenhouse gas concentrations in a UBC Vancouver laboratory for part of the study. Dr. Craig Nichol and Mesfin Fentabil analyzed greenhouse gas concentrations in their UBC Okanagan laboratory for the latter part of the study. Dr. Andy Black and Rachpal Jassal provided guidance on data interpretation of greenhouse gas emissions.

Christine Terpsma and Jason Lion assisted regularly in data collection and data analysis. Sean Kearny conducted the mid-infrared spectrometry for soil samples in the Sustainable Agricultural Landscapes Laboratory at The University of British Columbia (Vancouver).

Dr. Maja Krzic and Dru Yates advised on the sampling, laboratory, and data analysis for aggregate stability samples.

Rick White provided statistical analysis design and coding assistance for R statistical analysis software.

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LISTS OF ABBREVIATIONS

C – carbon

CH_4 – methane

CO_2 – carbon dioxide

CO_2e – carbon dioxide equivalent

DF&WT – Delta Farmland and Wildlife Trust

EMS – equivalent soil mass

GHG – greenhouse gas

GWP – global warming potential

N – nitrogen

N_2O – nitrous oxide

N – nitrogen

PF – production field

PH – planted hedgerows

PPF – production fields that neighbour planted hedgerows

RH-remnant hedgerows

RPF – production fields that neighbour remnant hedgerows

UBC – The University of British Columbia

WFPS – water-filled pore space

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DEDICATION

I would like to dedicate my thesis to the family and friends that helped me see it through: My parents Leah Hull and Robert Thiel for encouraging and supporting me to pursue higher education in a field about which I am passionate, to my brother Matthew Thiel for understanding and advising me through the tough times of my graduate work, to my friend Bonnie Do for encouraging me to never to give up, and to my partner Adam Outhwaite for cheering me on and being proud of the hard work I put into my research. I would also like to dedicate this thesis to Isla (the cat) for the many hours she kept me company as I analyzed my data and wrote this report.

1 GENERAL INTRODUCTION

Woody habitat on and around farmland has been shown to provide numerous valuable environmental functions such as providing habitat for a range of species, some of which are beneficial for production, or reducing soil erosion by acting as wind breaks (Baudry et al., 2000; Smukler et al., 2010). To enhance the environment and provide habitat for a number of species of concern, the Delta Farmland and Wildlife Trust (DF&WT), a not-for-profit conservation organization that works with farmers in the lower Fraser River delta, established a Hedgerow Stewardship Program in 1995 (Taitt, 1997). This Program has resulted in planting of woody vegetation in the form of hedgerows along the edge of farm fields throughout the lower Fraser River delta. While this program, started in 1996, has been highly successful in establishing new hedgerows, remnant hedgerows (RH) are now being removed from farm field margins extensively (Vala, 2000) to make room for regional transportation as well as drainage infrastructure upgrades. DF&WT's resources may thus be better served incentivizing farmers to maintain these areas of habitat that are already established, but it is unclear if their current strategy of planting new hedgerows, or the latter, is the most cost effective for optimizing environmental outcomes. DF&WT partnered with researchers from the University of British Columbia (UBC) to quantify and compare the environmental benefits provided by planted (PH) and remnant hedgerows (RH). This study provides a critical component of the analysis of on-farm woody habitat management to identify options that are most likely to maximize multiple environmental outcomes for the lower Fraser River delta. Specifically, we analyzed the climate change mitigation potential of two key options, PH and RH. Quantifying the mitigation benefits of these two woody habitat management strategies will be important not just to DF&WT, but also to other stakeholders in the region and throughout Canada who seek to improve environmental outcomes on agricultural lands.

1.1 Natural and Farming History of Delta, British Columbia

1.1.1 Natural History

The Corporation of Delta, British Columbia (Delta, BC) is located in the lower Fraser River valley and is bounded by water on three sides: to the north by the southern arm of the Fraser River, to the west by the Strait of Georgia, and to the south by Boundary Bay (Luttmerding & Sprout, 1969). Bedrock of the Fraser River lowland is comprised of coarse textured igneous rocks resulting from weathering of the Coast and Cascade mountains (Dakin, 2014). The advance and retreat of glaciers from the last ice age have resulted in deposition of low and higher permeability till overlain by mass wasting of fluvial and marine sediment during non-glacial periods. Following glaciation, depression of the land surface resulted in lowlands being repeatedly inundated by marine, glaciomarine, and deltaic sediments.

The medium to moderate fine textured Fraser River deltaic deposits (100 cm from the surface) make up the parent material of Delta, BC (Luttmerding, 1981). According to the Canadian System of Soil Classification, Delta soils are Orthic Humic Gleysol: saline phase. This region is slightly undulating with slopes 1-3% and elevations 1-3 m above sea level. Soil textures can be classified as silt loam to silty clay loam at the surface grading to sand and loamy sand in the subsoil. As such, soils have high water holding capacity and poor drainage. During the winter, water tables are close to the surface, but recede in the summer. The cultivated top 20 cm of soil is friable to firm with high soil organic matter (10-20%). High to very high nutrient holding capacity is found in these soils, and pH is acidic throughout the profile. In the deeper layers of the soil profile, salinity and massive textures can restrict crop rooting.

Characteristic of Delta's maritime climate are mild (0.8 – 9.1^{o}C), rainy winters, and warm (10.8 – 24 ^{o}C), dry summer (Luttmerding & Sprout,1969; Ministry of Environment 2014). This temperate climate is an effect of sheltering by local mountain systems; the Coast Mountains protect the region from polar air coming from interior BC.

1.1.2 Farming History

Delta is a significant agricultural producer in BC. With farm receipts of $170 M in 2010, it is home to 50% of potato, 50% of greenhouse vegetable, and 25% of the vegetable area in the province. In Delta, 80% of the Agricultural Land Reserve, land protected for agricultural use by the Province of BC in 1973, is used for agriculture (British Columbia Agriculture & Food Climate Action Initiative, 2013). This makes up nearly 7000 hectares (ha) in area and comprises 202 farms. Statistics Canada census data collected in 2011 found that total land farmed in Delta decreased by 532 ha in the five years since the last census. The average size of a farm is 35 ha (Metro Vancouver, 2012). Farm size distribution is skewed towards midsize farms in the range of 4-28 ha (91 farms). Only 9 farms are over 162 ha, and 47 are under 4 ha. Over half land farmed is owned by farmers (51%), 8% is leased from the government, and 39% is rented or leased from other providers (Metro Vancouver, 2012). Of the crop production farms found in Delta in 2010, 103 produce hay and field crops; 45 vegetables; 55 fruit, nuts and berries; 12 nursery products; 23 greenhouse products; and 23 potatoes (Metro Vancouver, 2012).

1.2 Hedgerows and Climate Change Mitigation

1.2.1 Hedgerows in Agricultural Landscapes

A hedgerow is a linear collection of trees, shrubs, forbs, or grasses typically found along roads, ditches, waterways, and field margins on farmland. Historically, hedgerows found in Europe and North America have been used as living fences to demark property boundaries and organize fields. Today, though there is consensus that incorporating woody non-production areas into agricultural landscapes is beneficial for improving landscape diversity, habitat, and species migration, how to best manage these areas is a much-debated topic (Fischer et al., 2008; Gibbons et al., 2008; Manning et al., 2006). Some argue that land sparing approaches, in which agricultural landscapes are divided into mosaics of distinct production and non-production areas provide the greatest environmental benefits (Balmford et al., 2005; Green et al. 2005. Others argue that land sharing approaches, in which networks of non-production areas such as hedgerows are connected over a larger geographical area, are more effective particularly for habitat connectivity purposes (Franklin Egan & Mortensen, 2012).

At the same time, deforestation of both land sparing non-production parcels and land sharing hedgerow networks continues to occur (Sklenicka et al., 2009) in response to land development for intensive agriculture or residential purposes. For example, 500,000 km – 740,000 km of hedgerows were removed in parts of Europe in the latter part of the 20th century (Le Coeur et al., 2002). Despite the fact that these areas generally occupy a small percentage of the landscape (e.g.,~ 5% of agricultural land) (Schoeneberger, 2008; Smukler et al., 2010),hedgerows can impose a cost on farmers when they occupy land that would otherwise be cultivated, reduce yields by shading crops near field borders, or harbour diseases and pests that negatively impact production (Marshall & Moonen, 2002). For these reasons, many farmers (including those in Delta, BC) continue to remove hedgerows and perceive removal as an improvement to their farm operations (Vala, 2000).

While removing hedgerows comes at an environmental cost, trying to increase hedgerow habitat through planting programs such as DF&WT's Hedgerows Stewardship Program has a very real financial cost. The cost to establish (plant and maintain for 10-20 years) new hedgerows in Delta, BC is estimated at $1,580 (CAD) per kilometer (Smukler et al., 2014). Costs include soil and site preparation, seed and plant purchase, installation labour, irrigation (in initial years), and maintenance weeding for invasive species in the future.

1.2.2 Ecosystem Services Provided by Hedgerows

Hedgerows have the capacity to provide a number of environmental functions that could substantially contribute to the overall function of agricultural landscapes. In North America, hedgerows have been used as windbreaks to mitigate wind erosion and crop damage, provide shelter for livestock, and enhance farmland habitat diversity (Brandle & Hodges, 2004). Hedgerows have been shown to increase species richness and diversity of small mammals in semi-arid environments (Sullivan et al., 2012), provide habitat for birds largely threatened by agriculture (Hinsley & Bellamy, 2000), and provide overwintering sites for beneficial insects and pollinators (Morandin & Kremen, 2013); Nicholls & Altieri, 2012). In Delta, hedgerows provide habitat for songbirds and raptors, while production fields provide habitat for both migrating and resident waterfowl (http://www.deltafarmland.ca/page/farmland-wildlife/ retrieved December 22, 2014). Hedgerows, similar to tree-based intercropping systems, can reduce nutrient leaching (Bergeron et al., 2011), affect landscape hydrology (Thomas et al., 2012), and also provide the source for seed diversity on farmland (Evans et al., 2011). Some of these functions have a direct value to the farmer (e.g. crop pollination), while other environmental functions benefit the general public who today have high expectations of the environmental functions (e.g. biological diversity) that should be provided by farms (Van Riper, 2014).

In Delta, BC, the DF&WT has conducted a number of studies to determine the ecosystem and agricultural benefit or costs of including hedgerows and field margins on farmland. One study observed that significantly more pests were found in crop fields than in hedgerows, but that hedgerows reduced the migration of thrips (pest) from setasides after mowing (E.S. Cropconsult Ltd., 1998). The same study reported equal numbers of beneficial insects in both hedgerows and production fields, and that weeds were minimal in established hedgerows because of shading (E.S. Cropconsult Ltd., 1998). Another study designed to create a baseline of the quantity and composition of present and future hedgerows in Delta, BC using orthophoto maps, ground-truthing, and farmer surveys, reported 76 species of hedgerow trees and shrubs in the region with low species diversity in remnant hedgerows compared to planted ones (Vala, 2000). This study also suggested that the 10 linear kilometers of hedgerows planted by greenhouse operators and the 7.8 kilometers by DF&WT would be of interest to compare to remnant hedgerows in the future for their wildlife habitat potential (Vala, 2000). While these studies have been valuable for evaluating the benefits of hedgerows in farmland in Delta, BC, there are a number of other ecosystem services that they may be provided that have yet to be quantified including their climate change mitigation potential.

1.2.3 How to Mitigate Climate Change in Agricultural Landscapes

The Intergovernmental Panel on Climate Change (IPCC) recognizes that agriculture is a multi-source and major contributor to climate change (Smith et al., 2007). Much research has been done to determine how carbon (C) sequestration can be enhanced, particularly in soils, and how emissions of greenhouse gases, including carbon dioxide (CO_2), nitrous oxide (N_2O), and methane (CH_4) can be reduced in agricultural systems. Management practices that have shown potential for mitigating climate change include alternative cropland and grazing land management, restoration or conservation of organic soils and organic lands, improved livestock and livestock manure management, and the introduction of bio-energy (Table 1.1) (Smith et al. 2007). Agroforesty is one among many cropland management options that could help increase the quantity of C sequestered in both the soil and woody biomass of tree and shrub species, however the impact of agroforestry on net greenhouse gas emission, (CO_2, N_2O and CH_4) is unclear (Smith et al., 2007). Further, relatively little evidence seems to exist to support the current knowledge about the impact of agroforestry on net climate change mitigation (Table 1.1). The research that has been conducted has shown that agroforestry systems can substantially increase C sequestration by including trees and shrubs on even very small percentages of farmland (Falloon et al., 2004; Schoeneberger, 2008).

Table 1.1. Table outlining the potential contributions of certain agricultural management options to help mitigate the climate change impact of agriculture

Management option	Examples	Mitigative effects [a]			Net mitigation [b] (confidence)	
		CO_2	CH_4	N_2O	Agreement	Evidence
Cropland management	Agronomy	+		+/-	***	**
	Nutrient management	+		+	***	**
	Tillage/residue management	+		+/-	**	**
	Water management (irrigation, drainage)	+/-		+	*	*
	Rice management	+/-	+	+/-	**	**
	Agro-forestry	+		+/-	***	*
	Set-aside, land-use change	+	+	+	***	***
Grazing land management/ pasture improvement	Grazing intensity	+/-	+/-	+/-	*	*
	Increased productivity (e.g. fertilization)	+		+/-	**	*
	Nutrient management	+		+/-	**	**
	Fire management	+	+	+/-	*	*
	Species introduction (including legumes)	+		+/-	*	**
Management of organic soils	Avoid drainage of wetlands	+	-	+/-	**	**
Restoration of degraded lands	Erosions control, organic amendments, nutrient amendments	+		+/-	***	**
Livestock management	Improved feeding practices		+	+	***	***
	Specific agents and dietary additives		+		**	***
	Longer term structural and mangement changes and animal breeding		+	+	**	*
Manure/biosolid management	Improved storage and handling		+	+/-	***	**
	Anaerobic digestion		+	+/-	***	*
	More efficient use as nutrient source	+		+	***	**
Bio-energy	Energy crops, solid, liquid, biogas, residus	+	+/-	+/-	***	**

Notes:

a + denotes reduced emissions or enhanced removal (positive mitigative effect;
- denotes increased emissions or suppressed removal (negative mitigative effect);
+/- denotes uncertain or variable response.

b A qualitative estimate of the confidence in describing the proposed practice as a measure for reducing net emissions of greenhouse gases, expressed as CO2 - eq; Agreement referes to the relative degree of consensus in the literature (the more asterisks, the higher the agreement); Evidence referes to the relative amount of data in support of the proposed effect (the more asterisks, the more evidence)

Source: adapted from Smith et al. 2007.

1.2.4 Global Warming Potential

To better understand the overall contribution of agroforestry, and particularly hedgerows to climate change mitigation it is important to quantify both sinks, C storage, and sources, emissions of the three main GHGs (CO_2, N_2O and CH_4). To do this effectively the sources and sinks must be converted into a common unit of measure. N_2O and CH_4 from the soil contribute substantially to global warming as they have an increased radiative forcing of 298 and 25 times (over 100 year time period) respectively compared to CO_2 (Forster et al. 2007). Using the relative radiative forcing of each gas, or the amount of heat each gas can trap in the atmosphere, N_2O and CH_4 can be converted to units equivalent to the forcing of CO_2 gas, or "CO_2 equivalents (CO_2e)." This is referred to as the global warming potential (GWP) of that gas.

C sequestration is a measure of the net inputs and outputs of C of a system and is equal to net ecosystem productivity (NEP). In detail, NEP is the net primary productivity (NPP) of a system less heterotrophic respiration. The net primary productivity (NPP) is the organic growth of primary producers that synthesize solar energy, sugars, and proteins to sequester carbon within their structure (biomass), less the carbon that is lost via autotrophic (plant) respiration. The net C balance includes more than just plant exchange, as C can migrate into the soil through the decomposition of leaf litter or by belowground transfer of root exudates that is utilized by heterotrophic (decomposer) organisms, and either sequestered in the soil or respired. Changes in the plant species and functional diversity has been shown to increase or decrease net ecosystem productivity (Catovsky et al., 2002) and the net impact on climate change mitigation is unclear.

To estimate the overall impact on climate mitigation the net global warming potential (GWP) of a system can be calculated in CO_2e. In simple terms, the equation is the sum of the GHG emissions released and the carbon sequestered (Equation 1).

Equation 1 $$net\ GWP\ (CO_2e) = \left[\frac{CO_2soil}{year} + \frac{N_2Osoil}{year} + \frac{CH_4soil}{year} + \frac{GASother}{year}\right] - \left[\frac{C_1soil - C_0soil}{year_1 - year_0} + \frac{C_1biomass - C_0biomass}{year_1 - year_0}\right]$$

Where CO_2soil/year is the net flux in CO_2e of carbon dioxide from the soil in one year, similarly, N_2Osoil/year and CH_4soil/year are the net nitrous oxide and methane fluxes in CO_2e from the soil in one year. GASother/year is the sum of other GHG emissions not from the soil (e.g. from fossil fuel consumption by farm buildings and machinery or from aboveground plant respiration) on-farm in one year. C_0soil/year$_0$ and C_1soil/year$_1$ is the organic carbon content of the soil in a baseline year and subsequent year respectively, and C_0biomass/year$_0$ and C_1biomass/year$_1$ is the biomass carbon content of woody plants in a baseline year and subsequent year respectively.

For our study, the CO_2, N_2O, and CH_4 emission from the soil were captured for an entire year, however other GHG emissions were not captured. Similarly, we measured soil C storage (C_0soil/year$_0$) and biomass C (C_0biomass/year$_0$) as baseline measures to be able to calculate a sequestration rate for both, once future measures are collected for soil C (C_1soil/year$_1$) and biomass C (C_1biomass/year$_1$).

Through this study, we attempt to quantify key components of the GWP equation of both hedgerows and production fields, specifically by doing an inventory of perennial biomass and soil C, and monitoring soil CO_2 respiration, and N_2O and CH_4 fluxes generated in these systems.

1.3 Objectives

The overarching goal of this study was to determine how best to improve hedgerow management on farmland in the lower Fraser River delta to maximize positive environmental outcomes, specifically for climate change mitigation. To do this we:

1) Quantified *carbon storage* of PH & RH soil and vegetation and neighbouring production fields, to determine if there are differences between hedgerow types, and if so, why.

2) Quantified *greenhouse gas emissions* from PH & RH soil and neighbouring production fields, to determine if there are differences between hedgerow types, and if so, why.

Research was conducted on eight sites (operation farms) in the lower Fraser River delta, and field plots were established on these sites to test the following hypotheses:

1.3.1 Hypotheses Tested

1. PH have greater biomass C storage than RH.
2. PH have increased soil C content to a depth of one meter than RH.
3. PH have increased aggregate stability compared to RH.
4. PH have greater tree and shrub species diversity than RH.
5. Greater tree and shrub species diversity increases biomass C and soil C storage.
6. PH will have greater soil CO_2 equivalent GHG emissions relative to RH.

This analysis contributes to a better understanding of the potential for on-farm woody perennial hedgerows to contribute to climate change mitigation. Outcomes of this study provide the DF&WT with information that will help make hedgerow management decisions within the framework of their existing activities. These results will also contribute to future analyses of the global warming potential of hedgerows, as well as temperate deltaic agricultural systems.

2 FARMLAND HEDGEROW CARBON STORAGE AND BIODIVERSITY IN THE FRASER RIVER DELTA OF BRITISH COLUMBIA[1]

2.1 Introduction

Hedgerows (also known as field margins, shelterbelts, or windbreaks), have the potential to help mitigate greenhouse gas emissions (GHG) from agricultural activities that contributed 64.3 Mt CO_2e or 3.3% of total emissions in 2007 (Ministry of Environment, 2014) to global warming in British Columbia, Canada. Land management strategies at both the farm-scale and landscape scale that enhance carbon (C) sequestering in either perennial vegetation, soil, or both on farmland could substantially mitigate GHG contributions of agriculture and help reduce atmospheric concentrations of carbon dioxide (CO_2) to levels that would slow the anticipated effects of climate change (Schoeneberger, 2008; Schoeneberger et al. 2012; Udawatta & Jose 2011; Udawatta & Jose 2012). One such strategy is agroforestry, which includes practices such as riparian forest buffers, windbreaks, silvopasture systems, alley cropping, forest farming, and hedgerows within agricultural landscapes. A number of studies have provided estimates of C sequestration potential of agroforestry at a landscape scale (Falloon et al. 2004; Peichl et al. 2006; Schoeneberger 2008). In agricultural landscapes, biomass C, in particular the aboveground biomass C of agroforestry systems has been studied extensively because of the potential for these areas to sequester C without changing the production focus of the landscape (Schoeneberger, 2008). Simulation models of hedgerows have demonstrated the long-term benefits of

[1] A version of this chapter has been submitted as a manuscript to the Journal of Soil and Water Conservation on November 19, 2014 for publication under the title “Farmland hedgerow carbon storage and biodiversity in the Fraser River Delta of British Columbia” by Bryanna Thiel, Sean M. Smukler, Maja Krzic, Sarah Gergel, and Christine Terpsma.

using similar non-production areas on farmland for C storage in woody biomass (Schoeneberger 2008; Falloon et al. 2004). Further, the greater financial gains from forest farming and alley cropping for biomass fuel production have incentivized analyses of C sequestration in these systems (Christen & Dalgaard, 2013). On the other hand, plot level analyses of C storage in non-production systems, such as hedgerows particularly in North America, are still limited.

Hedgerows can store C in a number of ways including in the woody biomass of their associated vegetation, and in the soil, by accumulating C rich organic matter and protecting it from water and wind erosion (Schoeneberger et al., 2012). Several recent studies have evaluated the effects of hedgerows on litter accumulation and decomposition (D'Acunto et al. 2014; Sitzia et al. 2014; Sauer et al. 2007; Hien et al. 2013), biomass C sequestration (Wang et al., 2013), soil chemical and physical properties (Barreto et al. 2012), microclimates (Sánchez, Lassaletta, McCollin, & Bunce, 2009), and improved farmland biodiversity (García del Barrio, Ortega, Vázquez De la Cueva, & Elena-Rosselló, 2006). While it is acknowledged that C storage on farmland is not often the primary benefit sought by farm managers when planting hedgerows on their land (Schoeneberger, 2008), knowing how different hedgerow systems perform for C storage will improve our understanding of management options and help elucidate the best land use management decisions for agriculture and the environment

Various perennial plant species are planted as hedgerows in the lower Fraser River delta of British Columbia, as part of the Hedgerow Stewardship Program carried out by the Delta Farmland and Wildlife Trust (DW&WT). DF&WT is a local not-for-profit conservation organization that works closely with farmers to optimize regional ecosystem services of agricultural landscapes such as the provisioning service of food production, regulating service of nutrient cycling, supporting service of wildlife habitat availability, and cultural service of improved public awareness about landscape function. DF&WT plans their hedgerows to maximize on-farm biodiversity. DF&WT's Hedgerow Stewardship Program incentivizes farmers to establish hedgerows on non-production areas of their farms primarily to increase habitat for avian species. As part of their program, DF&WT encourages farmers to plant a diverse mix of native species. The program, however, is expensive for the DF&WT and its efforts are undermined by removing of existing, long-term hedgerows carried out by some farmers in the region.

Evaluation of the relative ecosystem service benefits, in particular the impact on C storage, of *planting* new hedgerows and protecting *remnant* ones is needed to enhance our understanding of the role hedgerows play in climate change mitigation in this important agricultural region in the province of British Columbia. It also provides an opportunity to assess DF&WT diversification efforts impacts on C sequestration as other research has shown that increased vegetation biodiversity results in increased C storage (Strassburg et al., 2010). The objectives of this study were to evaluate the effects of planted (PH) and remnant hedgerows (RH) on the soil C storage within the 1 m depth, C content in above- and belowground biomass of the perennial woody vegetation (trees and shrubs), aggregate stability, and species diversity. The overarching hypothesis for the study was that PH specifically designed to improve landscape diversity resulted in greater C storage than RH. A secondary goal was to ascertain how plant diversity, soil properties, and hedgerow age relate to soil C and total biomass of perennial woody vegetation.

2.2 Materials and Methods

2.2.1 Study Sites

The study was carried out during November 2012 to February 2014 on eight sites (operational farms) located in peri-urban landscape of the lower Fraser River delta (Figure 2.1) in the district municipality of Delta, British Columbia (49° 4'25.33"N, 123° 4'58.20"W). Four sites with RH and four sites with PH were selected based on the hedgerow's size, relative age, proximity to one another, and presence of a neighbouring production field (PF) with the goal of minimizing the variability of these factors within each hedgerow type. Hedgerows ranged from 250 m^2 to 2400 m^2. On all study sites, each hedgerow is neighboured by a production field planted with annual crops typical for the area with varying winter management practices, and some neighboured ditches that were seasonally filled with water (Table 3.2). Hence, PPF was a production field neighbouring PH, and RPF was a production field neighbouring RH.

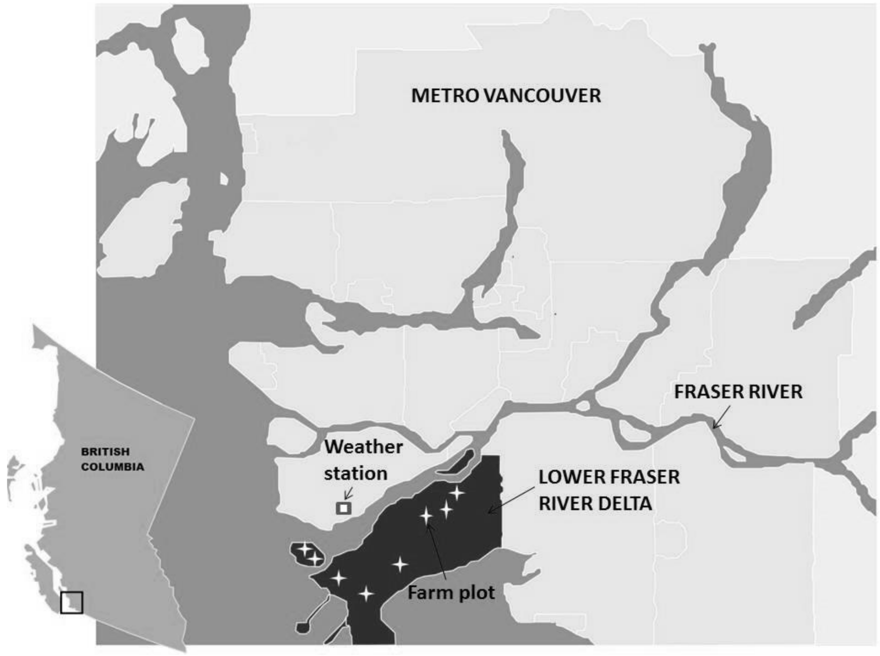

Figure 2.1. Map of lower Fraser River delta and study site locations within the municipality of Delta, British Columbia, Canada within Metro Vancouver.

Both RH and PH are perennial linear woody habitats consisting of trees, shrubs and ground-cover (grasses and forbs). RH are naturally regenerated areas established prior to the DF&WT Hedgerow Stewardship Program, have a mean age of 38 years at the time of site selection, a mean width of 7.5 m, and are largely unmonitored and unmanaged. PH have been planted using species such as Western red cedar *(Thuja plicata)*, red maple *(Acer rubrum)*, big leaf maple (Acer macrophyllum), red alder (*Alnus rubra),* Nootka rose *(Rosa nutkana)*, and red-osier dogwood *(Cornus sericea)* by the DF&WT along fields, property boundaries, waterways, or roads, range in age from 9-19 years, have a mean width of 4.0 m, and are monitored and managed by DF&WT.

The elevation of the study area ranges from 0 to 3.0 m above sea level. The thirty-year (1981-2010) climate record from a nearby weather station indicates a mean annual temperature of 10.6^{o}C (51.08^{o}F), rainfall of 1227.8 mm, and snowfall of 34.6 cm

(Ministry of Environment 2014). The soils in the region are Gleysols (Inceptisols) formed on fluvial deltaic deposits (Luttmerding 1981) (Table 2.1). Experimental sites were established on three soils series, namely the Ladner, Crescent, and Westham (Luttmerding 1981).

Monitoring soil properties can provide insight into the effects of land use. This can be done by developing a framework (Carter et al. 1997) to assess the physical, chemical, or biological properties of the soil to inform researchers about changes to soil processes. For example, assessing changes in compaction related to land use can provide information about soil porosity which may influence water and gas movement through the soil.

Table 2.1. Select soil properties of surface (Ap) horizons for Ladner, Crescent, and Westham soil series that are the most common soil types in the western Fraser Valley delta, British Columbia.

Subgroup, Great Group	US Classification	Soil Series	Parent Material	Clay Mineralogy		Structure	Organic Carbon %	EC (mS/cm)	pH	CEC (me/100g)	Texture
				Coarse	Fine						
Humic Luvic Gleysol	Typic Humaquept	LADNER	Fluvial	montmorillonite (40-65%)	montmorillonite (40-65%)	moderate fine subangular blocky	10.85	n/a	5.6	36.3	Silt Loam
Orthic Gleysol	Typic Haplaquept	CRESCENT	Fluvial	mica, vermiculite, interstratified vermiculited-mica, chlorite (20-40%)	montmorillonite (40-65%)	moderate medium to fine subangular blocky	2.03	0.3	6.1	16.9	Silt Loam
Rego Humic Gleysol (saline)	Entic Haplaquept	WESTHAM	Fluvial	montmorillonite, vermiculite, mica (~ 20-40%); chlorite, quartz and plagioclase feldspar (< 20%)	montmorillonite (40-60%); mica, vermiculite, chlorite and trace quartz (< 20%)	moderate fine to medium subangular blocky	2.44	n/a	6.1	18.5	Silt Loam

Source: adapted from Luttmerding (1981)

At each study site, a plot up to 1000 m^2 was demarcated in the hedgerow and neighbouring PF. Within each plot, three subplot pairs were randomly located with a perpendicular distance of 15 m between the hedgerow and PF subplot pair to account for spatial variability, which is expected from landscapes that are heterogeneous in terms of soil, biota, and microclimates at small scales. Within each subplot, soil samples were collected in July 2013 to assess the bulk density, equivalent soil mass (ESM), soil organic C (SOC), and aggregate stability; these measures were collected to determine the amount of C being stored in the soil as well as to determine indicators for differences observed between C storage. Within the hedgerow plots, all trees and shrubs were measured during August and September 2013 up to an area of 1000 m^2 to assess biomass C and tree and shrub species diversity.

2.2.2 Bulk Density, Equivalent Soil Mass and Soil Carbon

Soil bulk density samples were obtained using a core (7.3 cm inner diameter x 7.0 cm height) at the 6.5-13.5 cm and 26.5-33.5 cm depths, and oven dried at 105^{o}C until a stable mass was recorded (Blake, 1986).

Soil equivalent soil mass (ESM) samples were collected using an auger with a 5.5 cm inner diameter to a depth of 1 meter at intervals of 0-20, 20-40, 40-60, 60-80 and 80-100 cm. Field samples were taken to the University of British Columbia (UBC) laboratory where their wet weight was recorded. A subsample of approximately 40 g was weighed into a moisture tin and oven dried at 105^{o}C until a stable mass was reached, and field samples weights were adjusted for soil water content and their coarse fragments calculated from SOC samples (see below) to determine their dry fine earth fraction.

Soil total C samples were collected using the same method as ESM, though *three* subsamples were collected at each depth, composited in the field, homogenized, and then ~600 g was taken to UBC for analysis. Samples were air dried for more than 7 days before large aggregates were hand-crushed with a wood rolling pin from a 200 g subsample, sieved using a 2 mm mesh, and remaining coarse fragments (>2 mm) separated and weighed. The percent coarse fragment for each sample was calculated to adjust the associated ESM sample.

A stratified random sampling procedure using soil type and sampling depth was used to identify 30 samples to be sent to the Technical Service laboratory of the B.C. Ministry of Environment for total C by dry combustion analysis (Nelson and Sommers, 1982), using a Thermo “Flash 2000” analyzer (Thermo Scientific, USA). Separate sub-samples were oven-dried at 105°C to allow the C results to be reported on a standardized 100% dry weight basis.

In parallel , a 20-g subsample of all samples (x < 2mm) were hand-ground using a mortar and pestle and analyzed for soil C at UBC using Fourier-transformed mid-infrared spectroscopy (FT-MIR), run on a Tensor 37 HTS-XT spectrometer (Bruker Optics). Four replicates of approximately 0.025 g each were scanned 60 times for FT-MIR spectral reflectance between 600-4000 cm^{-1} at a resolution of 2 cm^{-1}. Using the subset of 30 randomly selected samples analyzed for dry combustion analysis, total percent C, were then predicted from reflectance results using partial least squares regression with the QUANT package in OPUS 7.2 (Bruker Optik GmbH 2012, http://www.brukeroptics.com).

The optimal regression model, preprocessing methods, and spectral wavenumber ranges were chosen using a “leave one out” cross-validation procedure to minimize the root mean square error (RMSE) of the model. The final model achieved an R^2 of 0.95 with an RMSE of 0.172 for total percent C.

Total soil C stocks were calculated using bulk density (Equation 2) estimates for 0-20 and 20-40 cm depths (Knowles & Singh, 2006) using the data for the 6.5 – 13.5 cm and 26.5-33.5 cm depths, and using ESM (Equation 3) to 0.4 t m^{-2} and 1.2 t m^{-2} (Gifford & Roderick, 2003).

Equation 2: $$\boldsymbol{Total\ Soil\ C} = \%\,\boldsymbol{C} \times \frac{\boldsymbol{m_s}}{\boldsymbol{V_t}} \times \boldsymbol{z}$$

Where *C* is the percent carbon, $\frac{m_s}{V_t}$ is the bulk density, and *z* is the depth of the sample.

Equation 3: $$\boldsymbol{c_s(t)} = \boldsymbol{c_s(z_a)} + \frac{\boldsymbol{c_s(z_b) - c_s(z_a)}}{\boldsymbol{m_s(z_b) - m_s(z_a)}} \times \boldsymbol{m_s(t)} - \boldsymbol{m_s(z_a)}$$

The C content of a standardized mass of soil in tonnes is represented by $c_s(t)$, $c_s(z_a)$ is the C content at the initial depth, $c_s(z_b)$ is the cumulative C content at the final depth, $m_s(z_a)$ is the total soil mass at the initial depth, $m_s(z_b)$ is the cumulative soil mass at the final depth, and $m_s(t)$ is a standardized total soil mass in tonnes (Gifford & Roderick, 2003). It was assumed that the carbonate content of the soils was negligible and thus total soil C is equivalent to soil organic C.

2.2.3 Aggregate Stability

Four soil samples were collected at a 0-10 cm depth from each subplot, composited in the field, and taken to UBC for analysis. The samples were stored at 4^{o}C until analysis. Samples were air dried 24 hours before large clods were gently separated by hand. The samples were dry sieved through a 6 mm sieve. A subsample of this fraction was dried to a constant weight at 105^{o}C to measure soil water content. Another 15 g subsample was transferred into nested sieves with openings of 2 mm, 1 mm, and 0.25 mm diameters to measure aggregate stability using a variation of the wet-sieving method (Nimmo & Perkins 2002). These subsamples were wetted using a humidifier before they were agitated in water for exactly 10 minutes, at 30 strokes per minutes over a vertical distance of 2.5 cm and an oscillation angle of 30^{o}. The agitated samples were oven dried at 105^{o}C for 24 hours prior to the fractions being weighed. The separate size fractions were ground and re-sieved to separate the coarse fragments. Mean weight diameter (MWD) was calculated using the following equation:

Equation 4: $$MWD = \sum_{i=1}^{n} x_i w_i$$

Where x_i, the mean diameter of adjacent sieves, and w_i, the fraction of soil retained in each sieve. Using this method, when all aggregates remain in the 2 mm sieve, the highest MWD possible of 4 mm is achieved which represents the most stable soil conditions. Alternatively, when all aggregates pass through the 0.25 mm sieve, the lowest possible MWD of 0.125 mm and the least stable soil conditions are achieved.

2.2.4 Hedgerow Tree and Shrub Biomass Carbon

Four 250 m^2 subplots were randomly selected for plots of about 1000 m^2. To estimate the biomass of the trees, a clinometer was used to determine the height, and measured the diameter at breast-height (DHB; 1.3 m). For trees that had major branches splitting from the trunk between 1.0 m and 1.5 m, each division was measured separately, and treated as separate trees. For vegetation where trunk separation occurred below 1.0 m, stem DBHs were small (<5.0 cm), stems were many (>3), and heights were low (<7.0m), plants were treated as shrubs. To estimate the biomass of the shrubs, the cross-sectional length, width and height of the shrub were measured, and the species recorded. Litter and groundcover vegetation was not measured in this study.

Aboveground biomass estimations were calculated using field data and allometric equations. Species specific allometric equations were used where available (Ter-Mikaelian & Korzukhin, 1997; Ung et al. 2008), and general Canadian hardwood or softwood equations for trees where species specific equations were not available (Ung et al. 2008). A general shrub allometric equation was employed for all shrub species using the biovolume calculated from the length, width, and height measurements of each shrub (Smukler et al. 2010). Equations were chosen based on the geographic proximity, climatic similarities, DBH and height ranges that were inclusive of our data, sample size, and the coefficient of determination (R^2). For trees, total aboveground biomass equations were selected when possible, otherwise individual stem wood, stem bark, foliage, and total branch equations were combined to estimate the total biomass. For shrubs, the total aboveground biomass was estimated by first calculating the ellipsoid biovolume and then estimating the biomass from this biovolume using an allometric equation. Belowground biomass was estimated using a regression equation that predicts root biomass density (*RBD*) in Mg ha^{-1} from aboveground biomass density (*ABD*) and the age of the stand (Cairns et al.1997):

Equation 5: $$\boldsymbol{RBD = \exp[-1.3267 + 0.8877 lnABD + 0.1045 lnAGE]}$$

Both above- and belowground biomass estimations were then used to determine the total C stored in the trees and shrubs by multiplying the biomass by 50% (Nair, 2011). Aboveground biomass was not measured for the annual crops in PFs given that the biomass was removed at the end of each season for consumption.

2.2.5 Hedgerow Biodiversity

Tree and shrub species diversity of hedgerows was assessed as an indicator of biodiversity. Tree and shrub species data collected during the inventory were used to calculate species richness, and relative abundance using the Shannon and Simpson index (Shaw, 2003) for each PH and RH up to 1000 m^{-2}. Species richness was calculated as the mean number of species in PH and RH. The Simpson index (*C*) was calculated by calculating the relative proportion (p_i) of each species' (*i*) biomass:

Equation 6: $$\boldsymbol{C = 1 - \sum_{i=1}^{i=S} p_i^2}$$

and the Shannon index (*H*) was calculated using the relative proportion (p_i) and the $\log_{10}$ transformed relative proportion of each species' (*i*) biomass:

Equation 7: $$\boldsymbol{H = -\sum_{i=1}^{i=S} p_i log_{10}(p_i)}$$

The Simpson index is a probability index that any unit of biomass in a community will be the same as the next individual in that community; the index value (probability) range of 0 to 1 means the population ranges from zero to full diversity (Shaw, 2003). The Shannon index is a similar probability index but it gives more weight to the presence of less abundant species to the overall diversity of the community, which is of value since the specific function of one species in small numbers, may greatly affect the total ecosystem function of a system (Shaw, 2003).

2.2.6 Statistical Analyses

Differences between the biomass C and tree and shrub species diversity of PH and RH were determined using a one-way ANOVA. Soil C, bulk density, ESM, and aggregate stability were analyzed using a linear mixed effects model with subsamples used as spatially repeated measures. The treatment effects (PH, RH, PPF or RPF) were tested for significant differences using a marginal ANOVA. Significant differences ($p<0.05$) between means of treatment pairs were then determined using a Tukey's Honestly Significant Difference (HSD) test. These tests were repeated for the relative values of PH and RH. A correlation matrix was developed using Spearman's rank correlation coefficient (r) to compare how certain plant diversity metrics, soil properties as well as hedgerow age affect soil C and total (above- and below ground) perennial woody plant biomass. All analyses were computed in R Version 3.1.1 (R Core Team 2014).

2.3 Results and Discussion

2.3.1 Bulk Density, Equivalent Soil Mass, and Soil Carbon

Soil C estimates on a soil volume basis in the 0-20 cm layer were significantly greater in PH than PPF (Figure 2.2). Soil C estimated using the standardized mass basis approach to a 1.2 t m^{-2} soil mass, PH treatment had greater soil C relative to PPF, RH, and RPF (Figure 2.2). The mean bulk density was 9% and 10% lower in hedgerows than in production fields at the 0-20 cm depth and 20-40 cm depth, respectively, and PH had significantly lower ($p<0.05$) bulk density than PPF at the 0-20 cm depth (Table 2.2). The lower bulk density in the hedgerows may be due to an absence of heavy farm machinery (e.g., for activities such as tillage) that are typical in annual crop production and can cause compaction (Korolev et al. 2012).

Our results show that PH have greater soil C than RH to a 1.2 t m^{-2} soil mass (Figure 2.2), which are roughly associated with a soil depth of 0-100 cm (Gifford and Roderick 2003). Other studies that measured soil C to 100 cm in agroforestry systems found differences between perennial vegetation that ranged from 30 and 300 t C ha^{-1}

(Nair 2010), while we found that PH have a mean soil C of 175.9 ±13.2 t C ha^{-1} and RH 132.7 ±7.3 t C ha^{-1}. Native boreal forest sites dominated by coniferous species adjacent to agricultural production sites in eastern Canada had mean soil C on a mass basis to 0.35 t m^{-2} ranging from 61 t C ha^{-1} to 107 t C ha^{-1} (Carter et al. 1998); comparatively, RH had 63 t C ha^{-1} and PH 80 t C ha^{-1} to the same mass.

Table 2.2. Total soil carbon calculated using bulk density estimates of four treatment types - planted (PH) and remnant (RH) hedgerows and their neighbouring production fields (PPF and RPF). Different letters shown within the same column at the same depth represent significant differences (p<0.05). Values in brackets are represent standard error.

Treatment	Depth (cm)	Bulk Density (kg m^{-3})	Total C (t C ha^{-1})
PH	0-20	1071.0 (98.83) a	59.8 (3.93) a
PPF	0-20	1242.6 (58.65) b	48.6 (3.58) b
RH	0-20	1196.5 (104.69) ab	47.4 (4.97) ab
RPF	0-20	1247.6 (95.71) ab	46.6 (3.85) ab
PH	20-40	1124.4 (107.20) a	46.7 (3.77) a
PPF	20-40	1313.6 (59.80) a	32.2 (3.36) b
RH	20-40	1227.8 (53.09) a	29.3 (3.41) b
RPF	20-40	1313.3 (86.38) a	26.3 (3.72) b

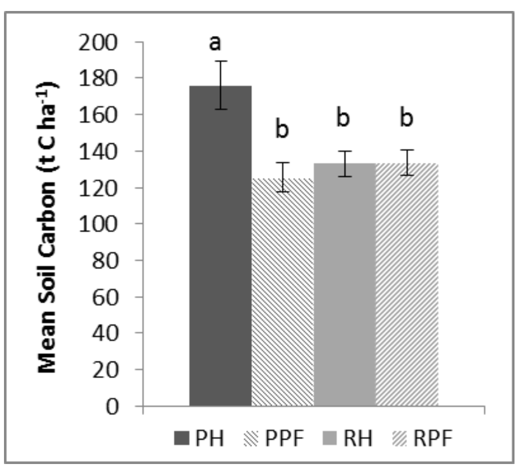

Figure 2.2. Mean soil carbon (t C ha^{-1}) calculated using standardized soil mass approach to a 1.2 t m^{-2} soil mass in planted (PH) and remnant (RH) hedgerows and their neighbouring production fields (PPF and RPF). Error bars are standard error and different letters represent a significant difference between means (p<0.05).

Observing higher soil C in hedgerows relative to production fields is expected given the more abundant, and diverse soil organic matter contributions from perennial plant litter and roots, and an absence of production disturbance (e.g., tillage) (Stockmann et al. 2013). Higher soil C was only observed for PH vs. PPF, but not for RH vs. RPF. Greater soil C accumulation in PH might be explained by biomass, vegetation diversity or structural differences between the two hedgerow types. For instance, greater plant diversity in PH could have resulted in a broader rooting depth range that can introduce organic matter through root exudates to deeper mineral layers (Harper and Tibbett 2013). Litter may accumulate at greater rates, more abundantly, or be more recalcitrant (D'Acunto et al. 2014; Sitzia et al. 2014; Sauer et al. 2007) in biodiverse or structurally dense PH, and levels of soil accumulation of wind or water eroded soil from adjacent production fields (Hien et al. 2013; Walter et al. 2003; Sauer et al. 2007) may accumulate more readily in PH.

It has been shown that different hedgerow types affect microclimates differently (Sánchez et al. 2009); hence, perhaps PH optimize temperature and moisture better for increased soil C contents than RH. Conversely, although efforts were made to manage for variability in PF sites selected for this study, differences in neighbouring PF management practices (e.g. organic or conventional) can also affect hedgerow diversity (Monokrousos et al. 2006), thereby altering soil C dynamics in the hedgerows. Last, plant diversity can influence the protection of C from decomposition through promoting increased aggregation (Six 2000; Jastrow et al. 2006) via increase organic matter additions to the soil and enhanced earthworm activity (and production of casts) due to improved habitat. For these reasons, diversity of trees and shrubs was also measured as was the aggregate stability of the soil.

The amount of soil C found in the PFs is typical of conventional, intensively-managed agricultural systems (Matson 1997). Agricultural sites neighbouring boreal forested areas dominated by coniferous trees in eastern Canada had a range of 54 t C ha^{-1} to 133 t C ha^{-1} to a soil mass of 0.35 t m^{-2} (Carter et al. 1998), while in our study the total mean PF soil C to the same soil mass was observed at 56 t C ha^{-1} with a range of 26 t C ha^{-1} to 98 t C ha^{-1}. Total soil C is characteristically lower in PFs because of wind and water erosion, enhanced by leaving fields bare during winter, or tillage which causes structural and compositional changes to the soil accelerating the rate of decomposition and soil C loss.

2.3.2 Aggregate Stability

Soil aggregate stability, as expressed by MWD, was greater in hedgerows than in neighboring production fields (Figure 2.3A). Both PH and RH had a MWD at least two times greater than neighbouring production fields. There was no significant difference in the MWD between PH and RH nor between PPF and RPF.

Other studies have reported similar aggregate stability differences between cultivated and non-cultivated land uses. For example, an evaluation of the distribution of water-stable aggregates in virgin forests, virgin pasture, cultivated ex-forest and cultivated ex-pasture in a mountainous Mediterranean climate of Iran, found that the MWD was significantly lower in the cultivated areas; the MWDs were found to be 3.62 ± 0.1 mm for virgin forest, 2.2 ± 0.1 mm for ex-forest, 3.55 ± 0.1 for virgin pasture and 2.13 ± 0.1 for ex-pasture (Emadi et al. 2009). Similarly, an agroforestry system in NW India that experience monsoon rains part of the year and a high water table reported a MWD 2.86 times higher relative to a sole poplar crop (Gupta et al. 2009).

The greater MWD in the hedgerows is in agreement with the higher soil C content in PH relative to the production fields, but this was not true for RH vs. RPF treatments that had similar soil C (Table 2.2). The residence time and thereby increase in stock of soil C depends on its protection from decomposition; soil C can be protected through mechanisms such as binding with soil minerals in aggregates, or protected within the pore spaces of aggregates (Jastrow et al. 2006). In soils that display 'aggregate hierarchy'(Figure 2.3B), such as soils dominated by the 2:1 clay minerals of our study, larger aggregates have been found to contain proportionally greater soil C than smaller aggregates (Six, 2000). Consequently, it was beneficial to have hedgerows in this agricultural landscape, since hedgerows had a greater proportion of aggregates in the largest (2-6 mm) size fraction relative to the production fields.

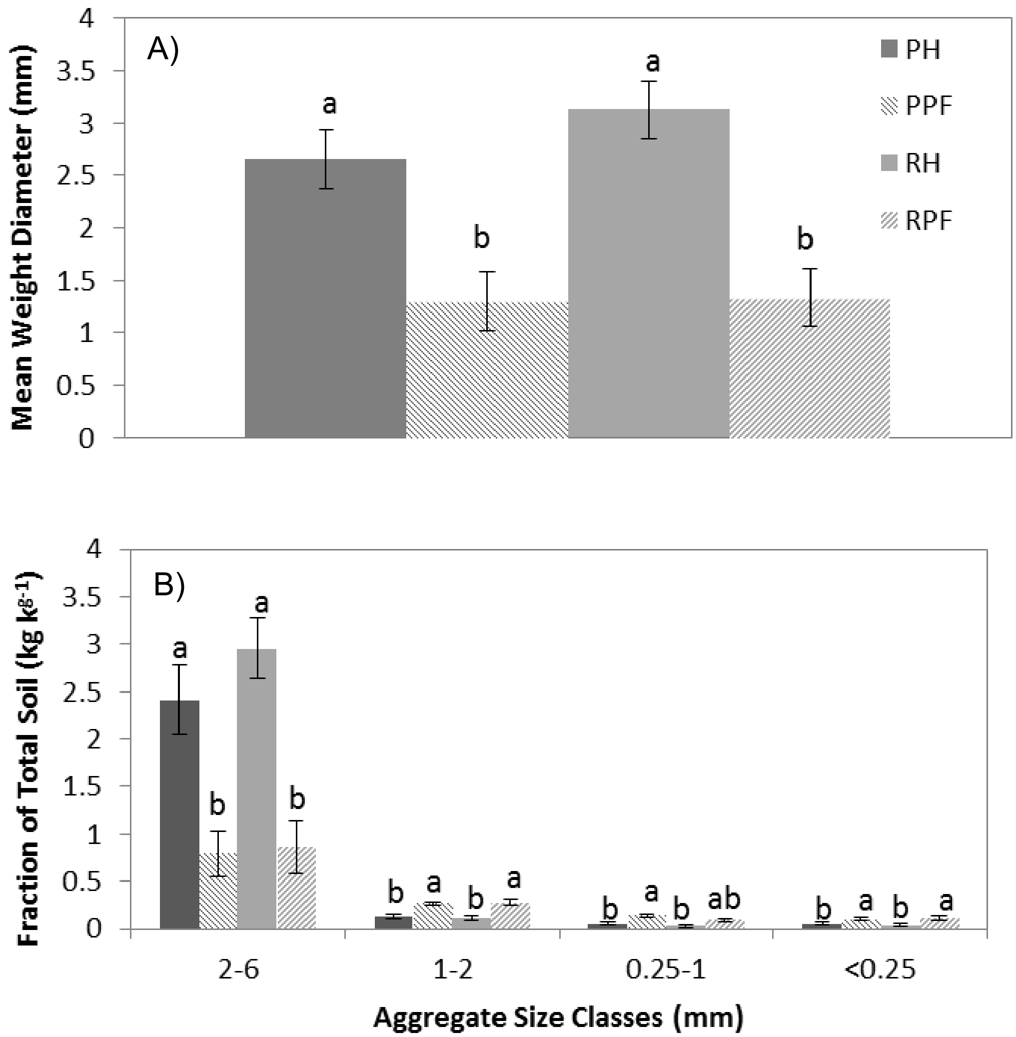

Figure 2.3. Mean weight diameter (mm) of planted hedgerows (PH), remnant hedgerows (RH) and their respective production fields (PPF & RPF) (A) and fraction of total soil sample present in four aggregate size classes (2-6, 1-2, 0.25-1, and < 0.25 mm (B). Error bars represent standard error. Bars with the same letter in each category are not significantly different from each other (p<0.05).

2.3.3 Hedgerow Tree and Shrub Biomass Carbon

There was substantial variability in the biomass of the perennial vegetation within and between the two types of hedgerows. Consequently, biomass C (total, aboveground (AG) and belowground (BG)) for trees and shrubs were not statistically different ($p<0.05$) (Figure 2.4). Both hedgerow types had substantial accumulations of C, the mean total (AG and BG) biomass C for PH was 76.2 ± 32.3 t C ha^{-1} and for RH, 124.0± 20.9 t C ha^{-1} (Figure 2.4).

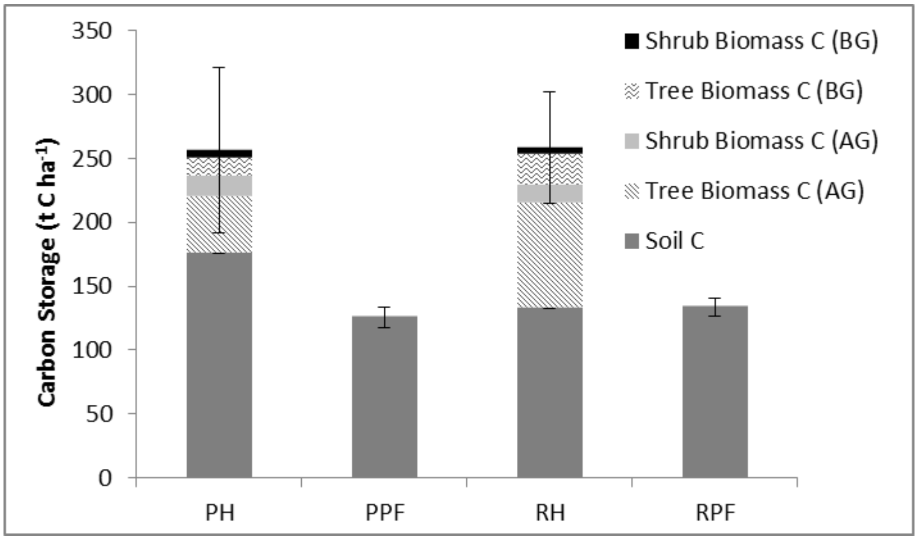

Figure 2.4. Distribution of carbon pools (t C ha^{-1}) for planted hedgerows (PH), remnant hedgerows (RH) and their neighboring production fields (PF) for belowground (BG) and aboveground (AG) carbon storage pools. Error bars represent standard error for the total carbon storage.

Similar results for hedgerows have been found in other farming systems. A recent study evaluating the benefit of field margins in the Argentinian Pampa region found woody field margins had 65.74 ± 13.76 t C ha^{-1} (D'Acunto et al. 2014), while an aboveground biomass model for a 20-year old single-row farmland shelterbelt in the US found 23.12 t C ha^{-1} could be contributed by shrubs (Brandle 1992 as reported by Kort & Turnock 1999).

Evaluating the impact of vegetation age on biomass C is important since C is sequestered by vegetation at different rates at different times in their development (Wang et al., 2013), and older vegetation has had longer to sequester C. In our study, a weak linear correlation (R^2= 0.40; p=0.09) was observed between the logarithm of hedgerow age and the logarithm of total biomass C (data not shown).

From our results, it is unclear if PH (that ranged in age between 9 and 19 years) could store greater biomass C if allowed to reach a similar age as RH (averaging 38 years of age). Knowledge of hedgerow age can help determine average sequestration rate of C in woody biomass as plants sequester C differentially throughout their growth (Wang et al. 2013). Thus, a one year study of sequestration rates in woody vegetation may not be representative.

Carbon storage in PH and RH are similar (Figure 2.4). Despite increased biomass C as the woody vegetation matures, soil C may be declining over time. This warrants further investigation, since it is possible that this data illustrates a spatial pattern, where RH are found on poorer soils.

Limitations for estimating biomass in agroforestry systems are that most allometric equations are developed for trees growing in a forest environment, and that non-timber species observed in hedgerows do not necessarily have species specific equations available. As a result, many of the species found in our study did not have specific allometric equations, particularly the shrubs. Additionally, 3% of the shrubs in our study exceeded the limits of the general allometric equation used, and a biomass limit was imposed equivalent to the maximum the equation could predict to provide a conservative estimate of the biomass C. These limitations may lead to inaccurate estimations in total biomass of the hedgerows (Nair et al. 2009) but we have, whenever possible tried to err on the side of underestimation. While there is the potential that the results are closer to the upper bounds which would mean that more C is present than reported here by using the lower bounds of the results, we are not overstating the total

C that is present in the vegetation of the hedgerows and our analysis errors will result in greater climate change mitigation, a net positive impact.

2.3.4 Hedgerow Tree and Shrub Species Diversity

Greater diversity of woody perennial vegetation was observed on PH relative to RH in terms of both species richness and relative evenness (Table 2.3). In total, 25 tree and shrub species were documented in PH relative to a total of 14 species in RH. In PH, the most common species were: red maple (*Acer rubrum),* red alder *(Alnus rubra),* paper birch *(Betula papyrifera),* willow *(Salix sp.),* Nootka rose *(Rosa nutkana),* yellow cedar *(Cupressus nottkatensis),* black cottonwood *(Populus trichocarpa),* Pacific red cedar *(Thuja plicata),* and red osier dogwood *(Cornus sericea)*. In RH, the most common species were: red alder (*Alnus rubra),* black hawthorn *(Crataegus douglasii),* Pacific crabapple *(Malus fusca),* and black cottonwood *(Populus trichocarpa)* (see appendix for full species list).

Table 2.3. Mean species diversity measures (species richness, Simpson and Shannon indices) of planted (PH) and remnant hedgerows (RH). Values in brackets represent standard error. Different letters shown within the same column represent significant differences (p<0.05).

Hedgerow Treatment	Richness	Simpson	Shannon
PH	8.00 (3.00) a	0.50 (0.07) a	0.46 (0.09) a
RH	4.56 (0.88) b	0.19 (0.10) b	0.17 (0.08) b

The diversity within the hedgerow provides insight into different characteristics of trees and shrubs, such as rooting depth, litter type, and biomass, that could potentially influence soil properties such as soil C. When diversity indicators were evaluated relative to soil C stocks (Figure 2.5), Pearson's correlation between soil C (to 1.2 t m^{-2}

standard soil mass) and the Simpson (R^2=0.50; p=0.048) and Shannon (R^2=0.58; p=0.027) indices were both positively and significantly correlated with soil C but richness was not. The correlation between the Simpson and Shannon index and soil C indicates that evenness among species is important, even in small numbers, for increasing soil C storage in the soil.

Hedgerows planted and managed for higher diversity (Staley et al. 2012) are arguably an effective tool for improving farmland C storage. Our findings agree with a study by Vesterdal et al. (2013) which has shown that the top mineral layer can have up to a 50% change in soil C as a result of tree species effect in temperate forest systems. Plant diversity can also influence bacterial and fungal communities which control rates of decomposition and soil C turnover (Jastrow et al. 2006). Since farmland plant species diversity is increased more effectively through introducing non-production areas to agricultural landscapes than the introduction of greater plant biodiversity in production areas (Franklin Egan & Mortensen, 2012). The presence of N-fixing species such as the red alder (*Alnus rubra*) could also impact the quantity of C stored in a hedgerow given natural additions of N to the system enabling increased plant growth, though the overall increases relative to systems without N-fixing plants seems to also depend on the density of trees (Bormann et al. 1984).To assess how other measured variables affect the soil C, perennial woody biomass C, or total combined C in hedgerows, a correlation matrix is given in Figure 2.5. In addition to strong positive correlations between soil C to a 1.2 t m^{-2} mass and both Shannon and Simpson index values in the 0-20 cm and 20-40 cm depths, and weak positive correlations were observed between hedgerows age and total biomass C as well as MWD and total biomass C, though none of these relationships were significant ($p<0.05$). A weak positive correlation was observed between species richness and soil C to 1.2 t m^{-2}, but it too was not significant.

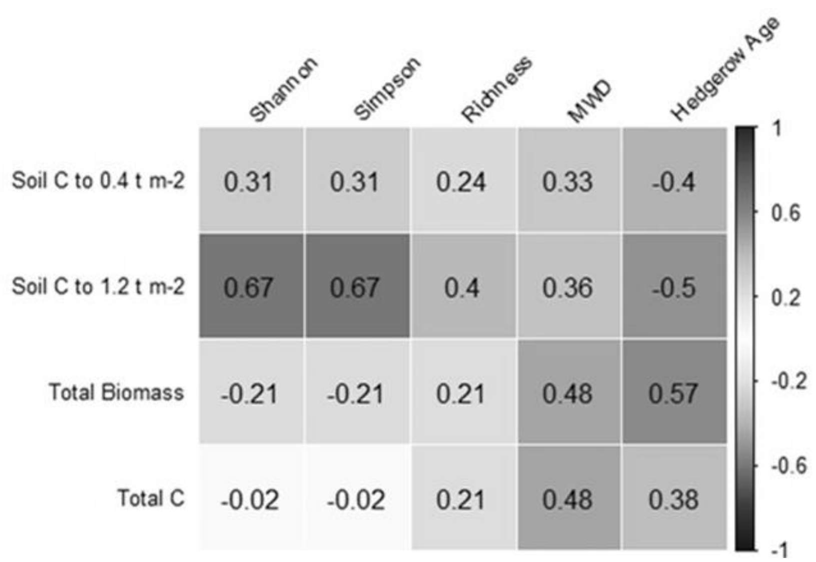

Figure 2.5. Spearman's correlation matrix. Values (r) show the positive or negative correlation between carbon storage properties and influencing variables of planted and remnant hedgerows.

2.4 Summary and Conclusions

Our results demonstrate that planting hedgerows designed for greater biodiversity, though resource intensive, does provide improved climate change mitigation through increased soil C storage on agricultural landscapes of the western Fraser Valley, British Columbia relative to naturally regenerated hedgerows. Looking forward, based on these findings, farm-scale management practices and landscape scale policies that promote the inclusion of non-production areas such as hedgerows planned for diversity, should be promoted for climate change mitigation on agricultural land.

PH showed significantly greater soil C storage to the 1.2 t m^{-2} equivalent soil mass relative to RH, which is correlated with significantly greater tree and shrub species diversity in PH relative to RH. Both PH and RH improved soil aggregation relative to the adjacent production fields particularly for the largest (2-6 mm) aggregate size fraction. Better soil aggregation in hedgerow treatments is likely the effect of minimal disturbance by farmland machinery. For PH, the increased aggregation may be also a result of increased organic matter relative to PFs. Despite the age difference between PH and RH, the perennial woody vegetation had a similar biomass. However, PH had significantly greater tree and shrub species diversity in both richness and evenness (Simpson and Shannon). In addition, though perennial woody vegetation species diversity strongly affected soil C storage to a 1-meter depth, it did not affect vegetation biomass C.

3 A COMPARISON OF CO_2, N_2O, AND CH_4 FLUXES FROM PLANTED AND REMNANT HEDGEROWS[2]

3.1 Introduction

Hedgerows on farmland have the potential to help mitigate climate change through C sequestration of carbon in their woody biomass and soil and improving nitrogen cycling; however, without an understanding of the greenhouse gas (GHG) emissions that are being generated from hedgerows their net climate change mitigation benefit is unclear. Agriculture's emissions of N_2O and CH_4 account for 10-12% of global anthropogenic greenhouse gas emissions (Smith et al. 2007). Agriculture contributes 38% of global N_2O emissions and 32% of global CH_4 emissions, while the *net* contribution of CO_2 from agriculture is less than 1% of the CO_2 global total (Smith et al. 2007). In Canada, agriculture contributes approximately 8% of greenhouse gas emissions (Environment Canada 2012), while in the Province of British Columbia (BC) approximately 3% greenhouse gas emissions are from agriculture (Ministry of Environment 2014).

In BC, the *Greenhouse Gas Reductions Target Act* was passed in 2007 which mandates that provincially all anthropogenic emissions be reduced by at least 33% by 2020 and 80% by 2050 from 2007 levels (Ministry of Environment 2014). Environmentally beneficial farm management practices are encouraged by programs available to farmers (B.C. Agricultural Research & Development Corporation 2013; www.deltaagricultural systems.ca/page/ourprograms/), and some of these practices have the co-benefit and potential to help mitigate climate change. For example, the Hedgerow Stewardship Program managed by the Delta Farm & Wildlife Trust (DF&WT),

[2] We plan to submit this chapter as a manuscript to Agroforestry Systems for publication.

a local not-for-profit conservation organization which incentivizes farmers to manage non-production areas on farms to improve the availability of ecosystem services in Delta, BC, supports farmers to have hedgerows planted on the margins of their production fields. This practice, a form of agroforestry, has the potential to help mitigate GHG emissions (Schoeneberger et al. 2012). A number of recent studies across a number of systems have explored the potential for agroforestry systems to help reduce GHG emissions by improving N cycling or offsetting GHG emissions through C sequestration in woody biomass and soil in agricultural systems (Schoeneberger 2008; Schoeneberger et al. 2012; Udawatta & Jose 2012; Udawatta & Jose 2011; Falloon et al. 2004) but research on on-farm woody hedgerows is limitted.

Primary benefits of planting woody vegetation are that it improves landscape diversity and creates habitat for avian species (Fischer et al. 2008; Franklin Egan & Mortensen 2012) such as raptors and songbirds (http://www.deltafarmland.ca/page/farmland-wildlife/) and other biota; however, it is not clear how much this activity may actually offset GHG emission, particularly relative to the production systems in which they are being utilized. Thus, to better understand the global warming potential (GWP) of program's like the DF&WT's Hedgerow Program, we need to assess the carbon (C) stored in hedgerow biomass and soil (Chapter 2), but also hedgerow CO_2, N_2O, and CH_4 emissions relative to the agricultural systems in which they have been planted.

There is the potential for management of on-farm hedgerows to alter their GHG emissions. While research has shown that soil CO_2 emissions are affected by the size of C inputs, temperature and moisture (Jabro et al. 2008), management decisions such as tree species selection (Vesterdal et al. 2012) and the overall diversity of the system (as hypothesized by Catovsky et al. 2002) may also significantly alter the emission rates. There may be hedgerow management options that could also impact N_2O emissions. N_2O emissions are of major concern because their radiative forcing is 298 times greater than that of CO_2 over a 100-year period (Forster et al. 2007). Planting more diverse hedgerows may affect emissions by capturing more labile N and increasing the efficiency of N use (Tillman et al. 1991), or could alter N cycles through different types of litter contributions to the soil (Ryszkowski et al. 2007). Finally, hedgerow management could change hydrologic conditions on the farm and thus impact CH_4 emissions. CH_4 emissions tend to be greatest from saturated soils (common in Delta, BC) and are largely affected by soil water management particularly in delta systems (Teh et al. 2011). Increased CH_4 emissions could greatly affect the GWP of a system, particularly because its radiative forcing is 25 times greater than CO_2 over 100-year period.

Understanding CO_2, N_2O and CH_4 emissions from hedgerows and their neighbouring production fields requires an effective monitoring methodology. The highly temporal and spatially heterogeneous nature of GHG emissions from agricultural landscapes (Chadwick et al. 2014; Norman et al. 1997), and concentrated emission periods of N_2O (Zona et al. 2013) make measuring and reporting emission patterns extremely challenging. A well-established, relatively cost effective way to measure soil GHG emissions is to take samples using closed static chambers in the field and analyze them using a gas chromatograph (GC) in the lab (Kutzbach et al. 2007; Rochette, Worth, Lemke, et al. 2008; Livingston & Hutchinson 1995).

Numerous studies have used closed static chambers to sample soil fluxes but there is debate as to how best to calculate the GHG emission rates from these chambers. Evidence supports both linear and non-linear regression analyses of concentration changes in the headspace of a chamber during the measurement period (Duran & Kucharik 2013). Often times a linear regression model is used as the most appropriate because of its simple application and the approximately linear changes in concentration observed, particularly for shorter deployment times. There are however, concerns that this method too often underestimates the true flux of a system by not accurately taking into account the sometimes substantial feedback effect of the measurement system particularly over longer deployment times required for N_2O and CH_4 flux measurement (Pedersen et al. 2010; Kutzbach et al. 2007).

Further, we do not have a conclusive understanding of the mechanisms that control GHG emissions in hedgerow or production systems, particularly in temperate river delta regions. Data collected from both agricultural systems and forests indicate soil temperature and water content (Christiansen et al. 2010; Jabro et al. 2008), plant diversity (Christiansen & Gundersen 2011; Vesterdal et al. 2012), soil texture (Boeckx et al. 1997), and fertilizer use (Jassal et al. 2008b; Jassal et al. 2010) are some of the important factors to consider. However, the unique structure, vegetation diversity, and exposure to neighbouring land uses of hedgerow systems can substantially affect C cycling and GHG emissions (Schoeneberger et al. 2012; Nair et al. 2010; Kumar & Nair 2011), while the high precipitation volumes, long periods of soil saturation, and high water tables relative to the surface of the soil in the deltaic system might also impact emissions (Teh et al. 2011). Hence, there is a need to evaluate the efficacy of these models for analyzing data taken from different environments and managements practices, such as hedgerows in agricultural systems.

There are two types of hedgerows in Delta, BC: those planted by DF&WT that are planned for species diversity, and those that are remnant in the landscape. If planted hedgerows (PH) demonstrate increased soil C relative to remnant hedgerows (RH), we anticipate this increased soil C in the system will result in higher CO_2 and CH_4 emissions. At the same time, greater species diversity of trees and shrubs in PH relative to RH may result in increased nutrient capture from production fields. Further, we anticipate hedgerows will have lower N_2O emission relative to production fields that are receiving large quantities of fertilizer applications.

This study was conducted to investigate differences in the GHG emission performance of PH versus RH relative to production fields on agricultural systems in Delta, BC. The objectives of this study were to 1) evaluate differences in linear and non-linear flux calculation methodologies from closed static chambers, 2) compare the production and non-production season (6-month means) and mean annual differences in CO_2, N_2O, and CH_4 fluxes, of hedgerow types relative to production fields and 3) determine which soil and vegetation properties may regulate emissions from these systems. The focal hypothesis of the study is that the planned diversity of PH will result in higher productivity thus greater CO_2 emissions, lower N_2O emissions due to improved nutrient capture, and increased CH_4 emissions due to greater soil and biomass C relative to RH.

3.2 Methods and Materials

3.2.1 Study Sites

The study was carried out from November 2012 to February 2014 on eight sites (operational farms) located in peri-urban landscape of the lower Fraser River delta in the district municipality of Delta, British Columbia (49° 4'25.33"N, 123° 4'58.20"W). Four sites had RH and four sites had PH. Sites were selected based on the hedgerow's size, relative age, proximity to one another, and presence of the neighbouring production fields' (PF) with the goal of minimizing the variability of these factors within each hedgerow type. Hedgerows included in this study ranged from 250 m^2 to 2400 m^2. At all study sites, the production field neighbouring the hedgerow was also sampled (*planted production field* (PPF) neighboured PH, and *remnant production field* (RPF) neighboured RH).

Both RH and PH are perennial linear woody habitats consisting of trees, shrubs and ground-cover (grasses and forbs). RH are naturally regenerated areas established prior to DF&WT Hedgerow Stewardship Program, have a mean age of 38 years at the time of site selection, a mean width of 7.5 m, and are largely unmonitored and unmanaged. PH have been planted with a diversity of native shrubs and trees by DF&WT along fields, property boundaries, waterways, or roads, range in age from 9-19 years, have a mean width of 4.0 m, and are monitored and managed by DF&WT.

The elevation of the study area ranges from 0 to 3.0 m above sea level. The thirty-year (1981-2010) climate record of a nearby weather station indicates a mean annual temperature of 10.6^{o}C (51.08^{o}F), rainfall of 1227.8 mm, and snowfall of 34.6 cm (Ministry of Environment 2014). The soils in the region are mainly Gleysols (Inceptisols) formed on fluvial deltaic deposits (Luttmerding 1981). Experimental sites were established on three soils series, namely the Ladner, Crescent, and Westham (Luttmerding 1981).

CO_2, N_2O, and CH_4 were measured between February 12, 2013 and January 23, 2014 using a closed-chamber method. A total of 24 collars were installed on the eight sites at least one week prior to measurements to minimize the effects of soil disturbance associated with chamber insertion (Livingston & Hutchinson 2001). One collar was randomly inserted within each of the four PH plots, the four RH plots, and the associated PF plots (PPF and RPF). The collars were inserted to a depth of 5 cm to reduce lateral diffusion (Livingston & Hutchinson 2001; Healy et al. 1996). During the production season (May to October), when farming operations (e.g., tillage, seeding, fertilization, harvesting) were frequent, the collar installations in the PFs were often limited to the day of sampling to avoid disturbance from farm operations. In the PFs, collars were inserted between rows of field vegetation and no vegetation was removed. In the hedgerows, ground cover was largely absent; in certain situations where vegetation growth was present and prevented a tight seal of the chamber lid, vegetation was cut back.

To capture temporal variability between GHG fluxes, chambers were sampled every two weeks for a 12-month period. To better understand the importance of spatial variability in this study a total of eight additional collars were installed on two sites one of each hedgerow type, and their associated PFs and sampled once per month for the 12-month period (Figure 3.1), these samples were also included in analysis. GHG sampling on the eight farms averaged 4.5 hours, and was scheduled between 9:00 and 14:00 to minimize variation in temperature.

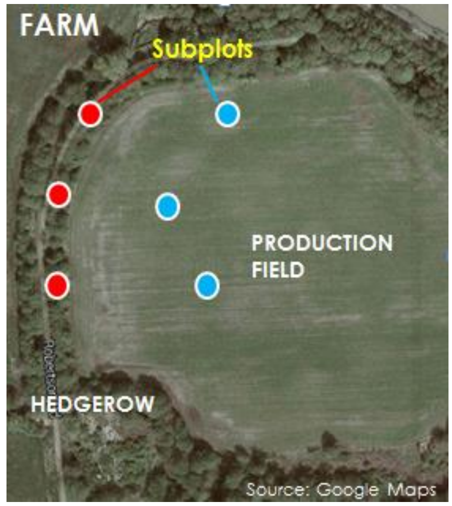

Figure 3.1. Paired plot sampling design with production field subplots (blue) and hedgerow subplots (red).

3.2.2 CO_2, CH_4 and N_2O flux measurements

To measure GHG, specifically CO_2, N_2O, and CH_4 fluxes from our treatment sites, we used non-flow-through, non-steady-state (or closed static) chambers (Kutzbach et al. 2007; Rochette, Worth, Lemke, et al. 2008; Livingston & Hutchinson 1995). The chambers were constructed following methods of Rochette et al. (2008a; 2011) and Jassal et al. (2008). Chamber collars were cut from 20 cm inner-diameter (with 0.6 cm thick walls) PVC pipe (Jassal et al. 2008b) to a collar height of 15 cm. The collars were inserted to a depth of 5 cm with a headspace height of 10 cm. The edges of the PVC collars were beveled to facilitate the insertion into the ground and minimize soil disturbance (Luo & Zhou 2006).

Square acrylic glass lids were cut and each outfitted with a 15 cm vent tube (1/4”), a fan, a silicon rubber septum (Plug-Type Rubber Sleeve Stoppers, Kimble Chase, NJ, USA) and circular inert foam seal (weather-and-fire-retardant foam, McMaster-Carr, USA) to attach the lids to the collars. To ensure that the headspace air was well mixed during the sampling, a small fan was affixed to the interior of the lid with air flow directed upward and powered by a 9V battery (attached to the top of the lid) (Pihlatie et al. 2013; Kutzbach et al. 2007; Jassal et al. 2008a). A silicon rubber septum was installed as the point from which air samples would be withdrawn by syringe during the measurement time interval (Jassal et al. 2008a). Foam seals were used to eliminate leaks at the point of contact between the collar and the lid (Jassal et al. 2012). The chamber lids were painted white to limit plant activity by creating an opaque surface (Luo & Zhou 2006) that reflects a high proportion of incident solar radiation.

3.2.3 Gas chromatography and calculation of gas flux rates

Gas samples were taken from closed chambers and analyzed on a GC. Ambient air samples were taken whenever chamber lids were deployed. Gas samples were subsequently taken using a 10 ml plastic syringe with a 22G needle at 3, 10, 20 and 30 minutes at each sampling event (Jassal et al., 2008). The 10 ml sample was injected into pre-evacuated 5.9 ml glass vials (Exetainers, Labco Limited, Ceredigion, UK). Samples taken from February to July 2013 were analyzed for all three gas species (CO_2, N_2O and CH_4) simultaneously using a gas chromatograph (GC) – Agilent 7890A (G3440A, Agilent Technologies) with a Combi Pal auto-sampler (CTC Analytics, Zwingen, Switzerland) and a run time of 11.5 minutes. Samples taken from August 2013 to February 2014 were analyzed on a Bruker 456 (Bruker Corporation, 350 West Warren Avenue, CA, USA) with a Combi Pal autosampler (CTC Analytics, Zwingen, Switzerland) and a run time of 1.7 minutes. ChemStation software (Rev.B.04.03[52]) was used to integrate the chromatograms of each gas species until July 2013, and Compass CDS data system (BR501481) was used from August 2013 onwards.

Collar heights were measured after each sampling interval to accurately calculate the volume of the chamber to account for any movement caused by environmental or sampling factors between sampling days. When collars were saturated with water above the soil surface, the depth of the water was also measured. To account for possible sources of error related to the climate, transportation or storage of the sample-filled glass vials, three reference glass vials were filled with Air Liquide Calibration Standards containing a gas mixture of 600 ppm CO_2, 5 ppm CH_4, and 1 ppm N_2O each day prior to field sampling. These reference vials were then transported to the study sites, stored, and analyzed with the sample-filled vials. Similarly, reference standards were injected into vials at the time of analysis to confirm the integrity of the GC. The measured lab standards varied by less than 5% for CO_2, less than 2.6% for N_2O and less than 1.3% for CH_4 for each batch of samples analyzed.

The flux rates $(\frac{\mathrm{dc}}{\mathrm{dt}})$ of each gas species were calculated using both linear and non-linear regression. The CO_2 flux rates were calculated using the change in concentration (dc) over the 0 to 3 minute time period (dt) for the linear regression analysis to minimize the feedback effect from the buildup of CO_2 in the chamber headspace (Healy et al., 1996), while the N_2O and CH_4 flux rates were calculated using the change in concentration (dc) over the 0 to 30 minute time period (dt) to allow for a measurable concentration change in these species (Norman et al., 1997). Gas fluxes were then calculated using:

Equation 8 $\mathbf{Flux} = \frac{\mathbf{dc}}{\mathbf{dt}} \frac{\mathbf{PV}}{\mathbf{RTA}}$

Where the *dc* is the change in concentration of a gas species in μmol (gas) mole air^{-1}, *dt* is the change in time in minutes, *P* is 1 atm of pressure, *V* is the volume of the chamber in litres, *R* is the gas constant 0.08206 L atm mol^{-1} K^{-1}, T is the air temperature in Kelvin and *A* is the basal area of the chamber in m^2. The dry air density was determined for each sampling day using the mean air temperature over the sampling period from a nearby weather station at Burns Bog, BC. (Burns Bog, http://climate.weather.gc.ca/).

Non-linear regression analyses were conducted using the HMR package (Version 0.3.1) in R Versions 3.1.1(R Core Team 2014) designed for flux estimations of trace gases from static chambers (Pedersen et al. 2010) using the Hutchison and Moisier non-linear regression equation (Mosier & Hutchinson 1981) to determine the chamber concentration (C_t) when t>0 shown in Equation 8:

Equation 9 $\mathbf{C_t} = \boldsymbol{\varphi} + \mathbf{f_0 e^{-kt}}$

where *t* is time in minutes, φ is the constant source concentration located at a depth *d* below the surface, f_0 is the flux, and *k* is a model parameter where $k = D_p/hd$ to account also for gas diffusion through the soil (D_p), and chamber height (*h*) (Pedersen et al. 2010).

Where the regression analysis resulted in a ‘No-Flux’ output because of high levels of noise in the data, a linear regression analysis calculated by the HMR package was forced and used instead.

The mean 6-month (from May to October for the production season, and November to April for the non-production season) and annual values for each management option were compared as were their relative 6-month and annual means; relative means are the differences observed between the hedgerow flux and its neighbouring production field flux for each gas to account for variation between planted and remnant hedgerows that may result due to site differences such as microclimates and soil type.

3.2.4 Environmental variables

Precipitation (mm) and air temperature (^{o}C) data were collected from nearby weather stations (Richmond Nature Park, BC Weather Station; Burns Bog, http://climate.weather.gc.ca/ retrieved April 8, 2014) and compared to the 30-year historical data to observe seasonal differences as well as annual differences from normal years. Volumetric soil water content ($m^3\ m^{-3}$) and soil temperature (^{o}C) were collected from each of the collar locations using a Pro-Check Digital Analog Sensor Handheld Readout and 5TM water content and temperature sensor (Decagon Devices, Inc., WA, USA) from 0-5 cm and 10-15 cm depths on every sampling day. Water filled pored space (WFPS) was calculated by first determining the total porosity of the soil:

Equation 10 $$\textbf{Total porosity}\ (\%) = \mathbf{1} - \frac{\mathbf{Bd}}{\mathbf{Pd}} \times \mathbf{100}$$

where *Bd* is the measured bulk density and *Pd* is the surveyed oven-dried particle density of the soil series equal to 2720 kg m^{-3} for Ladner (Luttmerding 1981), assumed to be the same for Westham and Delta soils. Dividing the measured volumetric water content by the porosity you determine WFPS:

Equation 11 $$\textbf{Waterfilled pore space}\ (\%) = \frac{\textbf{Volumetric Water Content}\ (\%)}{\textbf{Total Porosity}\ (\%)} \times \mathbf{100}$$

Bulk density was measured in the field at the 6.5 - 13.5 cm depth which we used as representative of the 0-20 cm soil layer (see chapter 2 for details). Soils were sampled at 20 cm intervals to a 1.0 meter depth and analyzed for a suite of properties with

Fourier-transformed mid-infrared spectroscopy (FT-MIR) using a Tensor 37 HTS-XT spectrometer (Bruker Optics) as described in Chapter 2. Approximately 10% of soil samples were analyzed using traditional wet chemistry methodologies to calibrate the FT-MIR analysis. For total C and N a subset was analyzed by elemental combustion (Thermo Flash 2000 analyzer, Thermo Scientific). For soil pH (Table 3.1) a subset was analyzed in a 2:1 water solution and a 0.01M $CaCl_2$ solution in a 3:1 ratio using an electronic pH meter (UB-10, Denver Instrument) calibrated every five samples using pH 4.0 and pH 7.0 standards. C:N ratios were calculated using percent C and percent N. Hedgerow tree and shrub diversity richness and evenness (using Shannon and Simpson indices) and biomass C were calculated as described in Chapter 2. Finally, management factors that would impact soil C and soil N were collected from farmers, and a 10 year history of PF uses were compiled for both summer and winter months (Table 3.2).

3.2.5 Statistical Analyses

For the GHGs, all measured data were included and analyzed using a linear mixed effects model with temporally repeated measures to account for correlations between samples taken from the same sampling location throughout the sampling period (Linear and Non Linear Mixed Effects Models “nmle” package in R Version 3.1.1) (R Core Team 2014). An ANOVA (type= “marginal” in R for Type III tests) was used to test for significant differences between main effects (management option (PPF, RPF, PH, RH) and sample date) and their interaction across all measurement days for the year and 6-month periods (production and non-production seasons). A Type III test was used to test the main effects of the management option and sample date even in the presence of an interaction.

A multiple comparison of the management options was done using a Tukey's Honest Significant Difference test to check for significant differences between means of the management options (Simultaneous Inference in General Parametric Models "multcomp" package in R). Testing significance for *relative* annual means for each gas in the planted and remnant system was done using a general linear hypothesis test ("glht" in R) after relative differences for each system were determined ("rbind" in R).

Emissions with unequal variance were log transformed before statistical analyses were performed. For linear versus non-linear flux calculation comparisons, Pearson's correlation coefficients ("cor.test" in R) were determined and significant differences between the total means were calculated using a t-test ("t.test" in R). A correlation matrix ("cor" test using method="spearman"; diagram using Visualization of a Correlation Matrix "corrplot" package in R) was developed using Spearman's rank correlation coefficient (r) to explore the relationships between annual means of GHG emissions and the environmental variables measured in each plot. All analyses were computed in R Version 3.1.1 (R Core Team 2014).

3.3 Results and Discussion

3.3.1 Linear versus non-linear flux calculations

We found variations between linear and non-linear calculations of fluxes of all three GHG types with far greater differences for N_2O and CH_4. Non-linear calculations resulted in an 11% lower estimated CO_2 efflux, a 113% higher estimated N_2O efflux, and a 497% higher estimated CH_4 fluxes relative to linear calculations (Figure 3.2). The differences were not significant for CO_2, but were significant for both N_2O ($p<0.05$) and CH_4 ($p<0.001$). The relationship between the linear and non-linear values was strong for CO_2 ($R^2 = 0.74$) and N_2O ($R^2 = 0.80$), but weak for CH_4 ($R^2 = 0.32$).

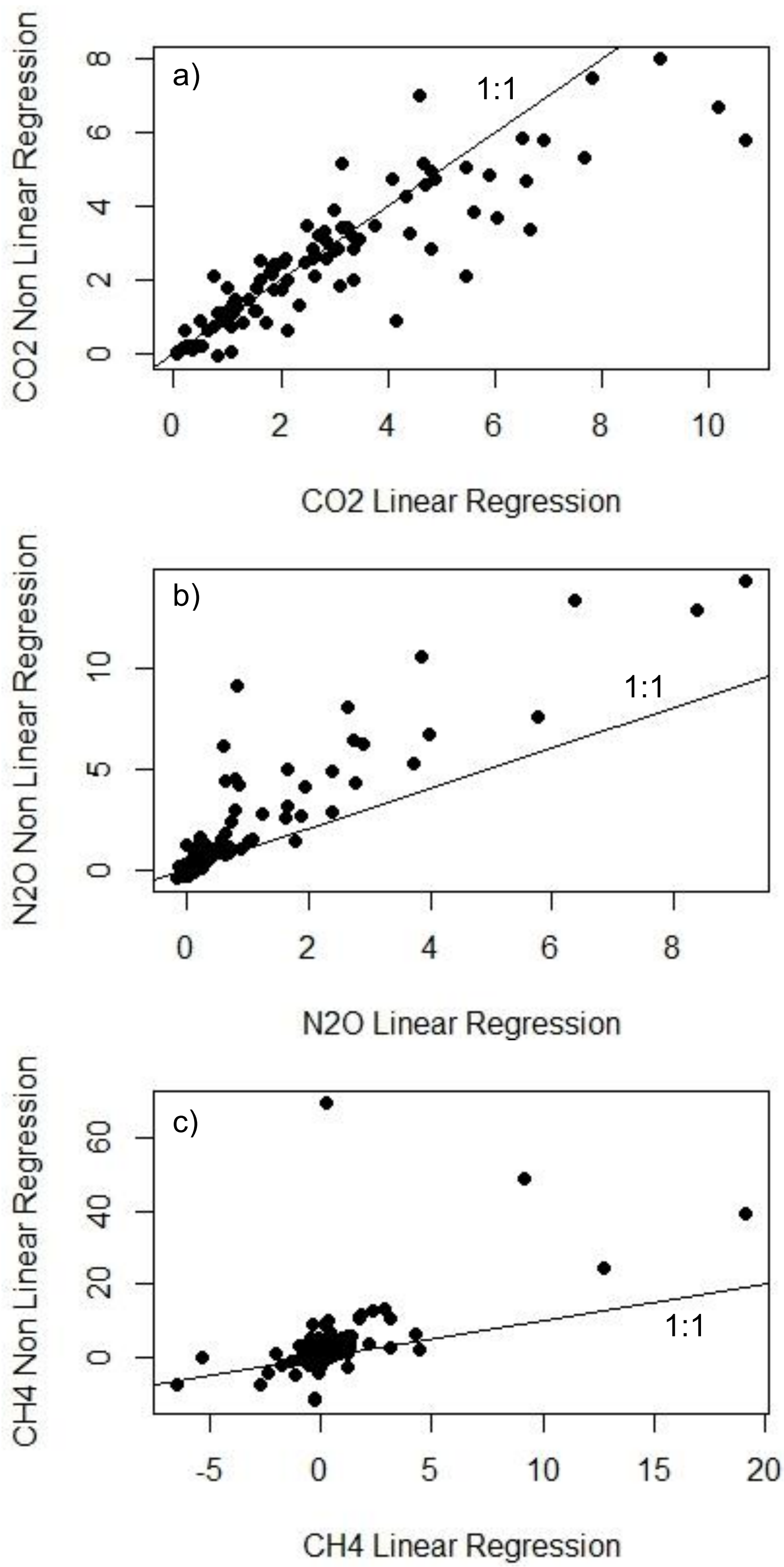

Figure 3.2. Correlation analysis between linear (x-axis) and non-linear (y-axis) flux regression analysis for a) CO_2 (μmol m^{-2} s^{-1}), b) N_2O (μmol m^{-2} hr^{-1}), and c) CH_4 (μmol m^{-2} hr^{-1}). The line indicates a one-to-one relationship.

Currently there are no universally agreed upon methods for using trace-gas flux chambers, and there is growing research into the field particularly with respect to flux calculations from closed chambers. Research in Wisconsin using closed static chambers on monoculture switchgrass, continuous corn, and hybrid poplar over a production season (May – August) showed 27 to 32% higher CO_2 fluxes and 28 to 33 % higher N_2O fluxes in all crops using the HMR non-linear flux calculation versus the linear approach (Duran & Kucharik 2013). We did not see similar increases in CO_2 emissions using the non-linear method relative to the linear method, and our results show almost three times greater increases in N_2O emissions using the non-linear method. Their findings suggest that linear and HMR non-linear methods may be appropriate for deployment times under 15 minutes (as applied to our CO_2 fluxes), but that the HMR non-linear method is most appropriate for deployment times from 15 to 60 minutes (as applied to our N_2O and CH_4 emissions) (Duran & Kucharik 2013). A laboratory experiment on static chambers using coarse, medium, and fine textured sand across different soil moisture gradients found the linear flux calculation underestimated the CH_4 emissions by 33% relative to a reference flux, whereas no difference was observed in the non-linear calculation from the reference flux (Pihlatie et al. 2013). Our results showed almost 17 times greater increases in CH_4 emissions using non-linear flux calculations relative to linear flux calculations comparatively. Pihlatie et al. (2013) suggest that underestimations of fluxes decrease with increasing chamber size.

For subsequent analyses, to ensure a more conservative estimate of impact on net GWP of our GHG emissions, the *linear* regression CO_2 fluxes, the *non-linear* regression N_2O fluxes, and the *non-linear* regression CH_4 fluxes are reported.

3.3.2 Carbon dioxide

CO_2 fluxes were significantly higher from hedgerows compared to PFs for any time period but differences in hedgerow type could only be distinguished when comparing relative emissions. Mean production and non-production season CO_2 fluxes were 111% and 186% greater, respectively in hedgerows than PFs (Figure 3.3). The mean annual CO_2 fluxes for PH (59.24 $\pm$ 7.77 Mg CO_2 ha^{-1} yr^{-1}) and RH (49.56 $\pm$ 6.51 Mg CO_2 ha^{-1} yr^{-1}) were significantly greater than PPF (20.92 $\pm$ 3.28 Mg CO_2 ha^{-1} yr^{-1}) and RPF (25.45 $\pm$ 4.20 Mg CO_2 ha^{-1} yr^{-1}). PH had significantly greater ($p<0.05$) relative CO_2 flux (38.33 $\pm$ 6.91 Mg CO_2 ha^{-1} yr^{-1}) than RH (24.10 $\pm$ 4.10 Mg CO_2 ha^{-1} yr^{-1}).

The differences observed between the bi-monthly means for each management option and the sample dates throughout the entire year (Figure 3.4) were significant ($p<0.0001$). An interaction effect between management option and sample date was observed ($p<0.05$). The mean bi-monthly fluxes observed throughout the year ranged from 0.06 to 10.70 μmol CO_2 m^{-2} s^{-1}.

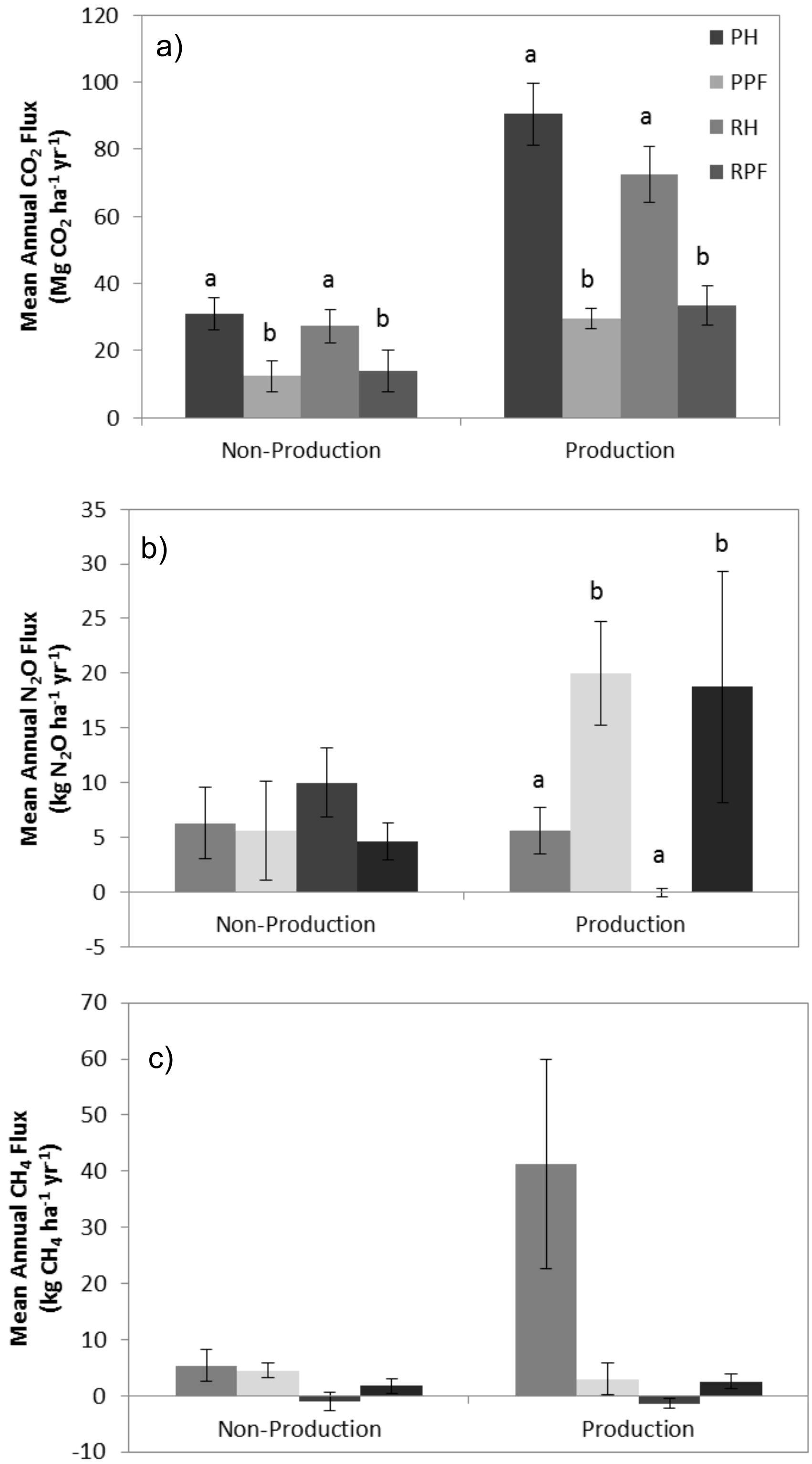

Figure 3.3. Annual mean CO_2 (a), N_2O (b), and CH_4 (c) fluxes calculated for the non-production (November to April) and production (May to October) seasons for planted hedgerows (PH), production fields neighbouring planted hedgerows (PPF), remnant hedgerows (RH), and neighbouring production fields remnant hedgerows (RPF). Column with different letters indicate significant differences ($p<0.05$) and error bars represent standard error.

A range of results of CO_2 emissions have been observed from temperate agroforestry systems. Wotherspoon et al. (2014) measured the soil CO_2 efflux from five different intercropping tree species in southern Ontario over the production season, and found emissions varied between 21.49 $\pm$4.50 and 22.91 $\pm$4.01 Mg CO_2 ha^{-1} yr^{-1} below different tree types, which are substantially lower than our observed emissions, while a neighbouring conventional cropping systems emitted only 16.77 $\pm$0.86 Mg CO_2 ha^{-1} yr^{-1}, which is comparable to PPF. Zhang et al. (2012) found significant differences between CO_2 emissions of two shelterbelt systems in temperate arid region in Northwest China, and drastic changes in annual emissions from one year to the next. They estimated mean annual emission rates ranged between 23.04 and 27.57 Mg CO_2 ha^{-1} yr^{-1} for shelterbelts planted with *U. pumila*, and 40.90 and 62.87 Mg CO_2 ha^{-1} yr^{-1} for those planted with *Populus* for the two years of the study respectively (Zhang et al. 2012). Their year-two results are similar to our hedgerow findings and support the need for multi-year data collection to validate results. Last, a number of the hedgerows in this study were located next to drainage ditches (Table 3.2), which may have also influenced the emissions observed as a result of temperature and moisture influences by the ditch. However, in a drained peat harvesting study in Sweden, it was found that ditches did not greatly affect CO_2 emissions which ranged from 2.3 to 10.0 Mg CO_2 ha^{-1} yr^{-1} (Sundh et al. 2000).

Since PH had significantly greater soil C than RH (Chapter 2), increased available C may be the cause of increased soil respiration. This may be the result of PH having greater tree and shrub species diversity (Chapter 2) which may alter substrate quality or increase available N through N-fixing plants, thereby increasing soil organism abundance and heterotrophic respiration relative to RH (Spehn et al. 2000; Schipper et al. 2001). While RH did have proportionally greater N-fixing red alder trees compared to PH, soil improving ground cover crops such as N-fixing clover are typically planted at the establishment of PH which may have contributed to higher CO_2 and N_2O in PH compared to RH.

There are a number of reasons for the differences observed between CO_2 fluxes in hedgerows and PFs over the annual, 6-month, and bi-monthly periods. Both increased rates of plant residue contribution and residue quality affect CO_2 emissions (Wang et al. 2013). Hedgerows have greater soil C from perennial litter fall and root exudation, which may explain the higher CO_2 emissions relative to PFs throughout the year; however, this was only true for PH in this study (Chapter 2). In addition, soil temperature and soil water content can significantly affect CO_2 emissions from agroforestry systems (Wang et al. 2013). CO_2 emission occur at their maximum typically when water-filled pore space is around 60% and temperature is between 25-30^{o}C (Brady & Weil, 2010). Hedgerows tended to have lower soil temperatures (Figure 3.7a) yet greater CO_2 emissions relative to production fields for the production season; emissions in this study were likely dominated by C inputs to the system (hence greater emissions from hedgerows despite lower temperatures), and thus temperature is not a driving mechanism. The soil moisture regime over the year was not very different for the management options, but still influences CO_2 emissions. Other noteworthy occurrences of greater CO_2 emissions of PPF and RPF relative to PH and RH observed the last week in April and the first week in May (Figure 3.4), may be the result of oxygen being introduced into the PF soil as a result of receding water levels and tillage enabling respiration (Teh et al. 2011).

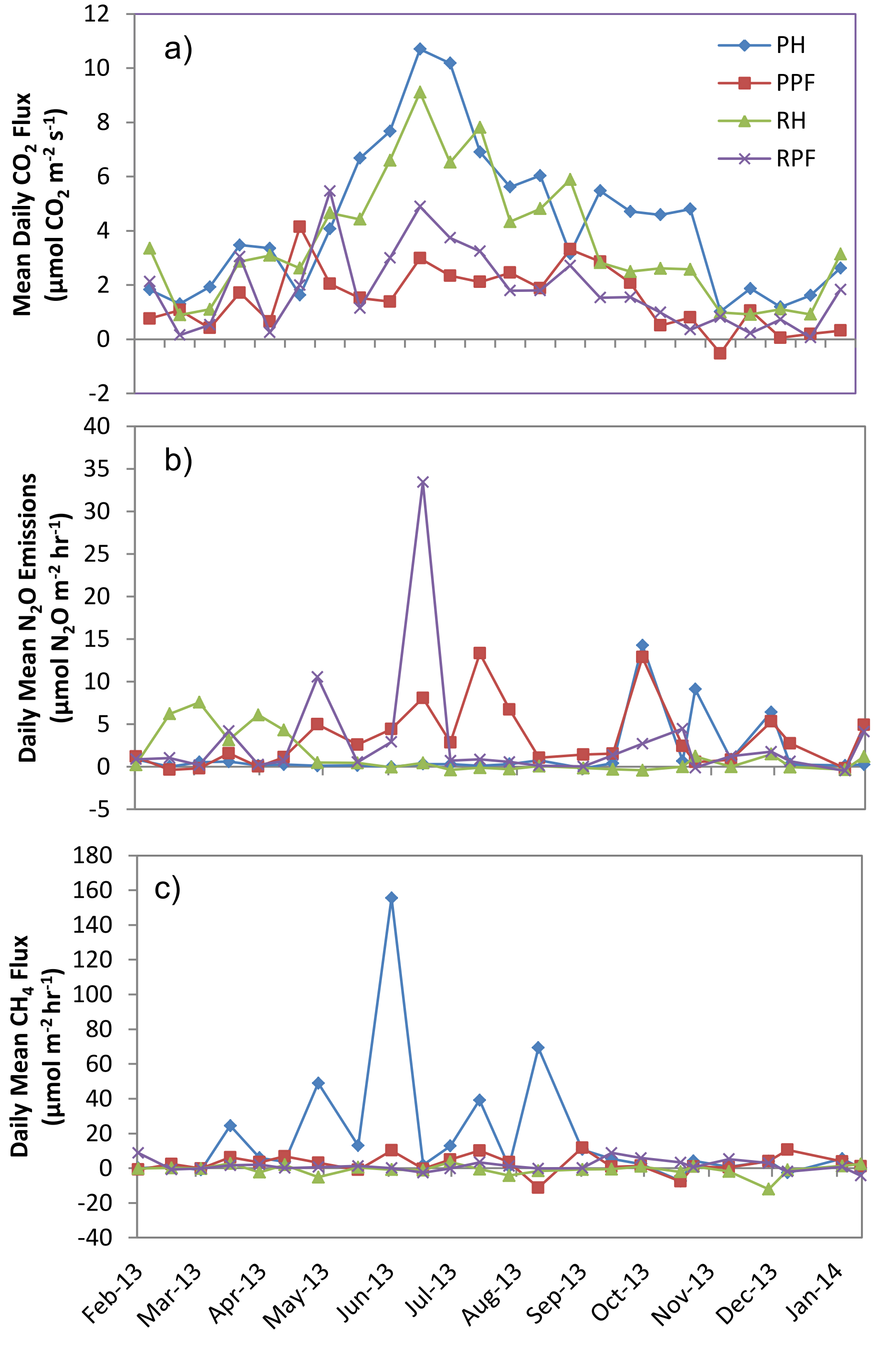

Figure 3.4. Daily mean (n=4) a) CO_2 fluxes measured in µmol CO_2 m^{-2} s^{-1}, b) N_2O fluxes (µmol N_2O m^{-2} s^{-1}), and c) CH_4 fluxes (µmol CH_4 m^{-2} s^{-1}) over a twelve month period for planted hedgerows (PH), production fields neighbouring planted hedgerows (PPF), remnant hedgerows (RH), and production fields neighbouring remnant hedgerows (RPF).

3.3.3 Nitrous Oxide

There were large seasonal differences in N_2O flux between hedgerows and PFs, but no differences between the hedgerow types. Due to high variability in N_2O emissions, the statistics were run on log transformed data; mean 6-month production season N_2O fluxes were 607% higher in the PFs compared to the hedgerows ($p<0.05$) but no differences were observed in the non-production season (Figure 3.3). The mean annual N_2O fluxes for PH (5.92 ± 2.73 kg N_2O ha^{-1} yr^{-1}), RH (4.96 ± 1.86 kg N_2O ha^{-1} yr^{-1}), PPF (12.81 ± 2.96 kg N_2O ha^{-1} yr^{-1}), and RPF (11.68 ± 5.42 kg N_2O ha^{-1} yr^{-1}) were not statistically different. Similarly, the relative N_2O flux of PH and RH were not statistically different.

Over the course of the year we did not see significant differences in the bi-monthly observations of N_2O emissions between the management options, we did however see large differences ($p<0.05$) between sampling times and a significant interaction effect between treatment and sample date observed ($p<0.05$). The mean bi-monthly fluxes range from 0 to 33.43 µmol N_2O m^{-2} hr^{-1} (Figure 3.4).

Our seasonal and annual mean N_2O emissions results are comparable to those found in other temperate forest and agricultural systems. In a temperate forest in Northern Europe, Christiansen et al. (2012) observed that the majority of N_2O fluxes measured over a two-year period were below 6.81 kg N_2O ha^{-1} yr^{-1}. Similarly, 81% of our mean bi-monthly observations in hedgerows in this study were below this value. A meta-analysis of agricultural systems reports flux ranges much higher than in forested systems. For example, in Quebec, fluxes from tilled silty clay loams ranged from 6.29 to 11.75 kg N_2O ha^{-1} yr^{-1}, and fluxes from both tilled and no-till barley fields in a clay soil ranged from

10.2 to 34.66 kg N_2O ha^{-1} yr^{-1} and 20.2 to 73.7 kg N_2O ha^{-1} yr^{-1}, respectively over a three year period (Rochette, Worth, Lemke, et al. 2008). Similarly, 98% of our values were below the maximum value reported of 73.7 kg N_2O ha^{-1} yr^{-1}.

No differences were observed in N_2O emissions from PH and RH over the year, though RH emissions did drop substantially in the production season relative to PH (Figure 3.3). Though no differences in total soil N were observed between hedgerows types (Table 3.1), differences in N_2O emissions may be the result of increased N contribution to the surface of labile organic pool (through more diverse plant litter) relative to the recalcitrant N pool of PH relative to RH (Thevathasan & Gordon 2004).

Table 3.1. Summary of soil properties from the 0-20 cm soil depth for planted hedgerows (PH), production fields neighbouring planted hedgerows (PPF), remnant hedgerows (RH), and production fields neighbouring remnant hedgerows (RPF). Values in brackets represent standard error, and different letters indicate significant differences ($p<0.05$).

Treatment	Bulk Density (kg m^{-3})	Total C (t C ha^{-1})	Total N (t N ha^{-1})	C:N	pH (water)	pH (1:3 $CaCl_2$)
			0-20 cm			
PH	1071.0 (98.8) a	59.80 (3.93)a	4.61 (0.26) a	12.9 (0.2) ab	4.9 (0.5) a	4.6 (0.5) a
PPF	1242.6 (58.7) b	48.57 (3.58)b	4.05 (0.28) a	12.0 (0.3)a	5.5 (0.3) a	5.1 (0.3) a
RH	1196.5 (104.7) ab	47.41 (4.97) ab	3.56 (0.39) a	13.8 (0.5) b	4.7 (0.2) a	4.2 (0.3) a
RPF	1247.6 (95.7) ab	46.56 (3.85) ab	3.88 (0.26) a	11.6 (0.5) a	5.5 (0.3) a	5.1 (0.3) a

PPF and RPF had significantly greater N_2O emissions than hedgerows in the production season, which is likely the result of broadcast fertilizer applications typical of this farming system (Figure 3.3). High peaks in RPF's N_2O mean bimonthly flux relative to PPF, such as the 313% higher N_2O emissions in June 2013, likely correspond to the spring applications of fertilizer to the PF. Recommended applications rates for the different crops found in RPF range from 50 to 140 kg N/ha (Painter 2009, Yang et al. 2009) compared to the PPF where the recommended application rates range from only 27.5 to 75 kg N/ha (BC Ministry of Agriculture Production Guide 2012) (Table 3.2).

Table 3.2. The 2004-2013 summer crop and winter management history of production fields including recommended regional fertilizer recommendations (Painter 2009, Yang et al. 2009, BC Ministry of Agriculture Production Guide 2012).

Farm #	Summer	Winter	2013 Crop	Neighbouring a Ditch	Regional Fertilizer Recommendations (kg N/ha)
Farm 1	barley/forage (2)[1], hay (2), pasture (2), potatoes (4),	cover (5), forage (1), hay (2), pasture (2)	barley/ forage	yes	90
Farm 2	barley/forage (2), cabbage (2), hay (2), pasture (2), potatoes (2)	cover (5), forage (1), hay (2), pasture (2)	barley/ forage	no	90
Farm 3	beans (1), cabbage (1), grain (4), peas (2), potatoes (2)	cover (6), fallow (4)	grain	yes	50
Farm 4	corn (2), hay (1), grain (4), potato (3),	cover (1), fallow (9)	corn	yes	140
Farm 5	beans (4), peas (2), potatoes (4)	cover (7), fallow (3)	beans	no	27.5
Farm 6	beans (6), peas (2), potatoes (2)	cover (8), fallow (2)	beans	no	27.5
Farm 7	grassland (3), hay (4), potatoes (3)	fallow (7), grassland (3)	potatoes	no	75
Farm 8	beans (4), peas (2), potatoes (4)	cover (8), fallow (2)	beans	no	27.5

[1]Brackets indicate number of years in specified production type

Fertilizer is a major source of N_2O emissions in both forests and agricultural systems (Jassal et al. 2008b; Rochette, Worth, Huffman, et al. 2008). When soils are aerated, ‘reactive nitrogen’ (Galloway et al. 2008) ammonium (NH_4^+) converts to nitrite (NO_2^-) then to nitrate (NO_3^-) and N_2O is released as a by–product in both steps. Under anaerobic conditions, NO_3^- can be reduced to nitrogen gas (N_2) also releasing N_2O as a by-product, consequently water filled pore space can be an indicator of N_2O emissions. One study from Scotland found in intensively managed (high-input fertilizer) agricultural systems, coincidence of fertilizer applications and major rainfall or irrigation events resulting in water-filled pore space of 70-90% resulted in greatest N_2O emissions, indicating that denitrification is a major source of N_2O loss from these systems (Dobbie & Smith 2003). In areas such as Delta, where agriculture is likely to be heavily fertilized, irrigated and susceptible to flooding from major rainfall events, N_2O emissions will continue to be a major concern. Globally N_2O emissions are expected to increase by

35-60% by 2030 as a result of increased fertilizer use and animal manure production (Smith et al. 2007).

3.3.4 Methane

Fluxes for CH_4 were variable for hedgerow types and production fields, and PH however strongly influenced by one site where emissions were substantially higher than all other sites. No significant differences ($p<0.05$) in CH_4 fluxes were observed between hedgerow or production field management options for the 6-month production and non-production season (Figure 3.3). Similarly, the mean annual CH_4 emissions for PH (23.35$\pm$ 9.93 kg CH_4 ha^{-1} yr^{-1}), PPF (3.75 $\pm$ 1.53 kg CH_4 ha^{-1} yr^{-1}), and RPF (2.15 $\pm$ 0.91 kg CH_4 ha^{-1} yr^{-1}), and the mean annual CH_4 consumption for RH (-1.17 $\pm$ 0.9 kg CH_4 ha^{-1} yr^{-1}) were not statistically different. Bi-monthly mean fluxes ranged from -12.1 to 155.6 µmol CH_4 m^{-2} hr^{-1} (Figure 3.4), yet management options, sample dates, or an interaction between the two fixed effects were not significant factors affecting bi-monthly mean fluxes.

CH_4 activity was highly variable between sites. While 88% of our bi-monthly observations fell within a range of -7.1 to 138.6 kg CH_4 ha^{-1} yr^{-1} observed by a meta-analysis of 5000 chambers from a variety of soils and ecosystems in the United Kingdom (Levy et al. 2012), 11% of the remaining observations demonstrated uptake of -7.2 to -78.7 kg CH_4 ha^{-1} yr^{-1}, while 1% of the observation (all from one PH site) demonstrated exceptionally high emissions (224.2 to 1286.5 kg CH_4 ha^{-1} yr^{-1}). Substantial differences in CH_4 fluxes between PH and RH are a result of the influence of the anomalous PH site; the maximum emissions observed from this site are similar to saturated peatland systems that have recorded maximum fluxes of 395.1 kg CH_4 ha^{-1} yr^{-}

[1] (Koebsch et al. 2013), and wetlands from the Clay Belt of northeastern Ontario where CH_4 emissions from a saturated marsh reached 1276.8 kg CH_4 ha^{-1} yr^{-1} during the summer (Bubier & Moore 1993).

Our observations of CH_4 consumption in RH are expected, as agroforestry systems have been reported to act as CH_4 sinks more effectively than production fields (Mutuo et al. 2005). Non-production areas typically have lower bulk density and granular pore spaces relative to production areas enabling methanotrophs to oxidize CH_4 resulting in CH_4 uptake into the soil system. We had expected to see greater CH_4 emissions from production areas particularly in the winter months when fields are saturated (Figure 3.7b); however, methanogens which cause the release CH_4 from anaerobic environments may have been affected by cooler non-production season temperatures. In the winter months too, hedgerows tended to have lower WFPS (Figure 3.7b) which may be the result of improved porosity compared to PFs as a result of larger water stable aggregates (Chapter 2) contributing to a porous soil structure.

3.3.5 Global Warming Potential

To better understand the combined contribution of the three gases we converted them to CO_2-equivalent emissions (Figure 3.5). To determine the CO_2e of N_2O and CH_4, both of which have greater radiative forcing and residence times in the atmosphere, their quantities were multiplied by a factor of 298 and 25 respectively (Forster et al. 2007). CO_2 contributed the majority of GHG emissions in all four management options, while N_2O and CH_4 played minor roles. PH had significantly greater GHG emissions relative to PPF and RPF, but not RH. RH had significantly greater emissions than PPF only, while both PFs were not different.

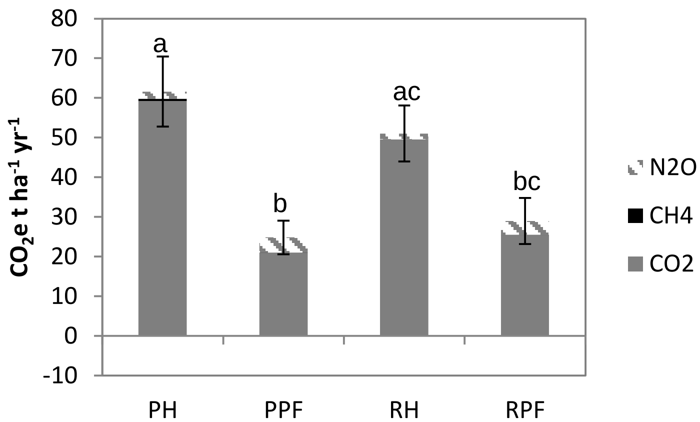

Figure 3.5. Mean annual CO_2e of CO_2, N_2O, and CH_4 fluxes measured over one year from the soil of planted hedgerows (PH), remnant hedgerows (RH) and their neighboring production fields (PPF and RPF). Error bars represent standard error. Letters represent signifcant differences ($p<0.05$). Note CH_4 shows as thin sliver.

3.3.6 Environmental properties affecting GHG emissions

Annual means observed in 2013 for rainfall (1040.8 $\pm$ 77.4mm) and temperature (10.7 1$\pm$0.7 ^{o}C) were similar to the 30-year historical averages (1227.8 $\pm$91.2 mm; 10.6 $\pm$1.5 ^{o}C), however the distribution of the precipitation was not typical (Figure 3.6). Substantially less rainfall was observed in July, October, November and December, and substantially greater rainfall was observed in September compared to historical averages (Figure 3.6b).

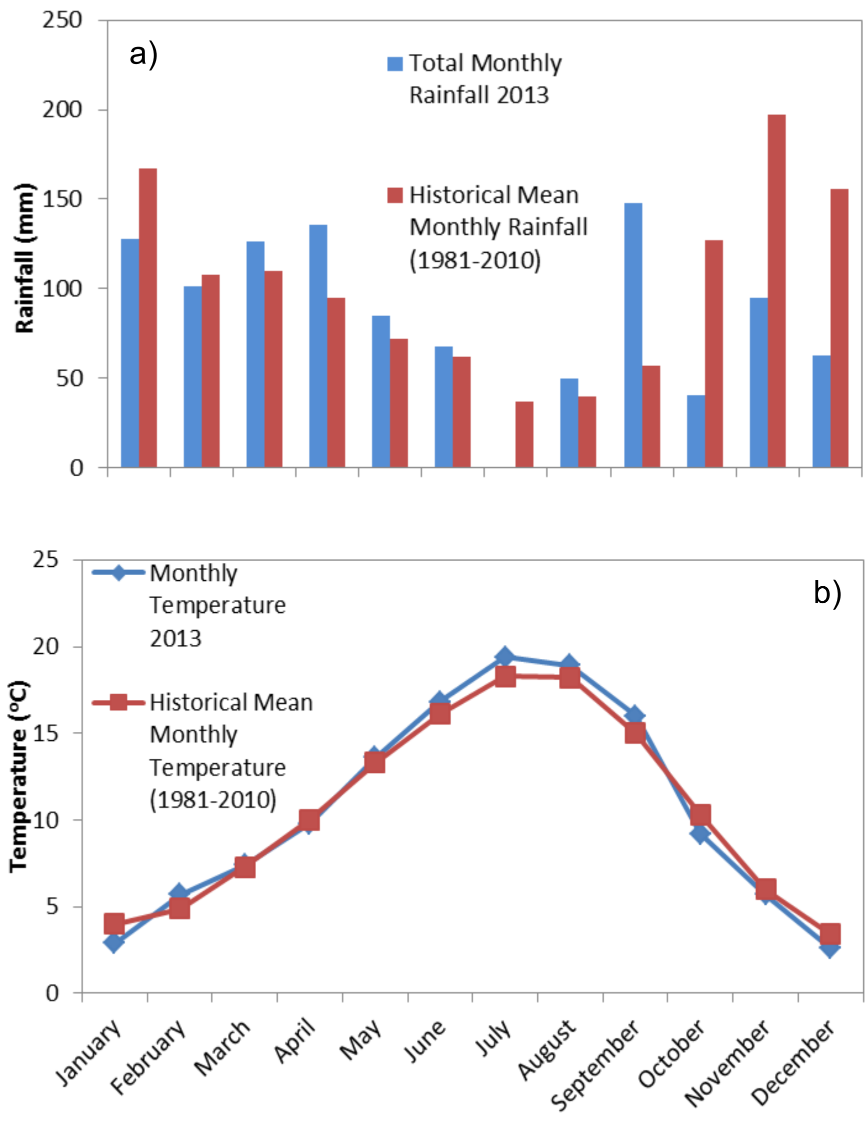

Figure 3.6. Comparison of a) total monthly rainfall in 2013 to historical mean annual rainfall (1981-2010) and b) mean monthly temperature in 2013 to historical mean monthly temperature from Richmond Nature Park, BC Weather Station.

The soil temperature and WFPS in the 0-5 cm depth were variable throughout the year between management options (Figure 3.7). The mean annual soil temperatures were 13.4 $\pm$ 1.8 ^{o}C, 14.2$\pm$ 1.6 ^{o}C, 16.0 $\pm$ 2.2 ^{o}C, and 17.0$\pm$ 2.0 ^{o}C for PH, RH, PPF and RPF respectively, and were not significantly different. The mean bi-monthly temperatures ranged from 0.60 ^{o}C to 35.66 ^{o}C (Figure 3.7a). In the spring and summer months, the PFs tended to have higher temperatures than the hedgerows, however in the winter months, the mean bi-monthly temperatures were comparable. Typically, increases in soil temperature have a positive correlation with increases in trace gas fluxes because microbial activity and photosynthesis is stimulated (Brady & Weil 2010).

The mean annual WFPS space was 32.1 $\pm$ 2.3 %, 36.5 $\pm$ 3.1 %, 39.9 $\pm$ 3.9 %, and 40.4 $\pm$ 4.1% for PH, RH, PPF, and RPF respectively, and were similarly not significantly different. The bi-monthly means ranged from 2.3 % to 76.0%. The WFPS tended to be lower in the hedgerows than the PFs Variations in soil water content levels affect gas emissions in different ways – for instance, it has been observed in forest systems that N_2O has higher emissions when water content ranges from 40-60% (likely as a result of denitrification), while CH_4 emissions were only be observed at water content ranges above 45% (likely as a result of methanogenesis) (Christiansen et al. 2010).

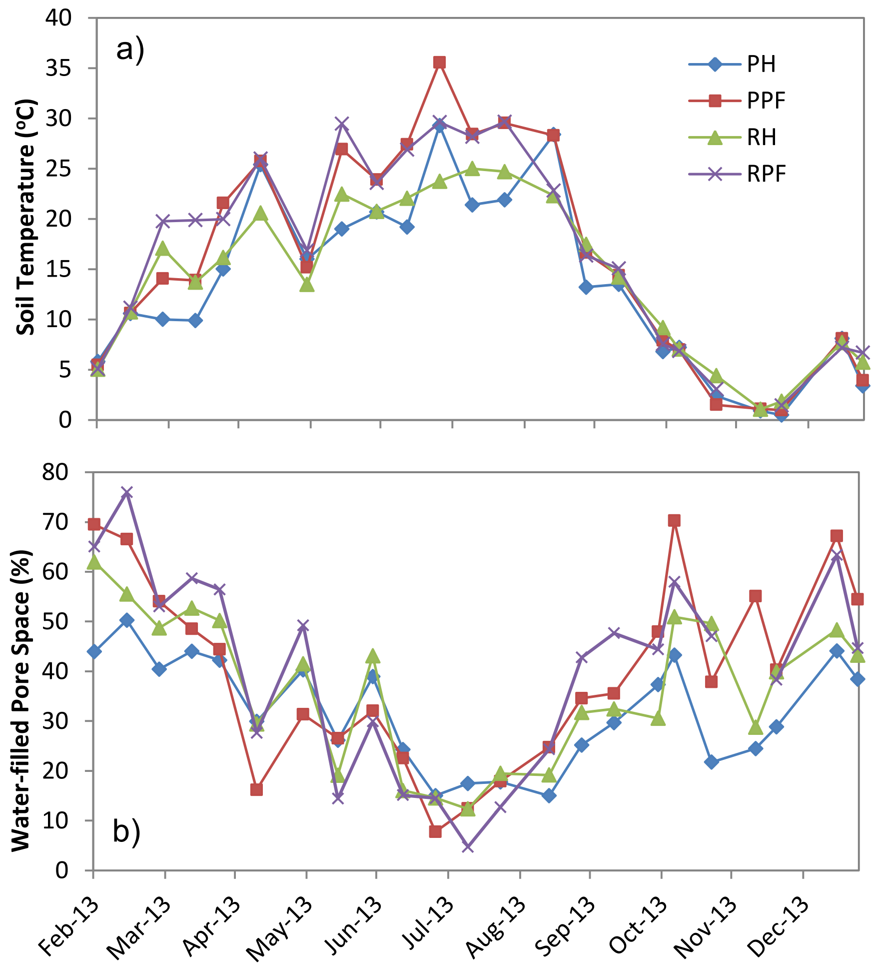

Figure 3.7. Mean daily a) soil temperature (^{o}C) measurements and b) water-filled pore space (%) measurements from sample days from 0-5 cm from planted hedgerows (PH), production fields neighbouring planted hedgerows (PPF), remnant hedgerows (RH), and production fields neighbouring remnant hedgerows (RPF).

A correlation analysis of the mean annual fluxes for each hedgerow and PF plot illustrated some significant relationships between environmental properties and GHG fluxes. Mean annual CO_2 flux was negatively correlated (R^2 = -0.57; p=0.022) with soil temperature in the top 0-5 cm of the soil and positively with the mean weight diameter of soil aggregates (R^2=0.63; p=0.009) (data not shown). A negative correlation between CO_2 emissions and soil temperature is surprising, given warmer temperatures are typically associated with positive and exponentially greater soil respiration (Wang et al. 2013). In this study, lower soil temperatures were observed in the hedgerows which may be a result of shading from the closed tree and shrub canopy. Higher CO_2 fluxes are likely largely driven by the greater concentrations of soil C from more abundant and diverse plant residues observed in the PH which in turn could have resulted in higher levels of autotrophic and heterotrophic respiration despite lower temperatures. While the relationship between total soil C and CO_2 flux was not strong, nor significant, the relationship between soil C and MWD was significant (R^2=0.68; p=0.009). Greater MWD improves the soil porosity in the hedgerows relative to production fields, likely as a result of increased organic matter inputs and reduced mechanical disturbance (i.e. tillage), which could have led to increased CO_2 emissions.

Mean annual N_2O flux was marginally significantly (R^2=0.49; p=0.053) correlated with total soil C in the 0-20 cm layer. More available N for plant uptake allows for better plant growth which could translate into greater litter fall and root exudation increasing soil C (Jassal et al. 2008b).

CH_4 had a marginally significant correlation (R^2=0.49; p=0.056) with water-filled pore space in the 0-5 cm layer. No other significant correlations were observed. CH_4 emissions are often correlated with moist environments in which methanogenesis can occur (Levy et al. 2012). Given the hedgerows seemed to be better drained particularly in the winter months, likely due to plant uptake as well as improved soil structure as a result of greater water stable aggregates for example, it is unusual that PH has such high CH_4 emissions. A number of hedgerows were flanked by ditches on one side which may increase total CH_4 emissions as a result of pooling water and relatively high water tables in those areas. One study in a peatland system found CH_4 emissions were always considerably higher in ditched areas than non-ditched areas, and ranged from 96.4 to 2190 kg CH_4 ha^{-1} yr^{-1} and -0.9 to 87.6 kg CH_4 ha^{-1} yr^{-1} respectively (Sundh et al. 2000).

A correlation analysis was also developed for the relative GHG emissions for PH and RH versus species richness and the Shannon and Simpson indices; however, no statistically significant relationships were observed.

3.4 Summary and Conclusions

In the one-year study of GHG fluxes in the lower Fraser River delta of British Columbia, we observed important difference between static chamber flux calculations methodologies, differences in emissions among planted hedgerows, remnant hedgerows, and production fields, and identified some key environmental variables that explain the variation in fluxes. The methods for calculating the flux rates from closed-static chambers in PH, RH, and PF were not significantly different for CO_2; however, substantial and significant differences were observed between linear and non-linear estimations for N_2O and CH_4. Large difference between hedgerow GHG fluxes and PF were observed particularly in the production season. Over the course of the year, CO_2 emissions were 135% higher in hedgerows than in PFs. Alternatively, in the production season N_2O was 607% higher in the PFs than the hedgerows. No significant differences were observed for CH_4 flux in either production or non-production period. When comparing the relative emissions of the two types of hedgerows, CO_2 fluxes were 59% higher in PH than RH, but both N_2O and CH_4 did not have significantly different relative fluxes. The environmental variables that explained the variation seen in fluxes differed among gases. For CO_2 emissions were significantly correlated with soil temperature and mean weight diameter. N_2O and CH_4 fluxes had marginally significant correlations with soil C and water-filled pore space of the soil, respectively.

The results reported here are critical for calculating the net climate change benefit of planting or preserving hedgerows. These data combined with soil and biomass C sequestration rates enable the calculation of net global warming potential. This information is valuable in making land use decisions on agricultural systems for climate change mitigation, as it stresses the need to ensure that the soil and woody vegetation carbon sequestration match the emissions generated from these zones. Finally, this information is valuable for the DF&WT, as it informs the organization about the GHG contribution of their hedgerow systems, one of the many impacts including hedgerows will have on the regional agricultural landscape.

4 GENERAL SUMMARY AND CONCLUSIONS

4.1 Research Conclusions

Land use management options in agricultural landscapes, particularly in the lower Fraser River delta, are numerous and sometimes produce conflicting results. There are a number of different types of stakeholders in the region including farmers, conservation groups, government bodies, and the general public, who may have divergent land use management objectives. The Delta Farmland & Wildlife Trust seeks to optimize environmental and production outcomes for agricultural land, which requires a better understanding of the environmental function of management options. Understanding the environmental benefit of planting new, or preserving remnant hedgerows, specifically quantifying their climate change mitigation potential, will help to make land management decisions that will have greatest overall benefit. This study contributed to a better understanding of the environmental outcomes of land two management options in Delta by quantifying key components for determining the mitigation potential of planted and remnant hedgerows relative to their neighbouring production fields.

4.1.1 Hedgerow Biomass and Soil Carbon

As expected we found that PH and RH differed in a number of ways but surprisingly not in their biomass C storage. There were no significant differences in overall tree and shrub biomass C between the two hedgerows types. On average, PH stored 76.2 $\pm$ 32.3 t C ha^{-1} and RH 124.0$\pm$ 20.9 t C ha^{-1}, representing a sizable C pool in the agricultural landscape. While our hypothesis that greater species diversity in planted hedgerows would result in increased soil C was supported by our findings, increased tree and shrub diversity did not correlate with increased biomass C. Nor did tree and shrub diversity (specifically Shannon and Simpson indices) correlate with aggregate stability either overall MWD or size class distribution of aggregates. Though both PH and RH had greater aggregate stability than neighbouring production fields, counter to our hypothesis, PH did not have greater aggregate stability than remnant hedgerows. The intentional diversification of planted hedgerows resulted in significantly greater tree and shrub species diversity, 75% greater richness, 160% greater Simpson diversity, 171% greater Shannon's diversity compared to remnant hedgerows. It is clear that hedgerows planted for increased species diversity store more soil C than RH and that overall hedgerows contribute a sizeable amount to landscape C storage density. The overall climate change mitigation potential of PH and RH is less clear given the results of soil greenhouse gas emissions.

4.1.2 Greenhouse Gas Emissions

The results for GHG emissions were complicated and variable, which may partly be a result of the locations of PH and RH not being random. Mean annual CO_2 emissions were higher in PH than in RH, but the two hedgerow types did not differ in N_2O or CH_4 fluxes. On average, hedgerows had 135% higher CO_2 emissions than PF, 607% lower N_2O emissions, and no significant difference in CH_4.

Our analysis showed that there were a number of measured environmental properties that were correlated with GHG emissions. Mean annual CO_2 fluxes correlated with aggregate stability and soil temperature, N_2O with soil C, and CH_4 with water-filled pore space (Chapter 3). While these correlations help elucidate the mechanisms that mediate emissions they do not translate into conclusions necessarily relevant for management of hedgerows.

4.2 Findings and Further Research

The result presented here contribute to a better understand of the relative environmental outcomes specifically the climate change mitigation potential of planting new or protecting remnant hedgerows. The data produced here will enable landscape level analyses that can scale results from a per hectare density to account for the relative sizes and distribution of hedgerows and production fields. The carbon densities and emissions reported here must be kept in the context that production fields take up substantially more of the landscape than planted and remnant hedgerows combined. Although these results could contribute to estimates of the overall global warming potential (GWP) of both hedgerow types as well as their neighbouring production fields they do not capture all of components required for an accurate determination of GWP. While we have captured one year of GHG emissions data from a relatively normal rainfall year, given the highly variable nature of fluxes an accurate GWP estimation would require multiple years of analysis. Further, we have established C stocks for hedgerow types but our understanding of annual sequestration rates are limited. For all of the PH we have data on age and thus can determine average annual biomass accumulation. We do not have accurate data on the age of RH, which has been estimated using aerial photos. Net changes in soil C are even more uncertain. To account for the limitations of only one time point for soil C we compared hedgerow types to their neighbouring production fields but this does not provide an accurate estimate of annual net change.

If we were to estimate GWP from these data, we actually see no significant differences between hedgerows and the production fields. By converting our tree and shrub woody biomass C to time averaged CO_2e, we could assume that biomass C is sequestered at an equal rate each year to divide the total biomass C by the age of the hedgerows. To convert our soil C data into a time averaged CO_2e sequestration rate, we could assume that any differences in the soil C observed in hedgerows relative to their neighbouring production fields would be a direct result of the presence of the hedgerows. The annual C sequestration rate would thus be determined by using the relative soil C (which was positive for PH but negative for RH) and dividing it by the age of the hedgerows. Using these data in this was to estimate GWP illustrates that of all the management options would be positive, indicating net CO_2e emissions from both production fields and hedgerows. Thus it is important that further data be collected before making conclusions on the net climate change mitigation potential of hedgerows in Delta.

4.2.1 Strengths and Challenges of the Research

Conducting research on operational farms presents both opportunities and limitations. A major strength of this research is that we collected data from operational on-farm sites. It is often difficult to find operators, producers, or land owners that are willing to provide access to their property for research purposes, which makes information from these ecosystems limited. Yet, data from these systems is important since replicating the complexity of interactions in a controlled laboratory or research station environment is arguably impossible. Further, this study contributes soil GHG emission data for CO_2, N_2O, and CH_4 for an entire year, something that has not been done in this region on hedgerows. Often soil greenhouse gas research is limited to studying the mechanisms of one specific gas or is limited to only seasonal data collection.

This study also raised a number of challenges. By working on operational farms we did not have control over a number of variables that could have impacted the data. For example, though we attempted to reduce the variability in land management by limiting our farm selection to a specific crop (potatoes in 2012), producers were on different crop rotations which resulted in a diversity of crops grown in our production fields in 2013. We also were not able to collect information on other management practices that could have affected the results including irrigation and drainage, tillage, herbicide, pesticide, or fungicide usage which limits our understanding of the differences observed. Further, the age of remnant hedgerows were not precisely known, affecting estimations of soil and biomass C sequestration. And last, a short period of time for data collection may have affected the variability seen from weather and seasonal (crop growth) changes, which could be reduced by a longer sampling period.

4.2.2 Overall Contribution of the Thesis Research to the Field of Study

This study contributes to the GWP analysis of agricultural landscapes – the balance of CO_2 sequestration in the soil and biomass of woody vegetation, and the CO_2e emissions of GHGs from the soil. To date, little research quantifies the GHG emissions from non-production hedgerows and none to our knowledge in temperate deltaic farmland systems. Although there have been several studies that quantify above ground biomass C and soil C from agroforestry systems (Udawatta & Jose, 2012), few focus on non-production hedgerows, particularly in temperate deltaic areas. These data provide information that can help assess the impact that land use changes can have on the climate change mitigation potential from farm-level to the landscape. The research also provides a more complete picture on which mechanisms affect C storage and GHG emissions in these systems, and how to quantify these effectively for conservative estimates for modelling.

4.2.3 Future Research Directions in the Field

Though quantifying C storage and GHG emission are important, it is critical when evaluating the climate change mitigation potential of these systems to understand other components as well. Future research should focus on measuring C sequestration rates in the soil and woody biomass. The data collected for the 12-month sampling period for CO_2, N_2O and CH_4 reveal some valuable insights into patterns of emissions that may be typical of this landscape, but need to be validated. The emission rates show spatial and temporal variability that confirm the complexity of quantifying this component of the global warming potential of hedgerows, and further research will be needed to assess the ranges of net annual emission of all three gases.

4.2.4 Implications for the Delta Farmland and Wildlife Trust

The overall aim of this project was to help the Delta Farmland & Wildlife Trust determine how to improve hedgerow management on farmland in the lower Fraser River delta to maximize positive environmental outcomes, specifically for climate change mitigation. Our research has shown planting new hedgerows with increased species diversity is likely to result in greater C sequestration than RH. It is, however, unclear whether there is a net climate change mitigation benefit from planting new hedgerows given the large quantities of CO_2 emitted from the system. Moving forward, it is critical to remember that climate change mitigation is just *one* of the co-benefits of including hedgerows on farmland. To decide whether the planted or remnant management option is best under different circumstances, total environmental value of each hedgerow type for the lower

Fraser River delta, including landscape diversity, habitat quality for birds and other biota, overwintering habitat for beneficial insects and birds, impact on hydrology, and impact on wind erosion, needs to be assessed for the ecosystem services they provide.

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APPENDIX

Species List and Allometric Equations

Species	Equation Type	Equation	Source	Original Source
Acer macrophyllum (bigleaf maple)	Species Specific	0.0302*DBH^2.723+0.01*DBH^2.574)+0.022*DBH^1.617+0.0129*DBH^2.43	Ter-Mikaelian 1997	Gholz 1979
Acer platanoides (Norway maple)	General Hardwood	0.0359*(DBH^2.0263)*(H^0.6987)+0.0094*(DBH^1.8677)*(H^0.6985)+0.0859*(DBH^1.8485)*(H^-0.5383)+0.0433*(DBH^2.6817)*(H^-0.5731)	Ung et al. 2008	
Acer rubrum (red maple)	Species Specific	0.1317*DBH^2.3199	Ter-Mikaelian 1997	Ker 1980
Alnus rubra (red alder)	Species Specific	EXP(5.13118+2.15046*LN(DBH))/1000	Helgerson 1988	
Betula papyrifera (paper birch)	Species Specific	0.0882*DBH^2.562	Ter-Mikaelian 1997	Schmitt and Grigal 1981
Cornus sericea (red osier dogwood)	General Shrub	0.0000082589*(Ellipsoid Volume)^3.7715+0.1627*(Ellipsoid Volume)^1.0247+EXP(1.0564*LN(Ellipsoid Volume)-0.6371*1.105213)+0.9284*(Ellipsoid Volume)^0.5542	Smukler et al. 2010	
Crataegus douglasii (black hawthorn)	General Shrub	0.0000082589*(Ellipsoid Volume)^3.7715+0.1627*(Ellipsoid Volume)^1.0247+EXP(1.0564*LN(Ellipsoid Volume)-0.6371*1.105213)+0.9284*(Ellipsoid Volume)^0.5542	Smukler et al. 2010	
Crataegus douglasii (black hawthorn)	General Hardwood	0.0359*(DBH^2.0263)*(H^0.6987)+0.0094*(DBH^1.8677)*(H^0.6985)+0.0859*(DBH^1.8485)*(H^-0.5383)+0.0433*(DBH^2.6817)*(H^-0.5731)	Ung et al. 2008	
Cupressus nootkatensis (yellow cedar)	Species Specific	0.2498*DBH^2.1118	Ter-Mikaelian 1997	Krumlik 1974
Cytisus scoparius (scotch broom)	General Shrub	0.0000082589*(Ellipsoid Volume)^3.7715+0.1627*(Ellipsoid Volume)^1.0247+EXP(1.0564*LN(Ellipsoid Volume)-0.6371*1.105213)+0.9284*(Ellipsoid Volume)^0.5542	Smukler et al. 2010	
Ilex aquifolium (holly)	General Hardwood	0.0359*(DBH^2.0263)*(H^0.6987)+0.0094*(DBH^1.8677)*(H^0.6985)+0.0859*(DBH^1.8485)*(H^-0.5383)+0.0433*(DBH^2.6817)*(H^-0.5731)	Ung et al. 2008	
Mahonia aquifolium (Oregon grape)	General Shrub	0.0000082589*(Ellipsoid Volume)^3.7715+0.1627*(Ellipsoid Volume)^1.0247+EXP(1.0564*LN(Ellipsoid Volume)-0.6371*1.105213)+0.9284*(Ellipsoid Volume)^0.5542	Smukler et al. 2010	
Malus fusca (pacific crabapple)	General Hardwood	0.0359*(DBH^2.0263)*(H^0.6987)+0.0094*(DBH^1.8677)*(H^0.6985)+0.0859*(DBH^1.8485)*(H^-0.5383)+0.0433*(DBH^2.6817)*(H^-0.5731)	Ung et al. 2008	
Philadelphus coronarius (mock orange)	General Shrub	0.0000082589*(Ellipsoid Volume)^3.7715+0.1627*(Ellipsoid Volume)^1.0247+EXP(1.0564*LN(Ellipsoid Volume)-0.6371*1.105213)+0.9284*(Ellipsoid Volume)^0.5542	Smukler et al. 2010	
Picea sitchensis (sitka spruce)	Species Specific	0.0402*DBH^2.552+0.003*DBH^2.78+0.0056*DBH^2.518	Ter-Mikaelian 1997	Bormann 1990
Populus trichocarpa (black cottonwood)	General Hardwood	0.0359*(DBH^2.0263)*(H^0.6987)+0.0094*(DBH^1.8677)*(H^0.6985)+0.0859*(DBH^1.8485)*(H^-0.5383)+0.0433*(DBH^2.6817)*(H^-0.5731)	Ung et al. 2008	
Rhamnus purshiana (cascara)	General Hardwood	0.0359*(DBH^2.0263)*(H^0.6987)+0.0094*(DBH^1.8677)*(H^0.6985)+0.0859*(DBH^1.8485)*(H^-0.5383)+0.0433*(DBH^2.6817)*(H^-0.5731)	Ung et al. 2008	
Ribes sp. (currant)	General Shrub	0.0000082589*(Ellipsoid Volume)^3.7715+0.1627*(Ellipsoid Volume)^1.0247+EXP(1.0564*LN(Ellipsoid Volume)-0.6371*1.105213)+0.9284*(Ellipsoid Volume)^0.5542	Smukler et al. 2010	
Rosa nutkana (nootka rose)	General Shrub	0.0000082589*(Ellipsoid Volume)^3.7715+0.1627*(Ellipsoid Volume)^1.0247+EXP(1.0564*LN(Ellipsoid Volume)-0.6371*1.105213)+0.9284*(Ellipsoid Volume)^0.5542	Smukler et al. 2010	
Rubus spectabilis (salmonberry)	General Shrub	0.0000082589*(Ellipsoid Volume)^3.7715+0.1627*(Ellipsoid Volume)^1.0247+EXP(1.0564*LN(Ellipsoid Volume)-0.6371*1.105213)+0.9284*(Ellipsoid Volume)^0.5542	Smukler et al. 2010	
Salix sp. (willow)	General Shrub	0.0000082589*(Ellipsoid Volume)^3.7715+0.1627*(Ellipsoid Volume)^1.0247+EXP(1.0564*LN(Ellipsoid Volume)-0.6371*1.105213)+0.9284*(Ellipsoid Volume)^0.5542	Smukler et al. 2010	
Sambucus racemosa (red elderberry)	General Shrub	0.0000082589*(Ellipsoid Volume)^3.7715+0.1627*(Ellipsoid Volume)^1.0247+EXP(1.0564*LN(Ellipsoid Volume)-0.6371*1.105213)+0.9284*(Ellipsoid Volume)^0.5542	Smukler et al. 2010	
Spirea douglasii (hardhack)	General Shrub	0.0000082589*(Ellipsoid Volume)^3.7715+0.1627*(Ellipsoid Volume)^1.0247+EXP(1.0564*LN(Ellipsoid Volume)-0.6371*1.105213)+0.9284*(Ellipsoid Volume)^0.5542	Smukler et al. 2010	
Symphoricarpos albus (snowberry)	General Shrub	0.0000082589*(Ellipsoid Volume)^3.7715+0.1627*(Ellipsoid Volume)^1.0247+EXP(1.0564*LN(Ellipsoid Volume)-0.6371*1.105213)+0.9284*(Ellipsoid Volume)^0.5542	Smukler et al. 2010	
Thuja plicata (western red cedar)	Species Specific	0.3721*DBH^1.2928+0.2805*DBH^1.3313+0.1379*DBH^1.5986	Ung et al. 2008	

Note: Diameter at Breast Height (DBH) is in cm; Height (H) is in m