IMPROVING ON-FARM WOODY HABITAT MANAGEMENT IN THE LOWER FRASER VALLEY

Final Project Report for the Investment Agriculture Foundation production except road and parcel

Improving On-Farm Woody Habitat Management in the Lower Fraser Valley

FINAL PROJECT REPORT FOR THE INVESTMENT AGRICULTURE FOUNDATION

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ABREVIATIONS

ALR	Agricultural Land Reserve
C	Carbon
CH_4	Methane
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalents
DF&WT	Delta Farmland and Wildlife Trust
ESM	Equivalent soil mass
GWP	Global warming potential
Ha	Hectare
LULC	Land use/land cover
Mg	Mega-gram or metric ton
MMU	Minimum Mapping Unit
MWD	Mean weight diameter
N	Nitrogen
N_2O	Nitrous oxide
PH	Planted hedgerows
PPF	Planted production fields
RH	Remnant hedgerows
RPF	Remnant production fields
UBC	University of British Columbia

EXECUTIVE SUMMARY

Woody habitat on and around farmland has been show to provide numerous, important environmental functions. To enhance the environment and provide habitat for a number of species of concern, the Delta Farmland and Wildlife Trust (DF&WT) established a Hedgerow Stewardship Program in 1993. This Program has resulted in planting of woody species as hedgerows along the edge of farm fields throughout the lower Fraser River Delta. While this Program has been highly successful in establishing new hedgerows, remnant hedgerows are now being removed from farm field margins extensively. The DF&WT's efforts may thus be better served encouraging farmers to maintain these areas of habitat that are already established but it is unclear which strategy is the most cost effective for optimizing environmental outcomes. To assess how best to improve hedgerow management the DF&WT has partnered with the University of British Columbia (UBC) researchers to quantify and compare the economic costs and environmental benefits provided by planted and remnant hedgerows and to communicate these results to key stakeholders. Specifically the research team set out to answer the following questions:

- Is the hedgerow-planting program offsetting the number of hectares of remnant hedgerows being cut down?
- Do planted hedgerows provide the same environmental function as remnant hedgerows?
- Could paying farmers to conserve remnant hedgerows under the existing DF&WT Hedgerow Program be a more cost effective way to ensure the availability of multiple environmental functions across the Delta region?

Results of this study have clearly answered each of these questions. The analysis of historical air photos from three time periods, 1966, 1986 and 2012 showed that while there was initially in decline, the overall the area of woody habitat has increased from 2.0% of the ALR in 1966 to 2.2% in 2012.

The analysis documented a clear difference in one key environmental function between hedgerows planted by the DF&WT and those that were remnant but found no differences for other functions. The analysis of potential future scenarios for perennial habitat across the ALR in the Delta also showed mixed results. This scenario analysis indicated that even if the DF&WT were to maximize its program and plant hedgerows on every farm field and road edge there would be no distinguishable increase in key ecosystem functions or indicators of habitat connectivity compared to a baseline

scenario. Our analysis does clearly show that if agricultural or urban development were to expand on the ALR there would be substantial losses in both key ecosystem function and indicators of habitat even with hedgerows, indicating the importance of perennial habitat beyond farm edges.

This study quantifies some of key environmental benefits of hedgerows but there are other benefits and potential costs that need to be quantified in order to fully understand the potential environmental and production tradeoffs of establishing hedgerows on the edges of fields. Better quantification of relative tradeoffs and potential synergies between environmental outcomes and agricultural production will help to provide clearer management recommendation and policy incentives that optimize multiple beneficial outcomes from agricultural landscapes.

1 INTRODUCTION

Woody habitat on and around farmland has been show to provide numerous, important environmental functions (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) established a Hedgerow Stewardship Program in 1993. This Program has resulted in planting of woody species as hedgerows along the edge of farm fields throughout the lower Fraser River Delta. While this Program has been highly successful in establishing new hedgerows, remnant hedgerows are now being removed from farm field margins extensively. The DF&WT's efforts may thus be better served encouraging farmers to maintain these areas of habitat that are already established but it is unclear which strategy is the most cost effective for optimizing environmental outcomes. To assess how best to improve hedgerow management the DF&WT has partnered with the University of British Columbia (UBC) researchers to quantify and compare the economic costs and environmental benefits provided by planted and remnant hedgerows and to communicate these results to key stakeholders. This study provides the analysis necessary to develop management strategies for on-farm woody habitat that will maximize multiple environmental outcomes for the lower Fraser River Delta. These strategies will be important not just to the DF&WT, but also to other stakeholders in the region and throughout Canada who seek to improve environmental outcomes on agricultural lands.

Problem or Opportunity

Agricultural production in the south-western coast of British Columbia has intensified substantially over the past 50 years. With that intensification has come the removal of hedgerows, namely trees and shrubs, from farmland. The presence of hedgerows on farms can pose a number of challenges to farmers, but also, opportunities. The vegetation can impose a cost on farmers because it occupies land that would otherwise be cultivated (lost opportunity cost) and it impedes drainage (e.g., roots blocking tile drains). For these reasons, many farmers have removed hedgerows to streamline their farm operations, despite the fact that these areas generally occupy a small percentage of the landscape (e.g.,~ 4% of agricultural land).

Hedgerows have the capacity to provide a number of environmental functions, including (but not limited to): windbreaks, improved landscape aesthetics, habitat for wildlife, soil biota and pollinators and other beneficial insects, carbon sequestration, and improved hydrology. Some of these functions have a direct value to the farmer, especially in the form of pest management and crop pollination. Other environmental functions benefit the general public, a group, who today have high expectations of the environmental functions that should be provided by farms.

Currently, there are two general types of hedgerows in the Delta. The first type includes large tracts of hedgerows that were either planted long before the DF&WT's Hedgerow Stewardship Program or were established without planting and are remnant of past landscape conditions. This type of hedgerow growing wild along field margins we consider ***remnant hedgerows***. The second type consists of ***planted hedgerows*** established under the DF&WT's Hedgerow Program. Costs for establishing planted hedgerows currently limits the amount of land that the DF&WT can facilitate within this Program. At the same time, farmers continue to cut down remnant hedgerows. This situation brings up a number of questions that are critically important for the future of the DF&WT program:

- Is the hedgerow-planting program offsetting the number of hectares of remnant hedgerows being cut down?
- Do planted hedgerows provide the same environmental function as remnant hedgerows?
- Could paying farmers to conserve remnant hedgerows under the existing DF&WT Hedgerow Program be a more cost effective way to ensure the availability of multiple environmental functions across the Delta region?

Objectives

The overarching goal of this study was to determine how best to improve hedgerow management in the lower Fraser River Delta to maximize positive environmental outcomes. To do this we quantified both ecologically and economically the costs and benefits of *remnant* and *planted* hedgerow management, relative to neighbouring production fields (PF). This analysis provides the DF&WT with information critical for making management decisions within the framework of their existing activities. To achieve this goal and answer the key management questions specified we completed the following four objectives:

- Objective 1: Quantify the relative environmental functions provided by various hedgerow management options relative to current agricultural production.
- Objective 2: Determine past and current distribution and quantity of hedgerows and their associated key environmental functions across the Delta region.

- Objective 3: Develop predictions for the relative quantity of key environmental functions provided by four management scenarios for the Delta region and the economic costs of each option.
- Objective 4: Synthesize and communicate project results to stakeholders throughout the Delta region and beyond.

Objective 1 focused on characterizing the *remnant* and *planted* hedgerows (RH and PH); or to use the land for agriculture by characterizing the production field neighbouring a remnant hedgerow (RPF) or planted hedgerow (PPF). To meet this objective, we inventoried these different management options and monitored them over a one year period to quantify indicators of green house gas (GHG) mitigation, plant biodiversity and hydrological functions, specifically: carbon storage (above and below ground); GHG emissions of nitrous oxides, methane and carbon dioxide; and soil aggregate stability.

To achieve **Objective 2** we used historical air photos of subset of the agricultural land reserve (ALR) in Delta to develop maps of a in the past distribution of *remnant* and *planted* hedgerows in the region and compared them with maps we developed of the current distribution of these management options.

For **Objective 3**, we analyzed 2013 satellite imagery to develop a basic land use/land cover (LULC) map of the entire ALR in the Delta. From this analysis we used the non-production perennial vegetation as a proxy for woody habitat (*remnant* and *planted* hedgerows) to develop scenarios for the following three management options for the Delta:

1. ***Business as usual***: The area of perennial habitat is maintained at the 2013 levels. Assumes incentives will be required to preserve 1% of the woody habitat (*remnant hedgerows*) that would otherwise be cut down per year;
2. ***Maximize Hedgerows***: The area of perennial habitat is maximized by planting hedgerows on all farm field and road edges;
3. ***Agricultural Expansion****:* The total of perennial habitat area is reduced by the conversion to agricultural production. What remains of perennial habitat is planted hedgerows on all farm field and road edges.

For each scenario we extrapolated field data for a key ecosystem function and ran landscape habitat analyses to determine the relative ecosystem function. The economic costs of these environmental outcomes were then compared for each scenario.

Finally for **Objective 4**, we used the findings of this study to inform various stakeholders including farmers, policy makers, and supporters of the DF&WT. We produced a variety of communication tools including, a video documenting the project, field days, and a series of extension briefs for farmers and other stakeholders.

2 METHODS

2.1 Study Area

The study area is located in the lower Fraser River Delta, in the district municipality of Delta, British Columbia, Canada (49° 4'25.33"N, 123° 4'58.20"W). The area is a peri-urban landscape with a population close to 100,000, 0.6% of which are farmers (Ministry of Agriculture and Lands 2008). In June 1974, 55% of the land base in Delta was protected under the provincially mandated Agricultural Land Reserve (ALR) as part of the Greater Vancouver Regional District's ALR Plan (Ministry of Agriculture and Lands 2008).

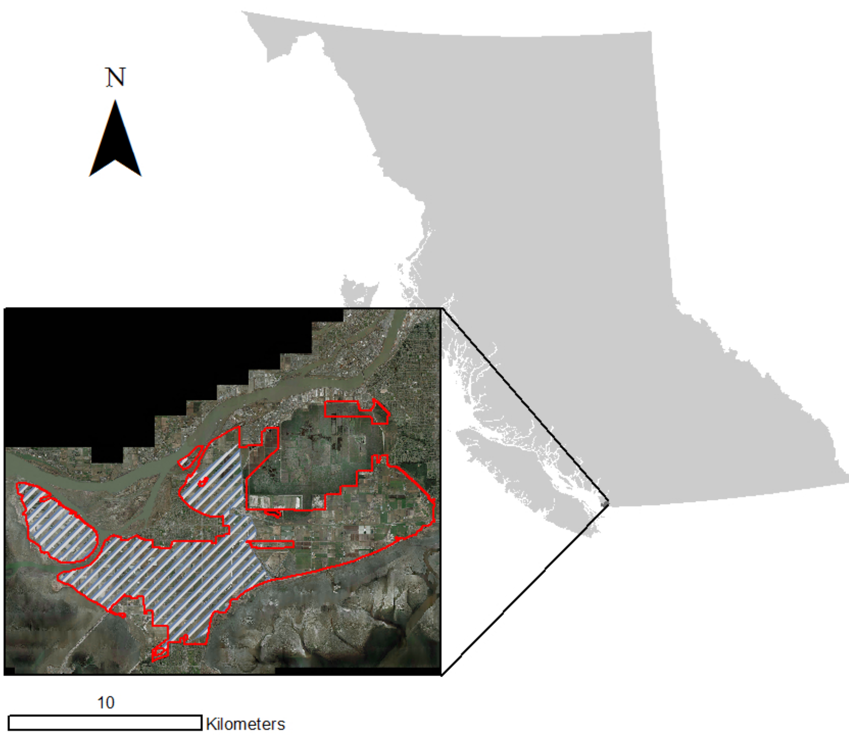

Figure 1. Location of the study area in the lower Fraser River Delta of southwest British Columbia. Red indicates the extents of the project analysis area and the grey the historical analysis area.

The analyses in this study have been confined to the area an area of 9802 ha located on lands designated as ALR (Figure 1) in Delta. A subset of this area (5420 ha) was utilized for analyzing historical land use change.

The region has a humid maritime climate characterized by wet winters and cool dry summers. 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 Government of Canada weather station located approximately 10 km from the project site indicates the mean annual temperature is 10.6^{o}C, the mean annual rainfall is 1227.8 mm, and the mean annual snowfall is 34.6 cm (Ministry of Environment 2014). In 2013, the annual climate values were similar to historical values with a mean annual temperature of 10.7^{o}C, a total annual rainfall of 1040.8 mm, and total annual snowfall of 13.2 cm (Ministry of Environment 2014b) (Figure 2).

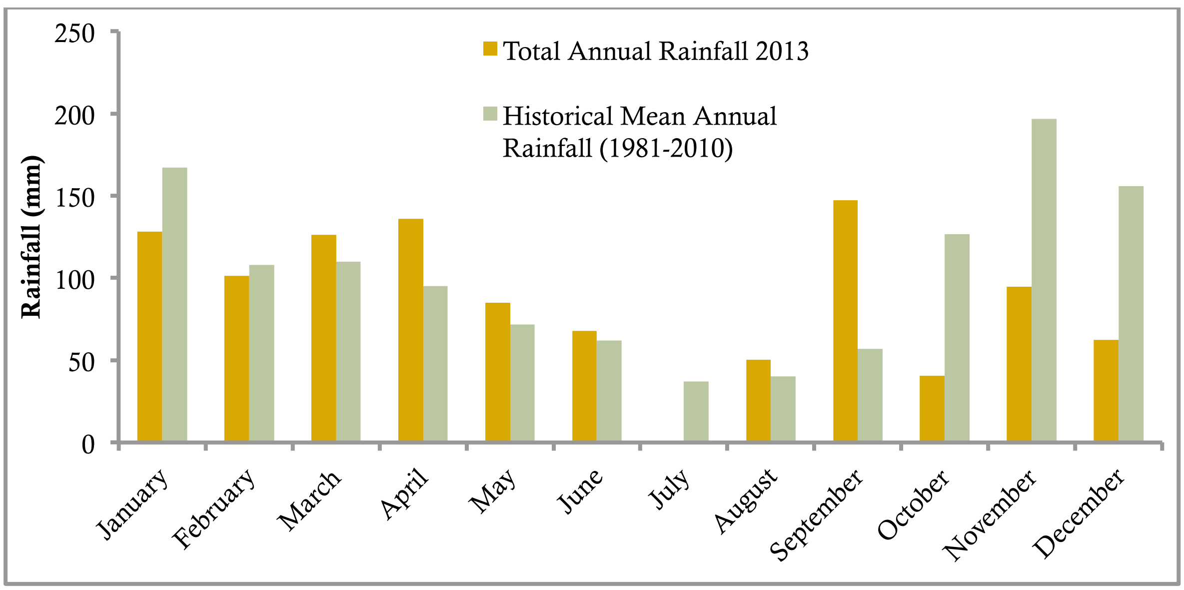

Figure 2. Comparison of total annual rainfall to historical mean annual rainfall (1981-2010) from Richmond Nature Park, BC Weather Station.

The soils in the study area are mainly Gleysols, formed by fluvial deltaic deposits, and the Organic soils, composed of peaty materials (Luttmerding 1981) (Table 1). Both soil types are characterized by long periods of saturation and are poorly drained. Three soils series, namely the Ladner, Crescent and Westham, were captured by our experimental design and represent 54.8 % of the soils in the study area (Luttmerding 1981) (Figure 3).

Table 1. Select soil properties for Delta soils (Luttmerding 1981) with greater than 5% land area in study zone. The soil series in bold and italic were captured in our experimental design.

Subgroup, Great Group	Soil Series	% of study area	Surface Horizon	Parent Material	Structure	Organic Carbon %	EC (mS/cm)	pH	CEC (me/100g)	Texture
Humic Luvic Gleysol	***LADNER***	***15.84***	***Ap; 0-15 cm***	***Fluvial***	***moderate fine subangular blocky***	***10.85***	***n/a***	***5.6***	***36.3***	***Silt Loam***
Orthic Gleysol	***CRESCENT***	***19.89***	***Ap; 0-20 cm***	***Fluvial***	***moderate medium to fine subangular blocky***	***2.03***	***0.3***	***6.1***	***16.9***	***Silt Loam***
Orthic Humic Gleysol (saline)	DELTA	22.68	Ap; 0-22 cm	Fluvial	subangular blocky	8.83	0.7	4.7	32.6	Silty clay loam
Orthic Humic Gleysol (saline)	GUICHON	6.74	Ap; 0-18 cm	Fluvial	moderate medium to coarse subangular blocky	7.61	1.25	5.5	30.2	Silt Loam
Rego Humic Gleysol (saline)	SPETIFORE	7.38	Ap; 0-17 cm	Fluvial	moderate medium to fine subangular blocky	12.06	6.4	4	35.7	Silty Clay Loam
Rego Humic Gleysol (saline)	***WESTHAM***	***19.07***	***Ap; 0-15 cm***	***Fluvial***	***moderate fine to medium subangular blocky***	***2.44***	***n/a***	***6.1***	***18.5***	***Silt Loam***

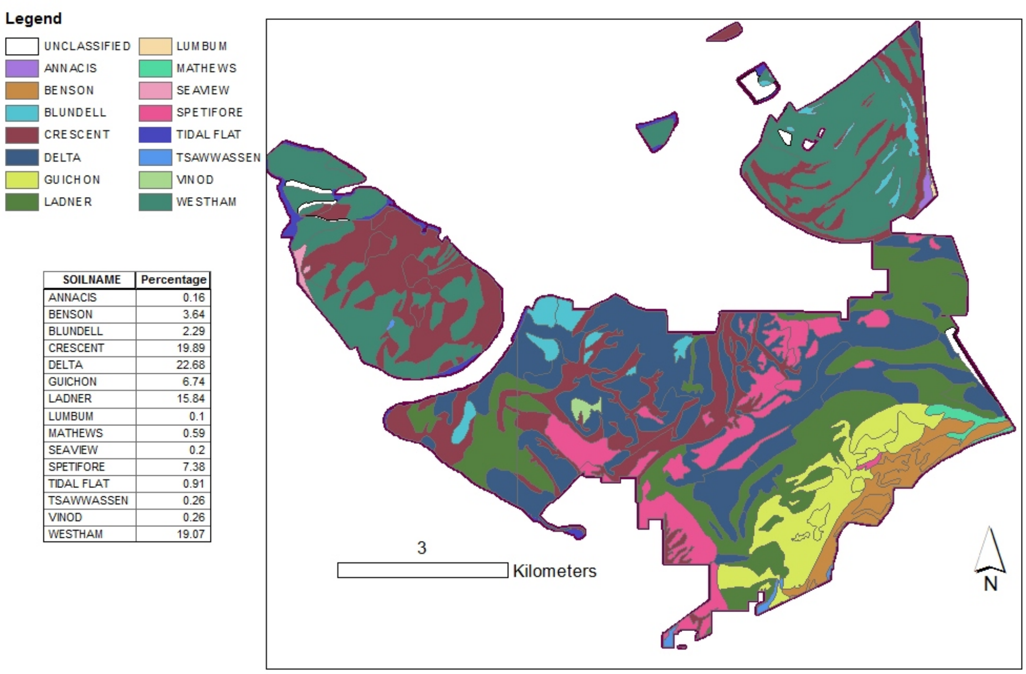

Figure 3. Map of all soils present in the study area.

2.2 Woody Habitat Inventories

Characterization of the two hedgerow types, *remnant* and *planted* was conducted by inventorying key vegetation and soil indicators and monitoring greenhouse gas emissions for one year within each habitat type and in their neighbouring production field. In this way, three land use types were evaluated during this study: *remnant* and *planted* hedgerows, and production fields (PF). *Remnant* hedgerows are defined here as linear woody habitats consisting of trees, shrubs and ground-cover that were established prior to the DF&WT Hedgerow Stewardship Program and are largely unmonitored and unmanaged. Their mean age at the time of site selection is 38 years. *Planted* hedgerows are defined here as linear woody habitats consisting of trees, shrubs and ground-cover vegetation that have been planted by the DF&WT along fields, property boundaries, waterways, or roads. *Planted* hedgerows are monitored and managed by DF&WT for the purpose of maximizing wildlife habitat in the region, range in age from 9-19 years and have a mean width of 4 m. Each neighboring production field is farmed by a single user under uniform management across the field. Production fields chosen for this study were planted with annual crops typical of those for the area. The production field history was compiled from personnel communications with the farm managers for the last 10 years from each farm (Table 2).

Crops commonly produced in these fields include hay, barley, potatoes, beans and grain. Wintering practices vary by field consisting of either hay or pasture production, protecting them from erosion with cover crops or grassland set asides (also a program of the DF&WT) or leaving them bare (fallow).

In total, eight farms – four with *remnant* and four with *planted* hedgerows (n=4) - were selected through an extensive landscape survey of Delta farmland in November 2012. Farms were selected based on the hedgerow's size, relative age, location, and the neighbouring PF's crop selection with the goal of minimizing the variability of these various factors. The selection was limited by the number of *planted* hedgerows (15) in the DF&WT Hedgerow Stewardship Program and the number of farmers willing to participate in the study. The eight hedgerows selected for the study ranged in area from 250 m^2 to 2400 m^2 and were on average 1160 m^2.

Table 2. 10-year Production Field History of Fields in Study

	2004		2005		2006		2007		2008		2009		2010		2011		2012		2013	
Farm #	Summer	Winter	Summer	Winter	Summer	Winter	Summer	Winter	Summer	Winter	Summer	Winter	Summer	Winter	Summer	Winter	Summer	Winter	Summer	Winter
Farm 1	hay	hay	pasture	pasture	potatoes	cover	potatoes	cover	barley/ forage	forage	hay	hay	pasture	pasture	potatoes	cover	potatoes	cover	barley/ forage	cover
Farm 2	hay	hay	pastures	pasture	potatoes	cover	cabbage	cover	barley/ forage	forage	hay	hay	pastures	pasture	potatoes	cover	cabbage	cover	barley/ forage	cover
Farm 3	cabbage	cover	peas	cover	beans	fallow	grain	fallow	peas	fallow	grain	cover	potatoes	cover	grain	cover	potatoes	fallow	grain	cover
Farm 4	hay	fallow	grain	fallow	grain	fallow	grain	fallow	grain	fallow	potato	fallow	potato	fallow	potato	fallow	corn	over crop	corn	fallow
Farm 5	potatoes	cover	peas	cover	beans	fallow	potatoes	cover	beans	cover	potatoes	fallow	peas	cover	beans	cover	potatoes	cover	beans	fallow
Farm 6	beans	cover	peas	cover	beans	cover	potatoes	cover	beans	cover	beans	cover	peas	cover	beans	cover	yukons	fallow	beans	fallow
Farm 7	grassland set aside		grassland set aside		grassland set aside		hay	fallow	hay	fallow	hay	fallow	hay	fallow	potatoes	fallow	potatoes	fallow	potatoes	fallow
Farm 8	potatoes	cover	beans	cover	peas	cover	potatoes	cover	beans	cover	peas	cover	potatoes	cover	beans	cover	potatoes	fallow	beans	fallow

2.2.1 Biodiversity

Species richness was determined as the average number of tree and shrub species across the sampled hedgerows. At each farm all trees and shrubs were identified to species in plots with a maximum area of 1000 m^2; for hedgerows where the total area was greater than 1000 m^2, 4 x 250 m^2 subplots were randomly assigned within the hedgerow.

2.2.2 Biomass

Biomass of perennial vegetation was measured at each of the eight farms. The sampling scheme was the same as that of species richness above. To estimate the biomass of the trees, we identified the species of each tree, used a clinometer to determine the height and measured the diameter at breast-height (DHB; 1.3 m). For trees that had major divisions of their 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 included in this study.

Aboveground biomass estimations were calculated using field data and allometric equations. Species specific allometric equations were used where available (Ter-Mikaelian and 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 allometeric equation was employed for all shrub species (Smukler et al., 2010). Equations were chosen based on the geographic origin, climatic similarities, DBH and height range, sample size, and the coefficient of determination

(R^2) value of the developed equations. For trees, total aboveground biomass equations were preferred, and where not available, individual stem wood (kg), stem bark (kg), foliage (kg) and total branch (kg) equations were combined to estimate the total biomass. For shrubs, the total aboveground biomass was estimated by first calculating the ellipsoid biovolume of the shrub and then estimating the biomass from this biovolume. Belowground biomass was estimated using a regression equation that links the aboveground biomass density (ABD) and the age of the stand to the root biomass density (RBD) (Cairns et al. 1997).

Equation 1: $$RBD, Mg\ ha^{-1} = \exp[-1.3267 + 0.8877 lnABD + 0.1045 lnAGE]$$

Both above- and belowground biomass estimations were then used to determine the total carbon stored in the trees and shrubs by multiplying the biomass by 50% (Nair, 2011).

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 biomass limit was imposed equivalent to the maximum the equation could predict to provide a conservative estimate of the biomass carbon. These limitations may lead to over- or underestimations the total biomass in the hedgerows (Nair et al. 2009) but we have, whenever possible tried to err on the side of underestimation.

2.2.3 Soils Properties

At each farm a plot was established in the hedgerow and neighbouring production field either *planted* production field (PPF) or *remnant* (RPF). Within each plot three subplots were randomly located to account for spatial variability. Subplots in the production fields were located with approximately 15 m perpendicularly from its hedgerow pair. Within each subplot, soil samples were collected to assess the soil bulk density, soil carbon content and soil cumulative mass.

2.2.3.1 BULK DENSITY AND EQUIVALENT SOIL MASS (ESM)

To assess the bulk density of the soil, samples were collected from the center of the subplot using a core (7.3 cm inner diameter x 7.0 cm height) centered on the 10 cm and 30 cm depth (to allow for comparison of the 0-20 cm and 20-40 cm bulk density and equivalent soil mass based soil carbon estimates), brought back to the UBC lab and oven dried at 105^{o}C until a stable mass was recorded. Bulk density was then calculated as the dry soil mass over the core volume (Blake et al. 1986).

To assess the equivalent soil mass of the soil, samples were collected from the center of the subplot 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. A total of 48 samples were collected from each depth. Samples were brought back to the UBC lab where their wet weight was recorded. A subsample of approximately 40 g was weighed into a tin and oven dried at 105^{o}C until a stable mass was reached to determine the soil water content of each sample. Sample weight was then adjusted for soil water content and coarse fragments (see methods below) to determine the dry fine earth fraction of each sample.

2.2.3.2 SOIL CARBON

Soil samples were collected using the same method as equivalent soil mass. Three subsamples from the center of the three remaining quadrants in the subplot were collected at each depth, composited in the field, homogenized and then a ~600 g subsample was taken back to the UBC lab for analysis. A total of 48 samples were collected from each depth. Soil 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 before being 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 cumulative mass sample. A 20-g subsample of each was then hand-ground using a mortar and pestle.

A stratified random sampling procedure using soil type and sampling depth was used to identify 30 of the ground samples to be sent to Technical Service laboratory of the B.C. Ministry of Environment for combustion elemental analysis. There the samples were ground to -100 mesh using a Rocklabs “ring grinder”. These samples were then analyzed for total C and N by combustion elemental analysis using a Thermo “Flash 2000” analyzer. Separate sub-samples were oven-dried at 105°C to allow the C and N results to be reported on a standardized 100% dry weight basis.

At the same time the ground samples were analyzed for Total C and N at the UBC SAL Lab using Fourier-transformed mid-infrared spectroscopy (FT-MIR), run on a Tensor 37 HTS-XT spectrometer (Bruker Optics). Samples were ground to a powder and 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}. Soil properties, specifically soil total percenMg Carbon, soil total percent nitrogen, and pH were then predicted from reflectance results using partial least squares regression based on the subset of 30 randomly selected calibration samples analyzed using combustion elemental analysis. 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 95 with an RMSE of 0.172.

Total soil C stocks were calculated for 0-20 and 20-40 cm depths using soil bulk density (Knowles & Singh, 2006) and an equivalent soil mass basis to 0.4 t m^{-2} and 1.2 t m^{-2} (Gifford & Roderick, 2003). First, total soil C was calculated using bulk density (Equation 2).

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

where $\frac{m_s}{V_t}$ is the bulk density and z is the depth of the sample. Second, total soil C was calculated using cumulative mass to 0.4 t m-2 and 1.2 t m-2 (Equation 3).

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

Where $c_s(t)$ is the C content of a standardized mass of soil in tonnes, $c_s(z_a)$ 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).

Relative C was calculated as the difference in soil C between the *remnant* and *planted* hedgerows and the soil C in their neighbouring production fields.

2.2.3.3 AGGREGATE STABILITY

Four soil samples were collected at a 0-10 cm depth from each subplot and composited in the field in plastic containers, which were brought back to the lab for analysis. A total of 48 samples were used for analysis. The samples were stored in a fridge at 4°C until analyzed to reduce biological activity from disturbing aggregate distribution. Samples were air-dried 24 hours prior to analysis. First, large clods were gently separated by hand before samples were dry sieved to separate the 2-6 mm soil fraction. A 7 g sample of this fraction was weighed and dried at 105°C to measure soil moisture. Another 15 g sample of the 2-6 mm fraction was transferred into nested sieves with openings of 2 mm, 1 mm and 0.25 mm diameters to calculate the mean weight diameter (MWD) using the wet-sieving method (Yoder, 1936). The samples were wetted using a humidifier following Kemper and Chepil (1965) variation to Yoder the method before samples 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°. Samples were oven dried at 105°C for at least 24 hours prior to the dispersed fractions of each sample being weighed. The separate size fractions were then ground and re-sieved to separate the coarse fragment.

The MWD of water stable aggregates of each field sample was then calculated using the following equation:

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

Where x_i is the mean diameter of adjacent sieves and w_i is 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 Green House Gas Emissions

To measure greenhouse gases (GHG), specifically carbon dioxide (CO_2), nitrous oxide (N_2O) and methane fluxes (CH_4) from our treatment sites, we used non-flow-through, non-steady-state (or closed static) chambers (Livingston and Hutchinson 1995, Kutzbach et al. 2007, Rochette et al. 2008). The chambers (Figure 4) were constructed using best-practice methodology agreed upon in flux measurement literature (Norman et al. 1997, Rochette et al. 2008, Rochette 2011). Chamber collars were cut from 20 cm inner-diameter (with 0.6 cm thick walls) PVC pipe (Jassal et al. 2008) to a collar height of 15 cm. Though Jassal et al. (2008) used a collar height of 10 cm with an insertion depth of 5 cm in their study, the increased collar height of 15 cm was chosen as more appropriate for this study because of the minimization effect an increased headspace would have on the error in flux calculations by decreasing the relative volume removed from the headspace during the syringe sampling. The edges of the PVC collars were bevelled to facilitate the ease of insertion into the ground so as to minimize soil disturbance which has been proven to be a major source of error in field flux measurements (Luo and 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 foam seal to attach the lids to the collars. Research shows that all non-steady-state chambers should have a properly fitted vent tube to minimize or eliminate possible air pressure gradients (or differences) that maybe be created between ambient air, soil air and the headspace air at any time during the emission sampling to minimize emission errors (Rochette and Eriksen-Hamel 2008). In order to ensure that the headspace air is 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) (Kutzbach et al. 2007, Jassal et al. 2008, Pihlatie et al. 2013). 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. 2008). 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 and Zhou 2006) that reflects a high proportion of incident solar radiation.

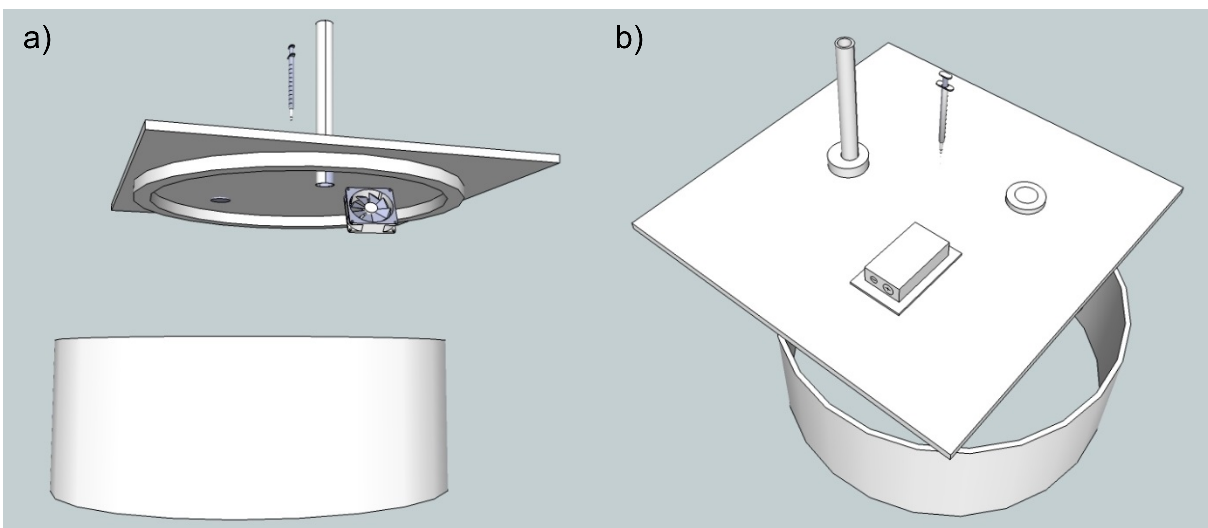

Figure 4. Chamber schematic a) bottom view of collar and lid with fan, vent tube, syringe septa, and sealing foam, and b) top view showing battery location for fan.

GHG were sampled between February 12, 2013 and January 23, 2014. A total of 24 collars were installed on the eight farms at least one week prior to measurements whenever possible to minimize the effects of soil disturbance associated with chamber insertion (Livingston and Hutchinson 2001). One collar was randomly inserted within each of the four *planted* hedgerow plots, the four *remnant* hedgerow plots, and the associated reference *production field* plots for both. The collars were inserted to a depth of 5 cm to protect against lateral diffusion effects (Healy et al. 1996, Livingston and Hutchinson 2001). During the summer, when farming operations (e.g., tillage) were frequent, the duration of collar installation in the production fields were often limited to the day of sampling. In the production fields, collars were inserted between field vegetation and no vegetation was removed. In the hedgerows, ground cover was not removed except in situation where tall vegetation prevented a tight seal of the chamber lid – in these cases vegetation was cut back to allow for a tight seal.

To capture temporal variability in GHG flux, chambers were sampled every two weeks for a 12-month period. To better understand the importance of spatial variability in this study additional collars were installed on two farms of each hedgerow type and associated reference plots (three total), and these subsample locations were sampled once per month for the 12-month period. The sampling the eight farms averaged 4.5 hours and was scheduled between 9 am and 2pm to minimize variation in temperature.

After the initial ambient air sample was taken and the lid installed, gas samples were subsequently taken at 3, 10, 20 and 30 minutes at each sampling event (Jassal et al., 2008) in pre-evacuated 5.9 ml glass vials (Exetainers, Labco Limited, Ceredigion, UK) using a 10 ml plastic syringe with a 22G needle. Samples taken February 2013 to July 2013 were analyzed at UBC, Vancouver 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 at UBC (Okanagan) 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 from. 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 ($\frac{dc}{dt}$) 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 5:

Equation 5.

$$Flux = \frac{dc}{dt}\ \frac{PV}{RTA}$$

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 1-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) designed for flux estimations of trace gases using static chambers (Pedersen et al. 2010). Where the regression analysis resulted in a 'No-Flux' result, the linear regression analysis calculated by the HMR package was used instead. Volumetric soil water content and soil temperature 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 and 10-15 cm depths on every sampling day.

2.2.5 Statistical Analyses

Differences between the biomass and biodiversity of PH and RH were determined using a one-way ANOVA. Soil C, bulk density, equivalent soil mass, 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 treatment pairs were then determined using a Tukey's Honestly Significant Difference (HSD) test. These tests were repeated with the relative values of PH and RH. For the GHGs, all measured data were included and analyzed using a linear mixed effects model with temporal repeated measures to account for correlations between samples taken from the same sampling location throughout the sampling period. A marginal ANOVA was used to test for significant differences caused by the treatments, sample date or interaction between the treatment and sample date across all measurement days for the year. A multiple comparison of the treatments was done using a Tukey's HSD test to check for significant differences between means of treatments. Contrasts of the two relative annual means for each gas in the planted and remnant system were done using a general linear hypothesis test. All analyses were computed in R (R development Core Team 2008).

2.3 Landscape Analysis

2.3.1 Historical Landscape Woody Habitat

To assess historical land use change we analyzed three time periods selected based on the availability and quality of air photos within project area. Photos from fly overs of the Delta in 1966, and 1986 were mosaicked and georeferenced. A contiguous aerial image (1 m resolution) was used to assess 2012. We were able to collect air photos from the 1930s and mosaicked these images but determined that were not sufficient enough quality for analysis. The 1930s photos did however provide information for determining the ages of some of the hedgerows included in the analysis. The common extent of all of the available imagery determined the analysis window for assessing woody habitat cover changes and the analysis was further restricted to the ALR within this area.

For each of the images woody vegetation was digitized by hand and classified as either *woody habitat* (consistent with many of the characteristics of *remnant* hedgerows) or *planted woody habitat* (consistent with many of the characteristics of the DF&WT's *planted* hedgerows). A spatial grid with 1km x 1km cells was created to divide the study area evenly to track which portions that had been digitized. Digitized patches were created at a scale of approximately 1:2000 and the minimum mapping units (MMU) varied as the imagery became more detailed (higher resolution):

- 0.015 ha in 1966
- 0.005 ha in 1986

- 0.005 ha in 2012

Woody habitat features were identified by presence of tree canopy, rough texture, dark hue (on black and white imagery), shadow and presence of healthy vegetation. *Woody habitat* was defined as: an area of contiguous vegetation greater than the MMU that contains a distinct pattern, distribution and composition of vegetation relative to surrounding vegetated and non-vegetated areas. *Planted woody habitat* was differentiated if it had clearly defined spacing or other evidence of active management or recent planting.

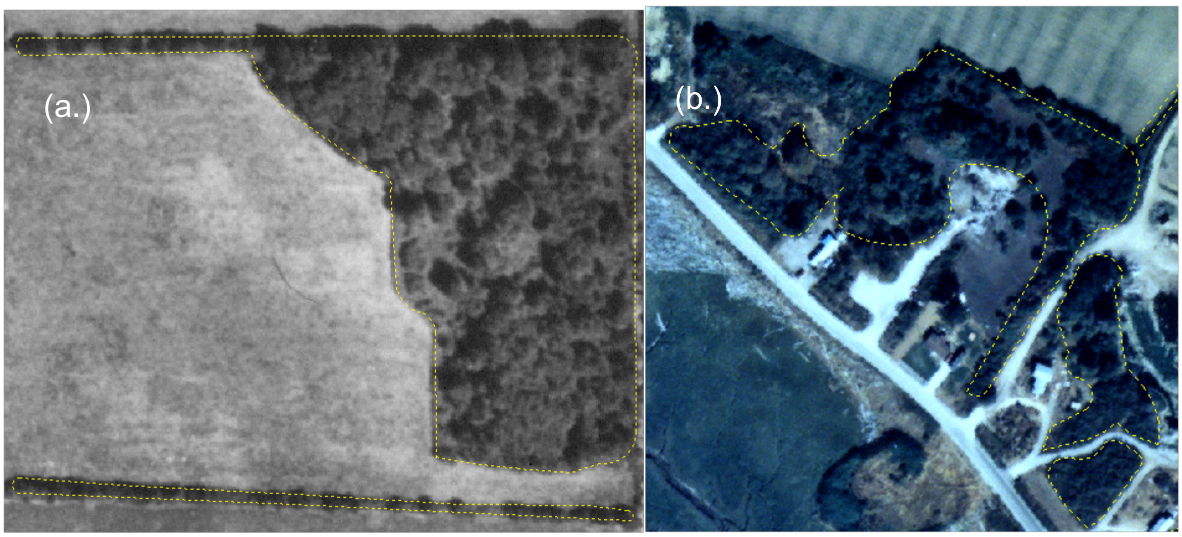

Figure 5. Examples of digitized woody vegetation from the (a.) 1966 and (b.) 1986 imagery.

2.3.2 Land Use Land Cover 2013

To determine the current distribution of woody habitat satellite imagery was acquired and analyzed using specialized software to develop a basic land use/land cover map. RapidEye (5.0m resolution) satellite imagery collected on October 8th, 2013 was acquired with <5% cloud cover.

Simple land cover classes were developed for mapping focused on identifying fine grain woody perennial features. Water class was excluded using provincial spatial dataset (BC Freshwater Atlas). Targeted land cover types included “Open cultivated” and “Bare/paved” (**Error! Reference source not found.**). While our intention was to isolate woody habitat in the imagery, due to limitation of the data (e.g. large pixel size) and methodology the habitat captured likely included some portion of non-woody understory vegetation. The class was termed “non-production perennial vegetation” and defined as any woody, perennial vegetation cover ranging from planted ornamental vegetation to natural forest or shrub cover or directly adjacent vegetation (within the same pixel). “Open cultivated” class included all large managed features, including field crops, perennial crop, pasture or fallow grass and was defined by its lack of woody cover. “Bare/paved” class included covers composed of bare mineral or reflective metals, such as roadways, gravel lots, residences and greenhouses.

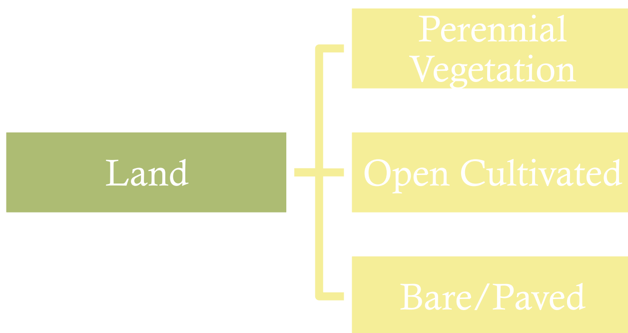

Figure 6. Land use/ land cover classification hierarchy.

Imagery was mosaicked and classified using ENVI 5.0 software using unsupervised rule-based feature extraction. Segmentation and merge levels were developed using reference features identified during fieldwork in combination with the 2013 Google Earth air photo imagery. Rules were developed iteratively with the use of the same reference features and air photos and included spectral, textural and spatial attributes. Final rule-sets identified the land cover classes through simple characteristics: open cultivated cover by large spatial areas, bare/paved cover by high spectral values in band 1, and perennial vegetation through low textural means in band 5.

Accuracy assessment was conducted using ground truthed polygons. Random polygons were developed for a total of 190 random points distributed throughout the classified boundary and identified using field observations and 2013 Google Earth air photos. Random points were assigned to one of the three classes and a polygon containing the point was created over the distinct portion of the feature (perennial vegetation polygons = 101 including 18 hedgerow specific; agriculture = 68;bare/paved = 21) for accuracy assessment. Accuracy was enhanced with a comprehensive scan of the classified vector image for major visible discrepancies in ArcGIS 10.2. Errors were verified in the original RapidEye imagery and 2013 Google Earth air photos and misclassified polygons were manually reclassified to the correct cover class. The scan particularly focused on misclassification of “open cultivated” polygons as “bare/paved” or “perennial vegetation” due to the highly cover types found in “open cultivated”. The overall accuracy of the analysis was 89.7% (Table 3) with a kappa coefficient of 0.64 indicating a high accuracy of analysis.

Table 3. Confusion matrix assessing the accuracy of satellite imagery analysis

Class	Perennial Vegetation	Bare/Paved	Open Cultivated	Total
Unclassified	3.5	0.1	2.8	2.8
Vegetation	61.2	1.0	0.5	6.3
Bare/Paved	0.3	94.2	4.1	8.6
Open Cultivated	35.0	4.8	92.6	82.4
Total	100	100	100	100

Unclassified polygons were reassigned to the most probable class. The class of “unclassified” polygons was evaluated using the confusion matrix. Classes were ranked in descending order by their percentage of pixels misclassified as “unclassified”. Unclassified polygon were reassigned sequentially to each misclassified class by reassigning “unclassified” pixels that shared a boundary with the targeMg Class. The remaining “unclassified” polygons were reassigned when sharing a boundary with the next most misclassified classes.

2.3.3 Landscape Environmental Function

Regional estimates of environmental function were determined for three possible future scenarios for the Delta’s ALR (the project area). Scenarios were designed to illustrate how some key environmental function might change depending on distinct land management options for the 9,802 of the ALR. These scenarios were:

1. ***Business as usual***: The area of perennial habitat is maintained at the 2013 levels. Assumes incentives will be required to preserve 1% of the woody habitat (*remnant hedgerows*) that would otherwise be cut down per year;
2. ***Maximize Hedgerows***: The area of perennial habitat is maximized by planting hedgerows on all farm field and road edges;

3. ***Agricultural Expansion:*** The total of perennial habitat area is reduced by the conversion to agricultural production. What remains of perennial habitat is planted hedgerows on all farm field and road edges.

In each scenario the amount of perennial habitat was varied to represent the change in land use management. The area of perennial habitat for the *Business as Usual* scenario was based on the *vegetation* (i.e. non-production perennial vegetation habitat) LULC type classified from the Rapid Eye satellite image. For the *Maximize Hedgerows* scenario, a future where the DF&WT maximizes its potential, ArcGIS 10.2 (ESRI 2014) was utilized to buffer all roadways and parcel edges by 5m and classify the buffer the buffer as *vegetation*. For the *Agricultural Expansion* scenario, all vegetation is removed from the ALR except the *vegetation* bordering roadways and parcel edges created from the buffer of the previous scenario.

To compare differences in the amount of carbon stored across the landscape for each scenario, plot data for the average carbon density of woody vegetation and soil observed for hedgerows were extrapolated to the landscape.

To estimate how these management scenarios would differ in terms of habitat quality three landscape metrics were calculated using FRAGSTAT (McGarigal et al. 2012). The ArcGIS maps for each scenario were converted to a binary raster image of perennial habitat and imported into FRAGSTAT to calculate patch size, patch contiguity and contagion as measures of habitat quality and landscape connectivity for each scenario. Patch contiguity is the degree to which individual habitat patches are connected to neighbouring habitat (McGarigal et al. 2012). Large contiguous patches result in larger contiguity index values which may indicate greater benefits for wildlife. Contagion measures both the type and dispersion pattern of habitat patches. Patch types that are small yet well interspersed will have lower contagion value (McGarigal et al. 2012). Alternatively landscapes with larger more contiguous patches would have a higher contagion value.

2.3.4 Cost Benefit Analysis

Costs and benefits were analyzed for each of the three potential land use future scenarios: *Business as Usual*, *Maximize Hedgerows* and *Agricultural Expansion*. To estimate the costs we calculated the area that would be required to plant or protect per year for each scenario to achieve or maintain a mature stand of woody habitat in 40 years time, assuming that it takes 20 years to mature. For the *Business as Usual* scenario we assumed that 1% of the landscape's woody habitat would be cut down and need protected at the same costs required for planting (Figure 7). This meant that each year 18 ha would need protected. For the *Maximize Hedgerows* scenario we assumed instead there the replacement rate would be the same area (18 ha) but then an additional 8 ha would need to be planted for the next 20 years to meet a target of establishing hedgerows on all bare 160 ha of road and parcel edges. For the *Agricultural Expansion* scenario we assumed that there would be no replacement or protection, as all the woody habitat would be cut down, and 8 ha would be planted per year for the next 20 years. To calculate net present costs, the annual costs per ha were discounted by 1.5% per year over the 40-year project period. We used the DF&WT average cost for establishing hedgerows of $158,000 per ha. The costs of each scenario were then compared to the benefits estimated for environmental function for each of the alternative scenarios.

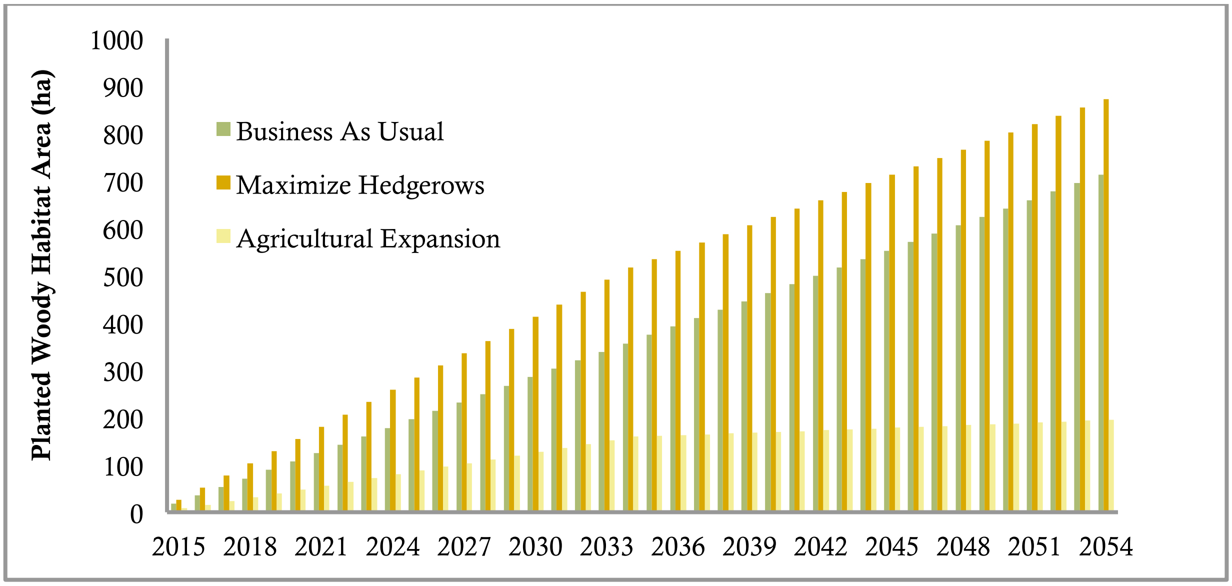

Figure 7. Total planted area per year required to establish mature stands of woody habitat by 2054 on the Delta's ALR for each of three future scenarios ("Business as Usual", "Maximize Hedgerows" and "Agricultural Expansion")

3 RESULTS AND DISCUSSION

3.1 Hedgerow Inventories

3.1.1 Vegetation

Inventories of the vegetation showed that there are key differences in structure, and function between RH and PH indicated by the results of our biodiversity and biomass analysis of trees and shrubs in each hedgerow type.

3.1.1.1 BIODIVERSITY

Our inventory of the two types of hedgerows currently present in Delta showed that they differed substantially in the composition of tree and shrub species. In the PH the mosMg Common species of trees and shrubs were: *Acer rubrum, Alnus rubra, Betula papyrifera, Salix sp., Rosa nutkana, Cupressus nottkatensis, Populus trichocarpa, Thuja plicata,* and *Cornus sericea*. In the RH the mosMg Common species were: *Alnus rubra, Crataegus douglasii, Malus fusca,* and *Populus trichocarpa*. The mean species richness for PH (210.6 $\pm$ 55.8 species ha^{-1}), though higher than that of RH (111.8 $\pm$ 34.7 species ha^{-1}) was not significantly different ($p<0.05$) (Figure 8).

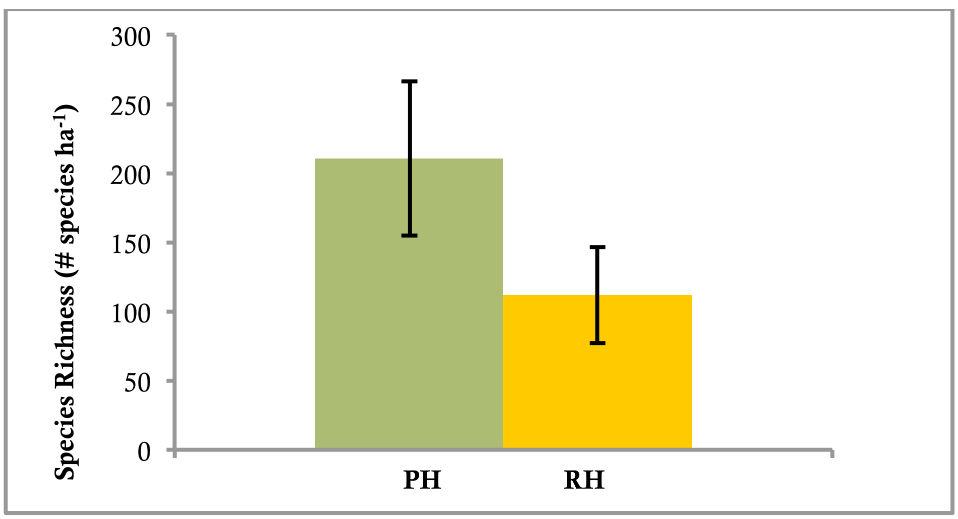

Figure 8. Comparison of species richness of hedgerow trees and shrubs in planted (PH) and remnant (RH) hedgerows. Error bars represent standard error.

In total 25 different species of trees and shrubs were documented in *planted* hedgerows and only 14 species in *remnant* hedgerows. On average, there were 8 different species found in each of the *planted* hedgerows and 5.25 in each of the *remnant* ones.

3.1.1.2 BIOMASS CARBON

There was substantial variability in the biomass of the perennial vegetation found in the two types of hedgerows. Neither the aboveground (AG) and belowground (BG) biomass C for trees and shrubs were statistically different ($p<0.05$). The mean total biomass C for PH, including that above- and belowground for both trees, shrubs, was 76.2 $\pm$ 32.3 Mg C ha^{-1} and for RH, 124.0$\pm$ 20.9 Mg C ha^{-1} (Figure 9).

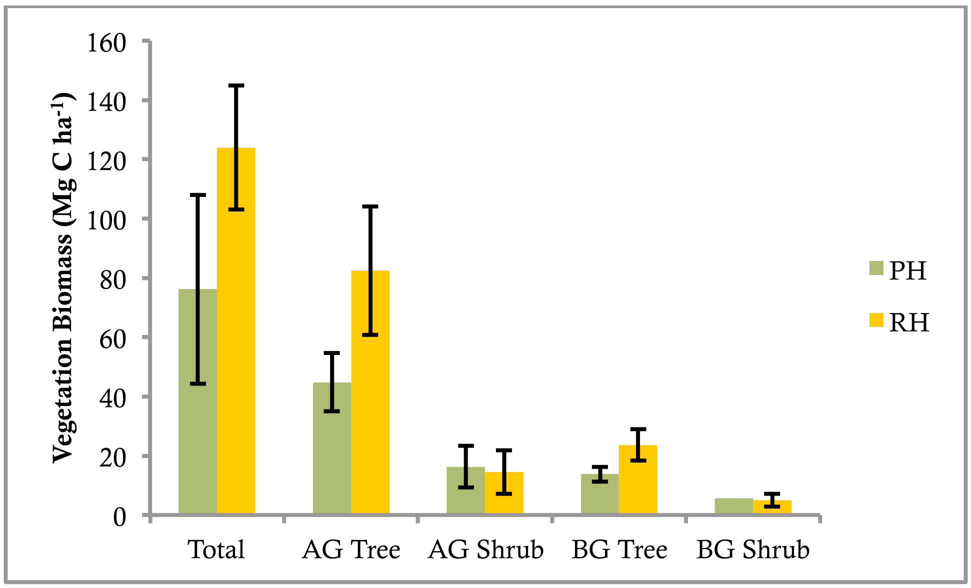

Figure 9. Comparison of aboveground biomass (AG) and belowground biomass (BG) Mg C ha^{-1} of trees and shrubs in planted (PH) and remnant hedgerows (RH). Error bars represent standard error.

Similar results for hedgerows have been found in various farming systems. In a recent study evaluating the benefit of field margins in the Argentinian Pampa region, woody field margins were found to have 65.74 $\pm$ 13.76 Mg C ha^{-1} (D'Acunto et al. 2014). In a US shelterbelt aboveground biomass scenario, reported by Kort & Turnock (1999) had 23.12 Mg C ha^{-1} could be contributed by shrubs in a 20-year old single-row shelterbelt. In a theoretical farm scale assessment of field margin contribution to farm biomass, aboveground biomass from wood was estimated at 72.0 Mg C ha^{-1} (Falloon et al. 2004). In a study assessing the age effect on the biomass C storage of shelterbelts in a plantation system in China, it was observed that the AG biomass was 61.3 ± 4.4 Mg C ha^{-1} and 65.2 ± 13.1 Mg C ha^{-1} for 13 and 18 year-old stands, and the BG biomass was 9.8 ± 0.72 Mg C ha^{-1} and 10.6 ± 2.16 Mg C ha^{-1} for the 13 and 18 year-old stands (Wang et al. 2013).

3.1.2 Soils Properties

3.1.2.1 BULK DENSITY AND EQUIVALENT SOIL MASS

Soil bulk density values were similar on hedgerows and adjacent production fields (Figure 10). The 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, but only PH were significantly lower ($p<0.05$) at the 0-20 cm depth (Figure 10).

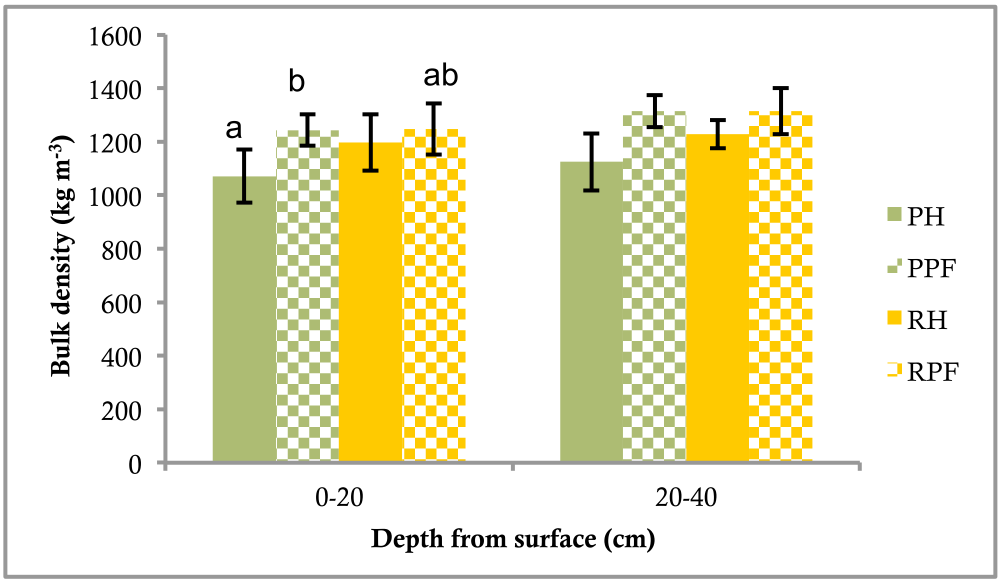

Figure 10. Mean bulk density (kg m^{-3}) for planted (PH) and remnant (RH) hedgerows and their neighbouring production fields (PPF and RPF). Different letters indicate significant difference ($p<0.05$) and error bars represent standard error.

Similarly, the equivalent soil mass (ESM) in hedgerows and adjacent production fields were similar (Figure 11).

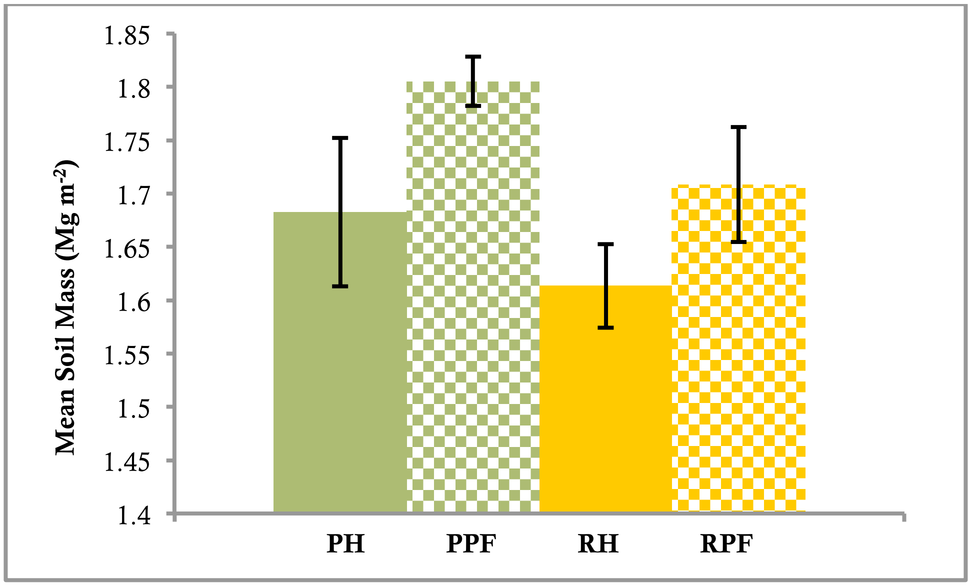

Figure 11. Mean soil mass (Mg m^{-2}) to a one meter depth for planted (PH) and remnant (RH) hedgerows and their neighbouring production fields (PPF and RPF). Error bars represent standard error.

Higher soil bulk density and ESM in the production fields is likely due to frequent operations of heavy machinery (e.g., tillage) that destroy soil structure and cause compaction. The lower soil bulk density in the hedgerows is important as it could contribute to improved hydrological condition on the farm by increasing rainfall infiltration and water holding capacity (Barzegar et al. 2002).

3.1.2.2 SOIL CARBON

We found significantly more carbon stored in soils under PH than the PPF, RPF or RH. For a soil mass of 1.2 Mg m^{-2}, soil C was 175.85 ± 13.22 Mg C ha^{-1} for PH, 125.72 ± 8.17 Mg C ha^{-1} for PPF, 132.7 ± 7.28 Mg C ha^{-1} for RH, and 133.82 ± 6.86 Mg C ha^{-1} for RPF. PH was significantly ($p<0.05$) greater than all PPF, RH and RPF (Figure 12). The quantity of soil C in PH hedgerows 50.13 ± 9.19 Mg C ha^{-1} greater than its neighboring production field a significantly greater higher relative difference than that of RH, which were actually 0.92 ± 8.32 Mg C ha^{-1} lower than their neighboring production fields (Figure 13).

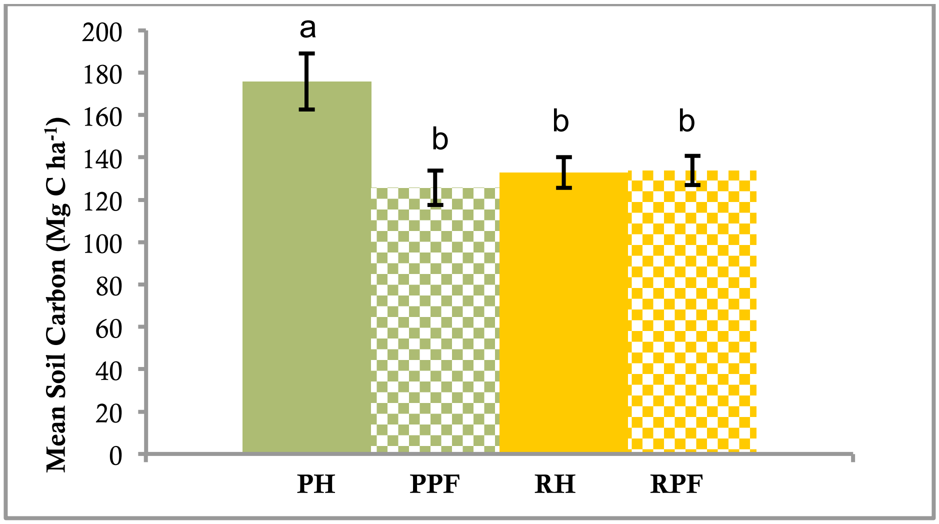

Figure 12. Mean soil carbon (Mg C ha^{-1}) in planted (PH) and remnant (RH) hedgerows and their neighbouring production fields (PPF and RPF) Error bars are standard error and different letters represent a significant difference between means ($p<0.05$).

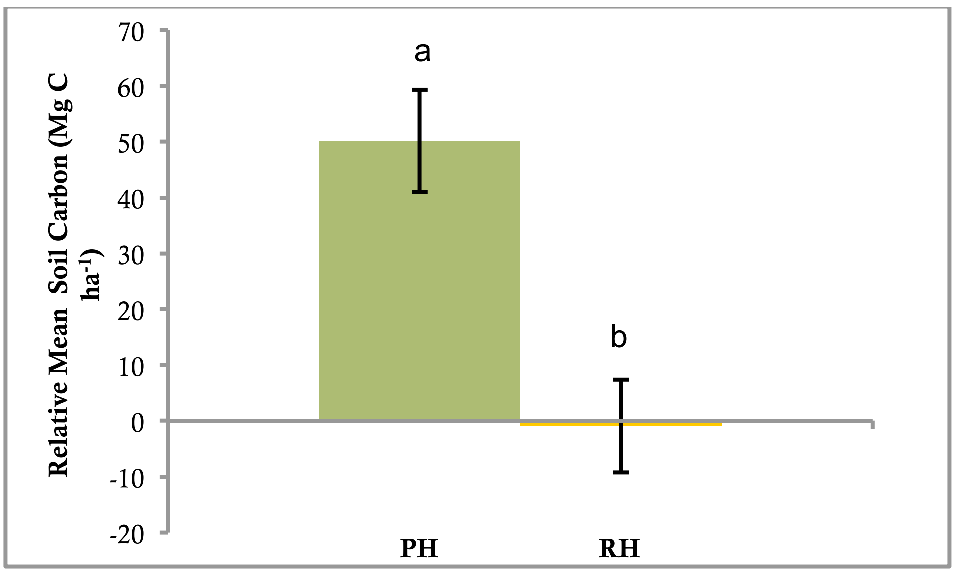

Figure 13. Relative soil carbon (Mg C ha^{-1}) in planted (PH) and remnant hedgerows (RH) relative to their respective neighbouring production fields. Error bars are standard error and different letters represent a significant difference between means ($p<0.05$).

We would expect that hedgerows, given their greater biomass and lack of tillage would sequester more than production fields. Yet our results show that only PH have greater soil C than PF even though they do not have more biomass than RH and are substantially younger in age. The amount of soil C found in the fields is typical of intensive agricultural systems The numbers we report here are for an equivalent mass soil for a dry soil mass of 1.2 Mg m^{-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 Mg C ha^{-1} (Nair 2010).

3.1.2.3 AGGREGATE STABILITY

Soil aggregate stability, as expressed by MWD, on production fields and hedgerows was significantly different ($p<0.05$) (Figure 14). Planted and remnant hedgerows had 104% and 134% greater MWD than neighbouring production fields, respectively The MWD for PH was 2.65 ± 0.28 mm, PPF was 1.30 ± 0.28 mm, RH was 3.12 ± 0.28 mm, and RPF was 1.34 ± 0.28 mm. There was no significant difference in the MWD between PH and RH nor between PPF and RPF. The average difference in MWD in hedgerows relative to their neighbouring production fields was an increase of 1.35 ± 0.17 mm and 1.79 ± 0.17 mm in planted and remnant hedgerows respectively (Figure 15).

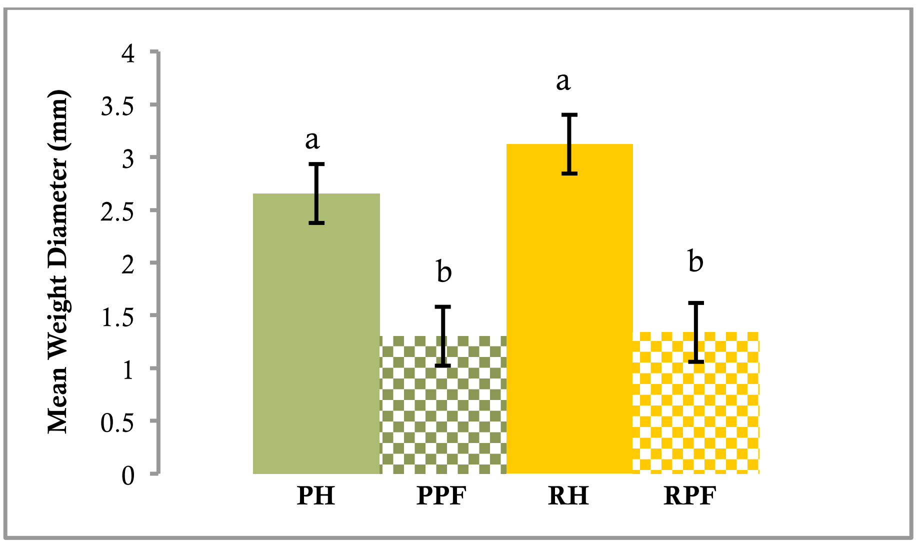

Figure 14. Mean weight diameter (mm)of planted hedgerows (PH), remnant hedgerows (RH) and their respective production fields (PPF & RPF). Error bars represent standard error. Bars with the same letter in each category are not significantly different from each other ($p<0.05$).

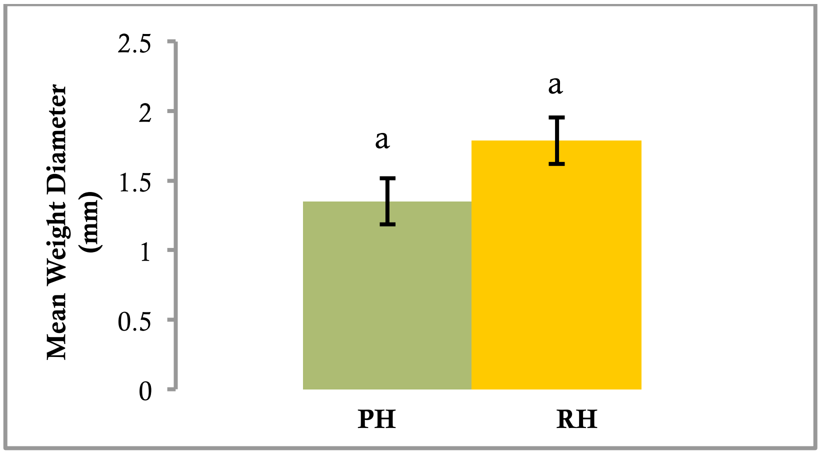

Figure 15. Mean relative weight diameter of hedgerows relative to neighbouring production fields. Error bars represent standard error. Bars with the same letter in each category are not significantly different from each other ($p<0.05$).

Other studies have also reported similar aggregate stability differences between cultivated and non-cultivated land use types. For example, a study in Iran that evaluated the distribution of water-stable aggregates in virgin forests, virgin pasture, cultivated ex-forest and cultivated ex-pasture land use types, 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). Study in India investigated the impact of agroforestry systems on aggregate stability in relation to sole poplar crops and found that MWD was 2.86 times higher in agroforestry systems averaged across loamy sand and sandy clay soil types (Gupta et al. 2009).

As with our indictors of compaction (i.e., soil bulk density and aggregate stability) these results have important implications for farm hydrology but also for the C storage. Greater aggregate stability has been shown to increase rainfall infiltration and water holding capacity (Barzegar et al. 2002). It also has been shown to protect SOC from decomposition and ensures that C stored in the soil is more recalcitrant (Kong et al. 2005).

3.1.3 Greenhouse Gas Emissions

3.1.3.1 CARBON DIOXIDE

The mean annual CO_2 flux was significantly higher in hedgerows than in production fields. The mean annual carbon dioxide flux calculated by non-linear regression was on average 11.3% and 9.0% lower than the linear regression for hedgerows and production fields we therefore report here the results of the linear flux as a more conservative estimate of impact.

The mean annual CO_2 flux was 59.24 $\pm$ 7.77 Mg CO_2 ha^{-1} yr^{-1} for PH, 20.92 $\pm$ 3.28 Mg CO_2 ha^{-1} yr^{-1} for PPF, 49.56 $\pm$ 6.51 Mg CO_2 ha^{-1} yr^{-1} for RH and 25.45 $\pm$ 4.20 Mg CO_2 ha^{-1} yr^{-1} for RPF (Figure 16). Both PH and RH were significantly different from both PPF and RPF ($p<0.001$); however neither PH and RH or PPF and RPF were significantly different from each other. The relative mean annual CO_2 flux was 38.33 $\pm$ 6.91 Mg CO_2 ha^{-1} yr^{-1} for the PH system which was significantly greater ($p<0.05$) than the 24.10 $\pm$ 4.10 Mg CO_2 ha^{-1} yr^{-1} for the RH system (Figure 17).

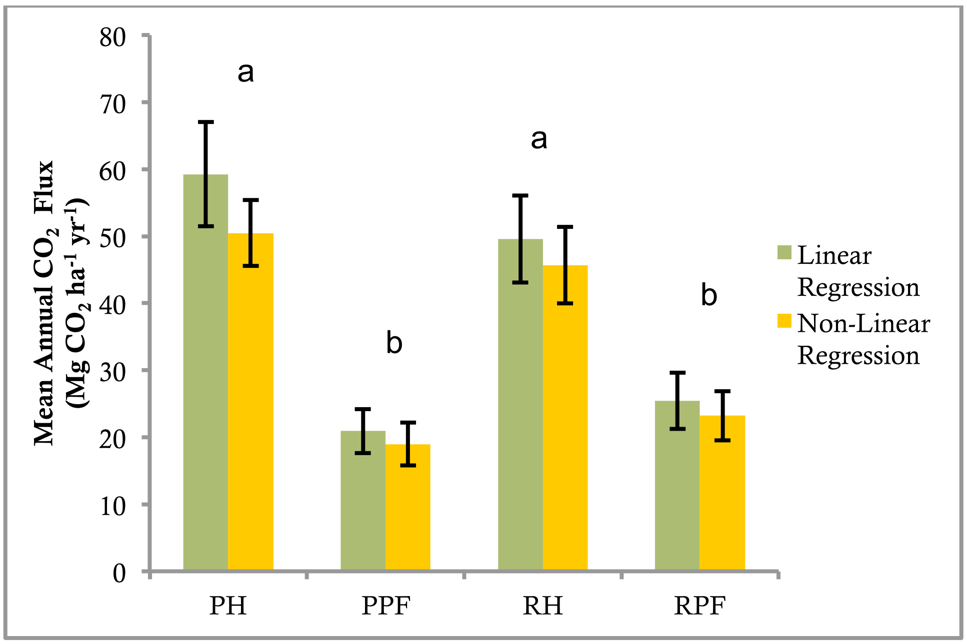

Figure 16. Annual mean CO_2 flux for each treatment type (planted and remnant hedgerows) and their neighbouring production fields. PH = Planted Hedgerows, PPF = production fields neighbouring planted hedgerows, RH = Remnant Hedgerows, RPF = production fields neighbouring remnant hedgerows. Error bars are standard error and bars with the same letter are not significantly different.

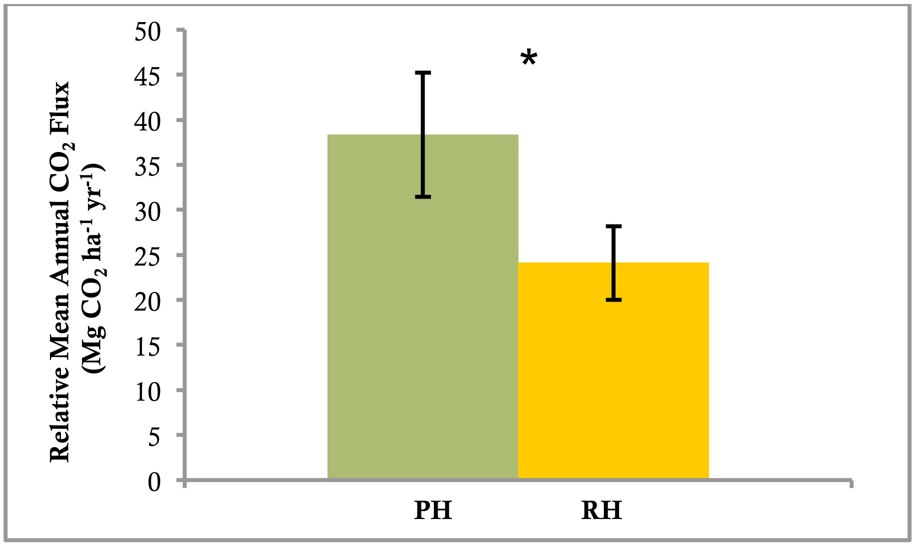

Figure 17. Annual mean CO_2 flux for planted (PH) and remnant (RH) hedgerows and their neighbouring production fields (PPF and RPF)Error bars are standard error and bars with the same letter are not significantly different.

When evaluating the differences observed between the daily sample means for each treatment throughout the entire year (Figure 18) both the treatment – PH, PPF, RH or RPF – and the sample date were significant factors ($p<0.0001$). Further, an interaction effect between treatment and sample date was observed ($p<0.05$), however, to interpret the treatment effect over the whole year, this interaction was not taken into consideration. The mean sample day fluxes observed throughout the year ranged from -0.52 to 10.70 µmol CO_2 m^{-2} s^{-1}. The greatest emission were observed in June and the lowest emissions in November. From May to November the hedgerow treatments tended to have higher CO_2 emission rates, sometimes more than double than their neighbouring production fields. Soil temperature and CO_2 flux were moderately correlated (Figure 19) for each of the land use types at the 0-5 cm depth – PH (R^2=0.45), PPF (R^2=0.54), RH (R^2=0.65) and RPF (R^2=0.51) – and no correlation was observed between soil moisture and CO_2 fluxes (Figure 20). Similar observations were made for the interaction at the 10-15 cm depth for both soil temperature and moisture.

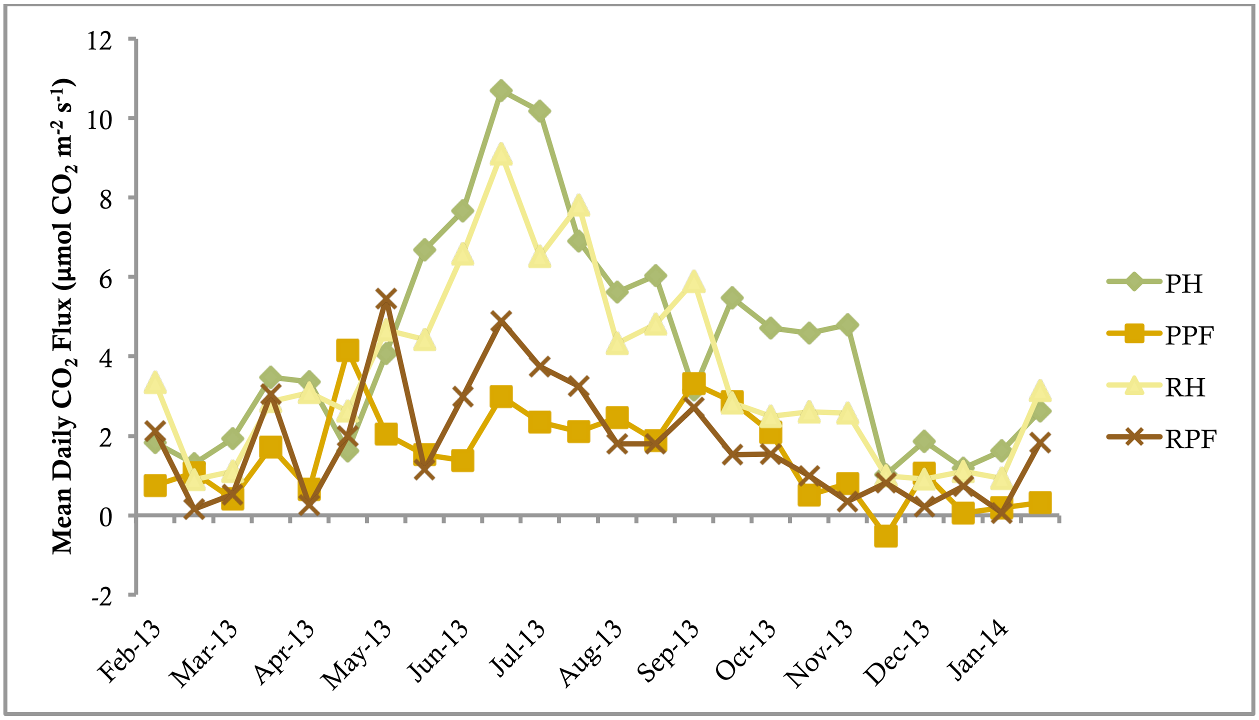

Figure 18. Daily mean (n=4) CO_2 fluxes measured in µmol CO_2 m^{-2} s^{-1} over a twelve month period for planted hedgerows (PH), neighbouring production fields to planted hedgerows (PPF), remnant hedgerows (RH), and neighbouring production fields to remnant hedgerows (RPF).

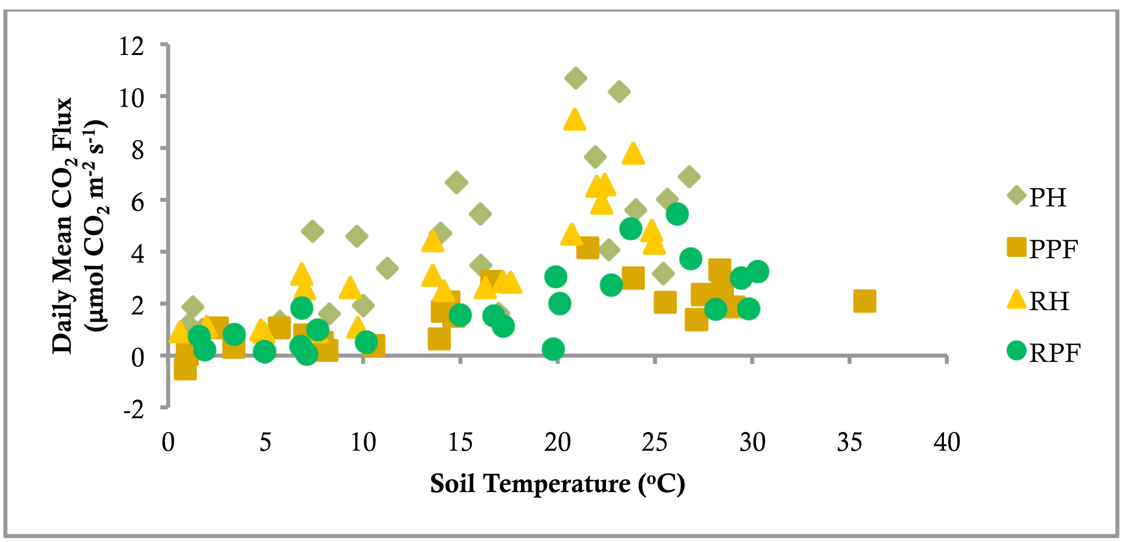

Figure 19. Daily mean (n=4) CO_2 flux and soil temperature interaction at the surface 0-5 cm depth.

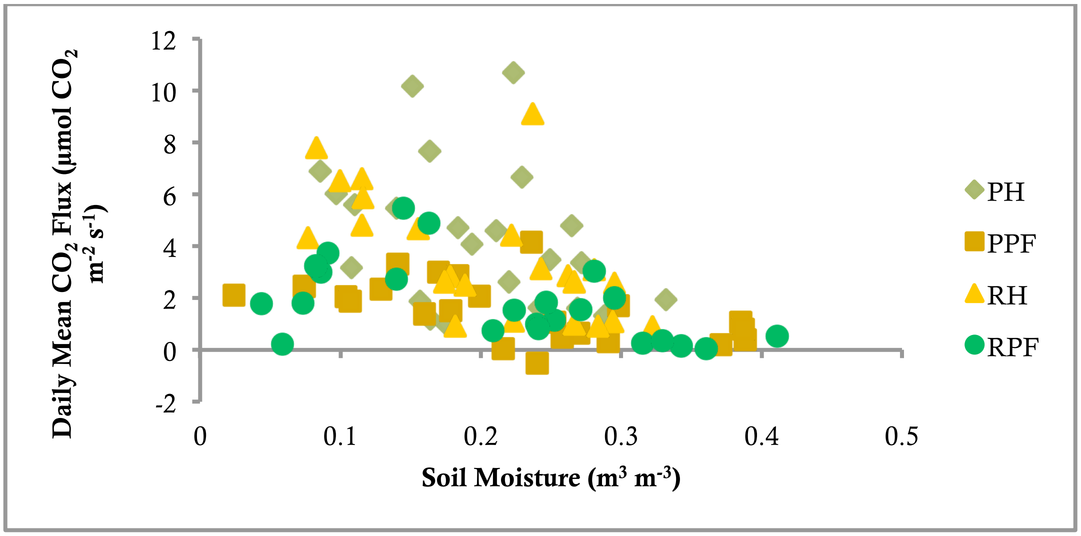

Figure 20. Daily mean (n=4) CO_2 flux and soil moisture interaction for the surface 0-5 cm depth.

Values of CO_2 measured here are comparable to other studies of systems of with perennial vegetation and agricultural production. Zhange et al. (2012) found significant differences between CO_2 emissions in a *Populus* shelterbelt and a *U. pumila* (Siberian Elm) shelterbelt during the growing season in an arid climate in China. The mean monthly emission rates ranged from 1.79 to 7.46 µmol CO_2 m^{-2} s^{-1} for the *Populus* site and 0.97 to 3.43 µmol CO_2 m^{-2} s^{-1} for the *U. pumila* site. The estimated mean annual emission rates were 23.04 $\pm$ 3.67 Mg CO_2 ha^{-1} yr^{-1} and 27.57 $\pm$ 5.12 Mg CO_2 ha^{-1} yr^{-1} for *U. pumila* in year one and two of the study, and 40.90 $\pm$ 6.96 Mg CO_2 ha^{-1} yr^{-1} and 62.87 $\pm$ 12.50 Mg CO_2 ha^{-1} yr^{-1} for *Populus* in year one and two for the study respectively (Zhang et al. 2012). This study also found a correlation between soil temperature and respiration, with the strongest relationship for temperatures from a depth of 35 cm (we measured temperature at 0-5 cm and 10-15 cm). Like us Zhang et al. (2012) did not find a correlation between soil water content and respiration. In another study Hatala et al. (2012), observed emission similar to ours on agricultural land in a delta region of San Francisco that is saturated and drained much like the farmland in the lower Fraser River delta. Grazed peatland produced 54.74 to 64.72 Mg CO_2 ha^{-1} yr^{-1}, and a rice paddy produced 43.12 to 49.5 Mg CO_2 ha^{-1} yr^{-1} in two years of the study (Hatala et al. 2012). In contrast, observed emission rates in non-saturated agricultural production fields (wheat-maize and faba bean-maize crop rotations) on a loamy clay soil in China were 24.21 Mg CO_2 ha^{-1} yr^{-1} and 25.52 Mg CO_2 ha^{-1} yr^{-1} (Guo et al. 2008).

The differences between the CO_2 emission from the field and the hedgerows may be explained by the larger and more continuous additions of organic matter in the perennial system. There are a number of expected sources of CO_2 in hedgerow and production field soils but we were focused on mainly one, soil respiration. Gross primary productivity is the total amount of CO_2 photosynthesized and incorporated into plant biomass. CO_2 is then lost through autotrophic respiration of the plant leaves aboveground and roots belowground. Carbon is transferred from the plant to the soil through leaf litter and root exudates, and CO_2 is released to the atmosphere when as soil organisms respire as they decompose this organic matter.

Though these processes will happen in both hedgerows and production fields, since there is higher organic matter contribution to the soil in the hedgerows, we could expect greater heterotrophic respiration from decomposers. Further, autotrophic respiration (and heterotrophic from herbivores) could continue for more of the year in the hedgerows given their perennial vegetation, as opposed to the shorter growing season of the production fields. .

3.1.3.2 NITROUS OXIDE

Although mean annual N_2O fluxes were higher in the production fields they were not significantly different from emissions observed from the hedgerows. The mean annual N_2O flux was 2.52 $\pm$ 1.50 kg N_2O ha^{-1} yr^{-1} for PH, 6.50 $\pm$ 1.67 kg N_2O ha^{-1} yr^{-1} for PPF, 2.55 $\pm$ 1.09 kg N_2O ha^{-1} yr^{-1} for RH and 3.62 $\pm$ 1.20 kg N_2O ha^{-1} yr^{-1} for RPF (Figure 21). The relative means were also not statistically different. The relative mean annual N_2O flux was for PH was 3.97 $\pm$ 1.27 kg N_2O ha^{-1} yr^{-1} lower than the neighbouring fields and for RH, 1.07 $\pm$ 1.74 kg N_2O ha^{-1} yr^{-1} their the neighboring fields (Figure 22).

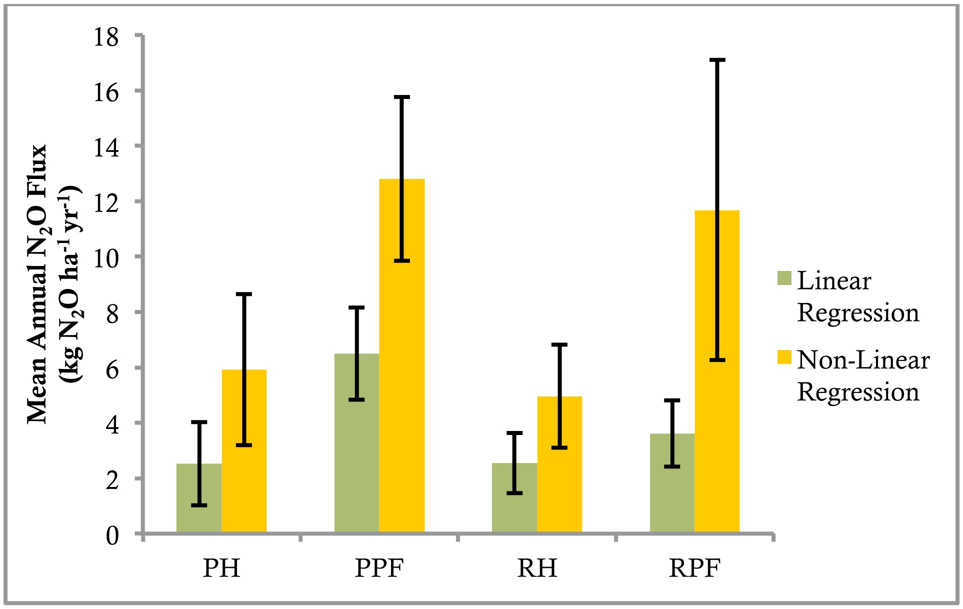

Figure 21. Annual mean N_2O flux for planted (PH) and remnant (RH) hedgerows and their neighbouring production fields (PPF and RPF). Error bars are standard error.

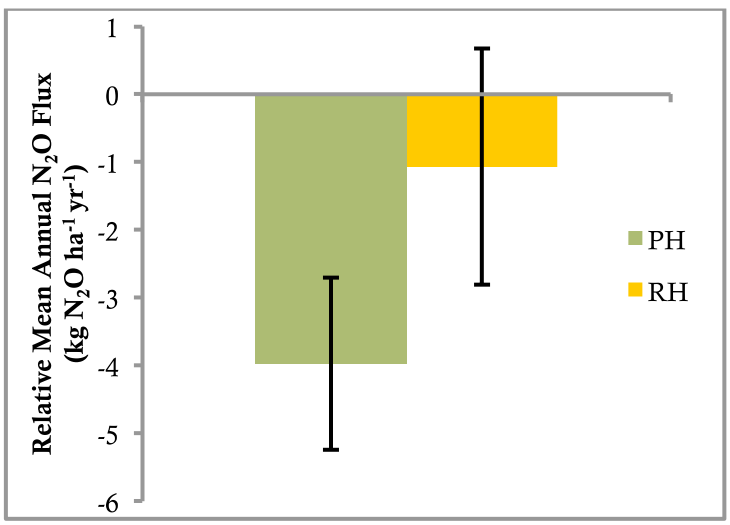

Figure 22. Relative mean annual N_2O flux for planted (PH) and remnant (RH) hedgerows relative to their neighbouring production fields respectively using linear regression analysis. The error bars represent standard error.

Mean annual values of N_2O are not clearly differentiated among the land use types partly because of the high variability we observed from sampling period to sampling period (Figure 23). Over the course of the year we did not see significant differences in the daily observations of N_2O emissions between the hedgerows and fields, 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 sample day fluxes observed throughout the year ranged from 0 to 9.20 μmol N_2O m^{-2} hr^{-1}. The greatest emissions were observed in October and the lowest emissions in November. There were no correlations between soil water content or temperature and N_2O flux at either the 0-5 cm or 10-15 cm depth. However, trends of increased N_2O emissions were observed for intermediate soil moisture contents of 0.15 to 0.35 m^3 m^{-3} (not shown).

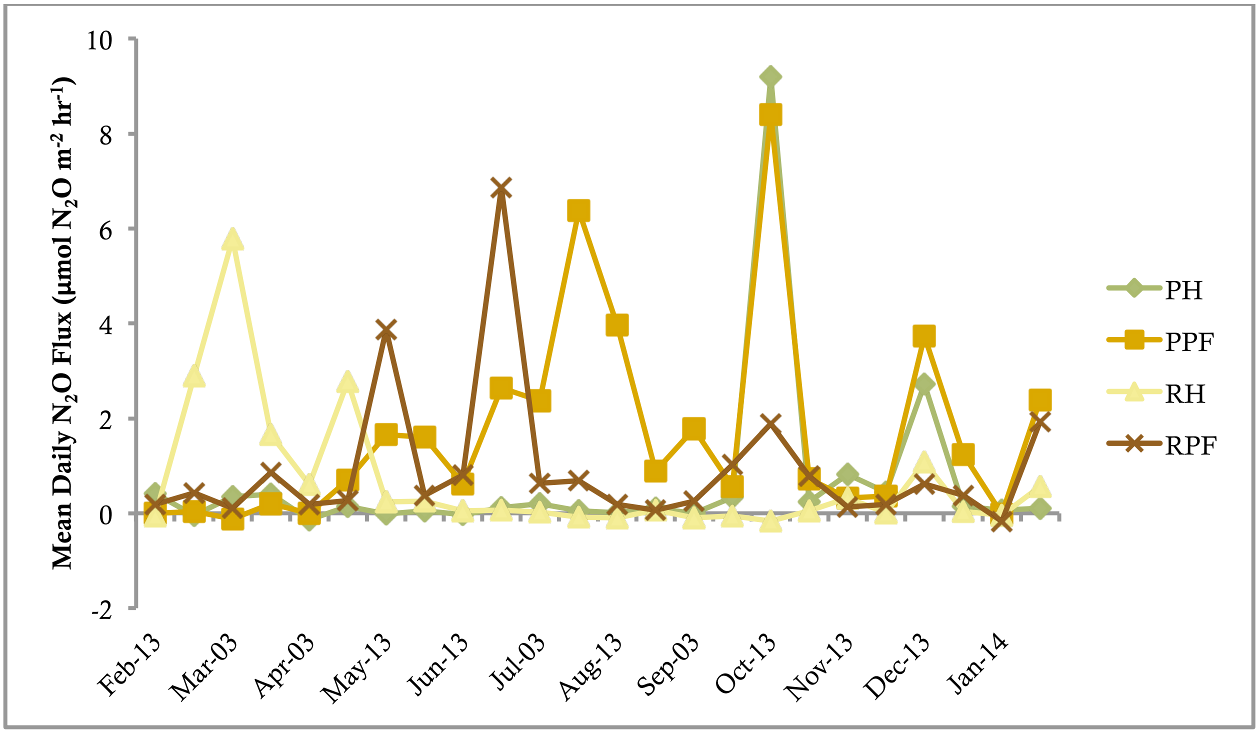

Figure 23. Daily mean (n=4) N_2O fluxes (μmol N_2O m^{-2} s^{-1}) measured over a twelve month period for planted hedgerows (PH), neighbouring production fields to planted hedgerows (PPF), remnant hedgerows (RH), and neighbouring production fields to remnant hedgerows (RPF).

Our N_2O emissions results are comparable to those in forest and agricultural systems. In a temperate forest in Northern Europe, Christiansen et al. (2012) observed that the majority of N_2O fluxes measured were below 6.81 kg N_2O ha^{-1} yr^{-1}, though the range of their modeled annual mean flux rates for their two sites (0.45 to 1.30 kg N_2O ha^{-1} yr^{-1}

and 0.4 to 1.2 kg N_2O ha^{-1} yr^{-1}) were slightly lower than those observed in our hedgerows (Christiansen et al. 2012). In a Quebec study conducted from May to October in a corn-soybean cropping system, MacKenzie et al (1997) found that N_2O emissions in conventional tillage system ranged from 5.53 to 6.95 kg N_2O ha^{-1} yr^{-1} depending on the soil type, and were 6.47 kg N_2O ha^{-1} yr^{-1} in a no-till system (MacKenzie et al. 1997).

N_2O emissions occur as a result of soil microbial activity naturally, but we expected to find higher emissions in production fields compared to the hedgerows as a result of farm management practices. Large quantifies of N (>100 kg ha^{-1}) are typically added as fertilizer to the production fields annually. This fertilizer can be transformed through nitrification, an aerobic process, that converts ammonium (NH_4) into nitrate (NO_3) and in the process releases N_2O as a by–product. Or in saturated conditions where soils area anaerobic, the transformation can be through denitrification, a process that converts nitrate (NO_3) into nitrogen gas (N_2) again with N_2O as a by-product. Denitrification may be common in the Delta's production fields where the soils are saturated for much of the growing season.

3.1.3.3 METHANE

The mean annual CH_4 flux was 23.35$\pm$ 9.93 kg CH_4 ha^{-1} yr^{-1} for PH, 3.75 $\pm$ 1.53 kg CH_4 ha^{-1} yr^{-1} for PPF, -1.17 $\pm$ 0.9 kg CH_4 ha^{-1} yr^{-1} for RH, and 2.15 $\pm$ 0.91 kg CH_4 ha^{-1} yr^{-1} for RPF (Figure 24). No significant differences ($p<0.05$) were observed between treatments.

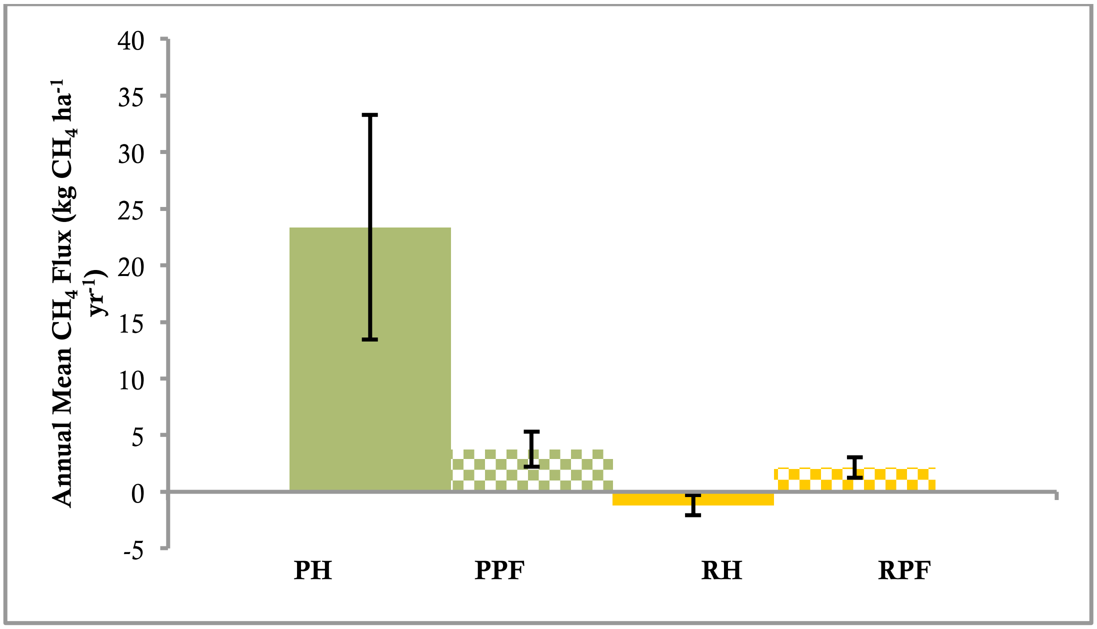

Figure 24. Mean annual CH_4 fluxes (kg CH_4 ha^{-1} yr^{-1}) from planted (PH) and remnant hedgerow (RH) treatments and their neighbouring productions fields using non-linear regression. Differing letters indicate significant differences ($p<0.05$) and error bars represent standard error.

As with the other GHGs, CH_4 fluxes varied widely from sampling plot to plot and over the year (Figure 25). There were significant ($p<0.05$) differences in daily sample mean fluxes between treatments (i.e.PH, PPF, RH or RPF) but no differences between dates were found and no interaction between treatment and sample date. The mean sample day fluxes observed throughout the year ranged from -12.05 to 155.56 μmol CH_4 m^{-2} hr^{-1}. There was no correlation between soil water content and CH_4 flux (data not shown), and similarly, no linear correlation was observed between the soil temperature and CH_4 flux.

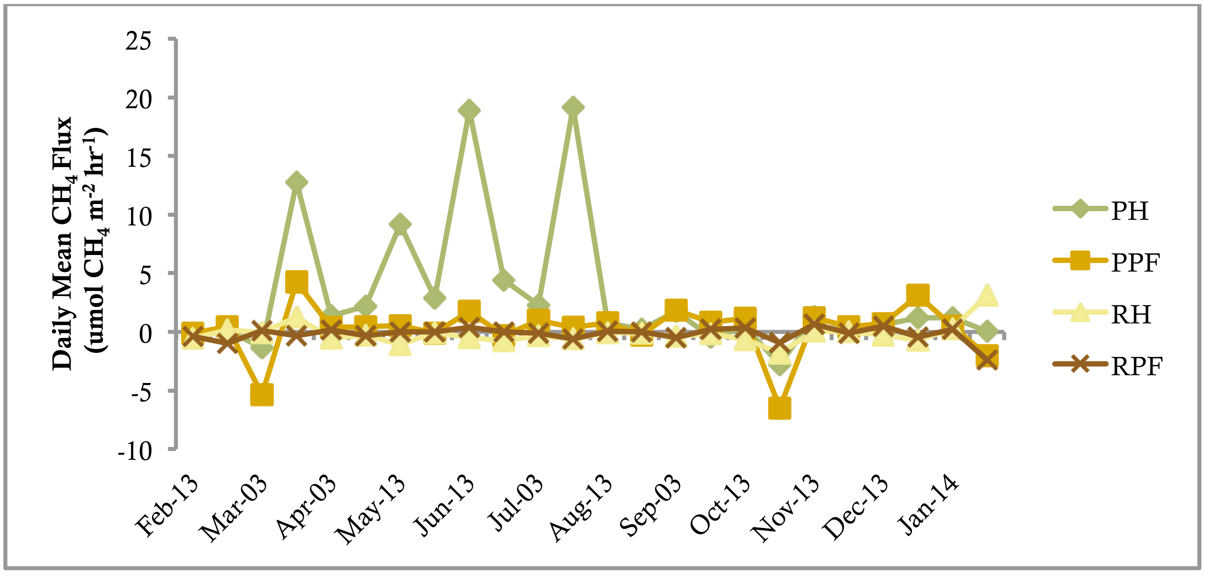

Figure 25. Daily mean (n=4) CH_4 fluxes (μmol CH_4 m^{-2} s^{-1}) measured over a twelve month period for planted hedgerows (PH), neighbouring production fields to planted hedgerows (PPF), remnant hedgerows (RH), and neighbouring production fields to remnant hedgerows (RPF) using non-linear regression.

Though CH_4 activity was highly variable over the year, results are comparable to findings from other studies. In a review of the range of CH_4 oxidation for a number of ecosystems focusing on Northern Europe Smith et al. (2000) reported annual CH_4 rates of uptake for studies measured for at least one year ranged from - 0.1 to - 9.1 kg CH_4 ha^{-1} yr^{-1} (Smith et al. 2000). In another study, Weslien et al. 2009 a observed net annual emissions in a forest that averaged 0.8 $\pm$ 0.1 kg CH_4 ha^{-1} yr^{-1} (Weslien et al. 2009).

3.1.4 Global Warming Potential

3.1.4.1 SOILS, VEGETATION AND GREENHOUSE GASES

To better understand the relative environmental outcomes of planting or protecting hedgerows we converted our biomass and soil C and GHG emission results to a standardized unit of CO_2 equivalents. CO_2 equivalents enable the evaluation of the overall impact on global climate change or the global warming potential. While we see differences in the carbon stored in the soil and tree and shrub biomass between the hedgerow types, when these carbon pools are converted to their CO_2 equivalent (Mg CO_2 ha^{-1}), their total mitigation potential is equal (Figure 26). The total carbon stored in PH is 940 Mg CO_2e ha^{-1} and in RH is 947 Mg CO_2e ha^{-1}. What is unclear from this data is how much is CO_2 is accumulated annually.

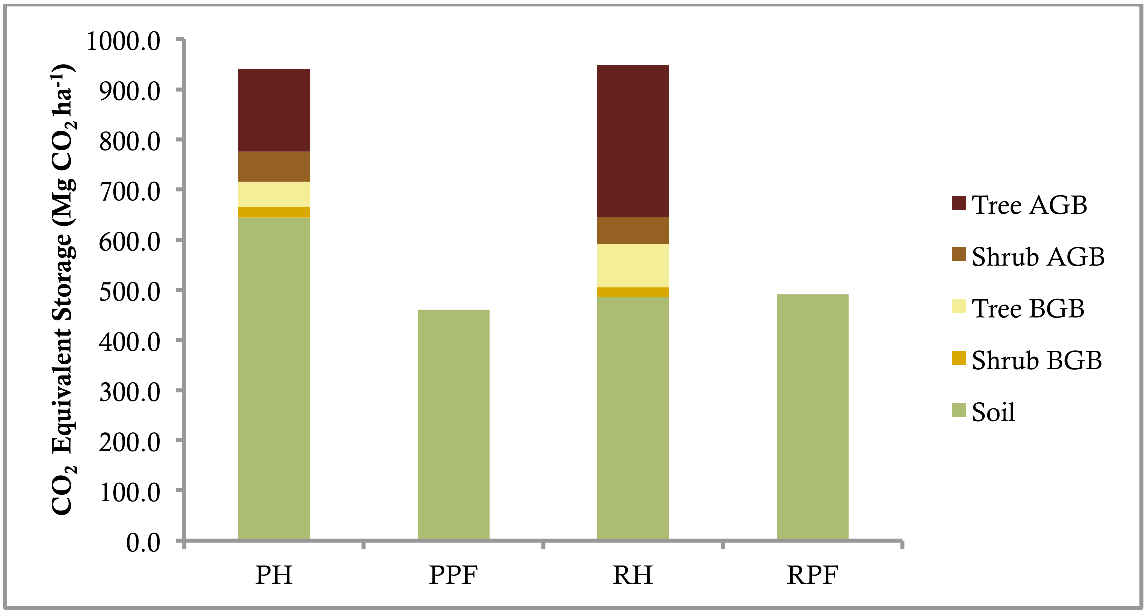

Figure 26. Distribution of carbon pools (Mg CO_2e ha^{-1}) compared for planted hedgerows (PH), remnant hedgerows (RH) and their neighboring production fields (PPF and RPF). Error bars represent standard error.

To try to understand the rate of accumulation of the carbon pools in the two hedgerow types we plotted the carbon pool either soil or biomass for the age of each hedgerow. While the linear relationship between age and carbon pool is not strong given the small size of the sample and the uncertainty of the remnant hedgerow age, the data illustrates a pattern that should be further explored (Figure 27). As would be expected there is increased biomass C as the woody vegetation matures. What is interesting is the indication that soil C may be declining over time. Although it is possible that this data illustrates a spatial pattern, where remnant hedgerows are found on poorer soils our CO_2 emission data suggests otherwise.

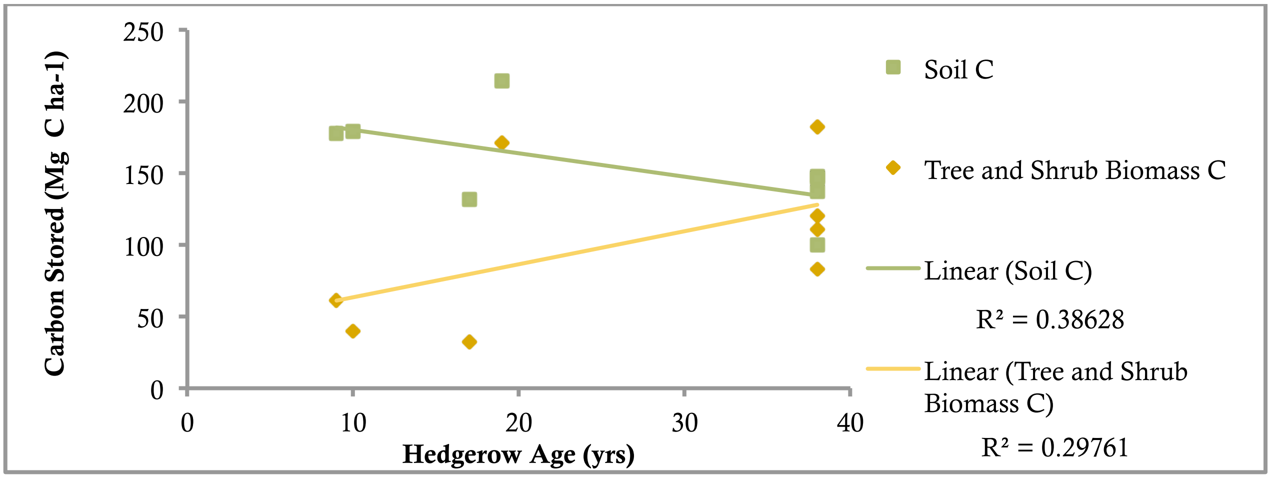

Figure 27. Carbon storage comparison of soil and biomass C compared to hedgerows age.

We can see from the CO_2e emissions data that an equivalent of almost 10% of the CO_2e stored in the soil was lost through soil respiration (Figure 28). Though understanding the dynamics of carbon storage is interesting, it is also important when evaluating the climate change mitigation potential of these systems to put them in the context of the landscape greenhouse gas emissions as well. Essentially, measuring the sequestration rates need to be balanced by measuring the emission rates from the system. 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 means and ranges of net annual emission of all three gases.

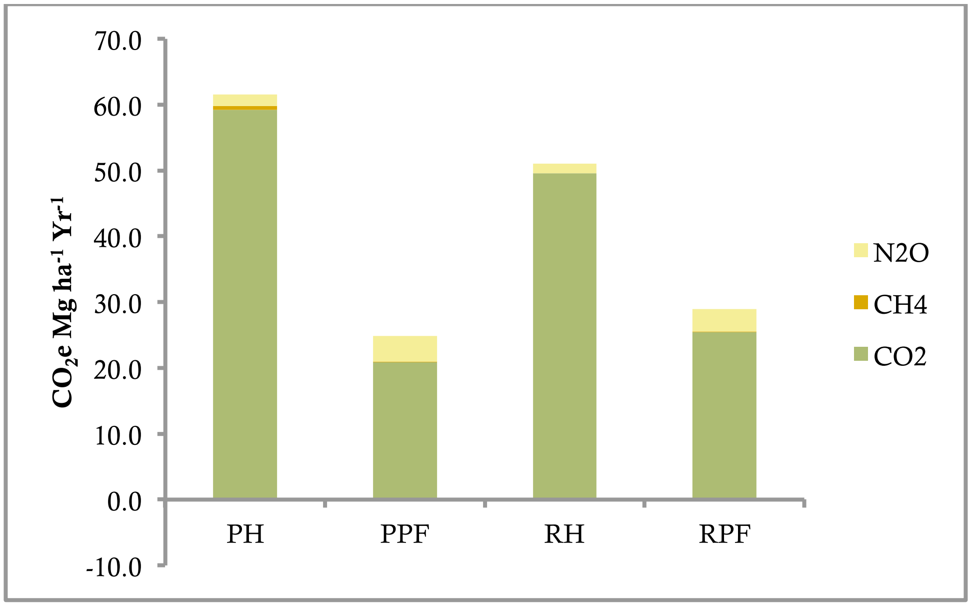

Figure 28. Annual net global warming potential of the three greenhouse gases measured over the year of planted hedgerows (PH), remnant hedgerows (RH) and their neighboring production fields (PPF and RPF). Error bars represent standard error.

3.2 Landscape Analysis

3.2.1 Historical Landscape Woody Habitat

The historical air photos were initially utilized to better determine the age of the *remnant* hedgerows in our study. From these photos it was clear that all of the *remnant* hedgerows had been established sometime after the 1930 photos (Figure 29) were taken but well before 1966 (Figure 30). We deduced that the hedgerows were between 20-56 years old and used the midpoint, 38 years, as a best estimate of their actual age.

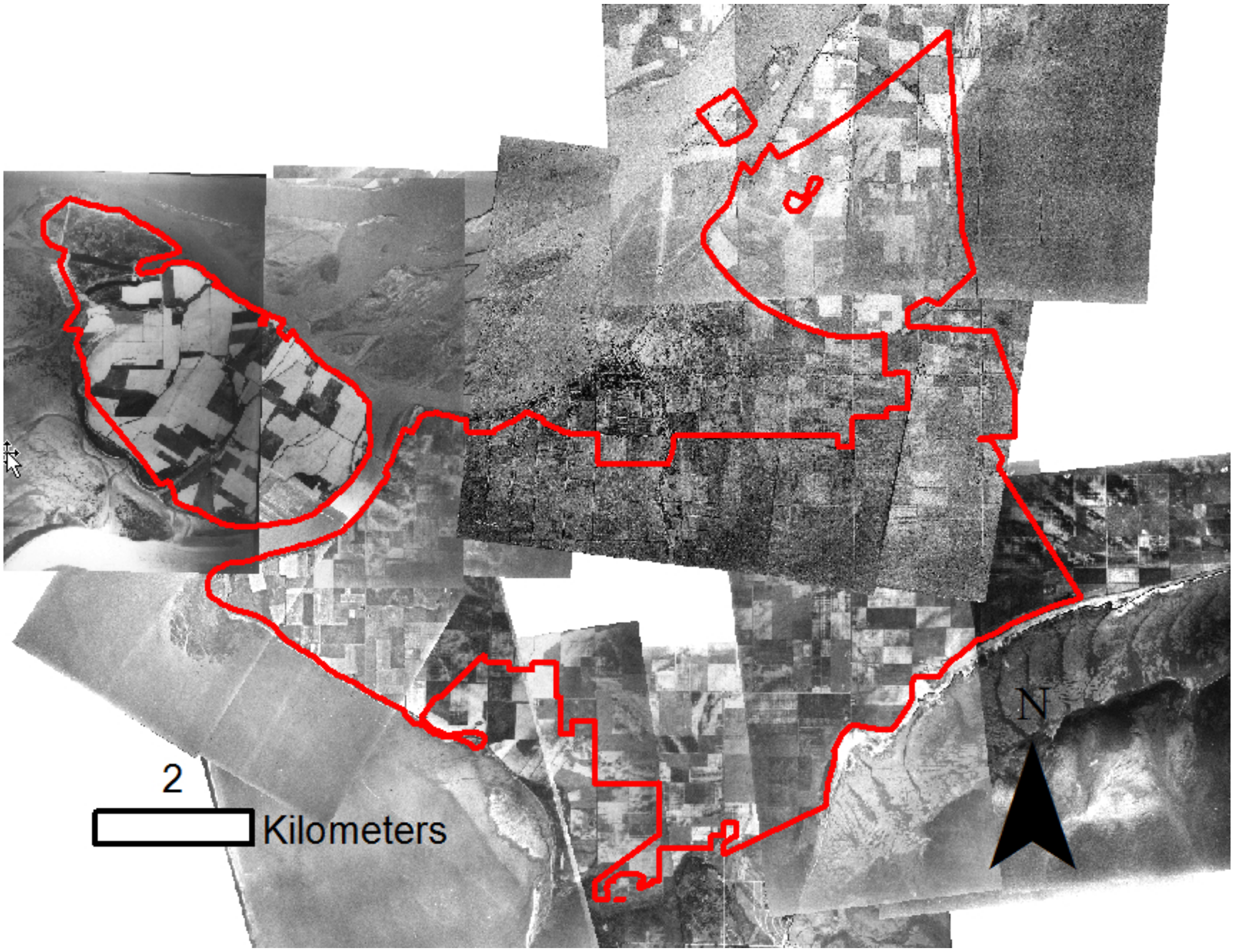

Figure 29. Scanned and mosaicked aerial photos from 1966. Red line indicates the boundary of the historical analysis area.

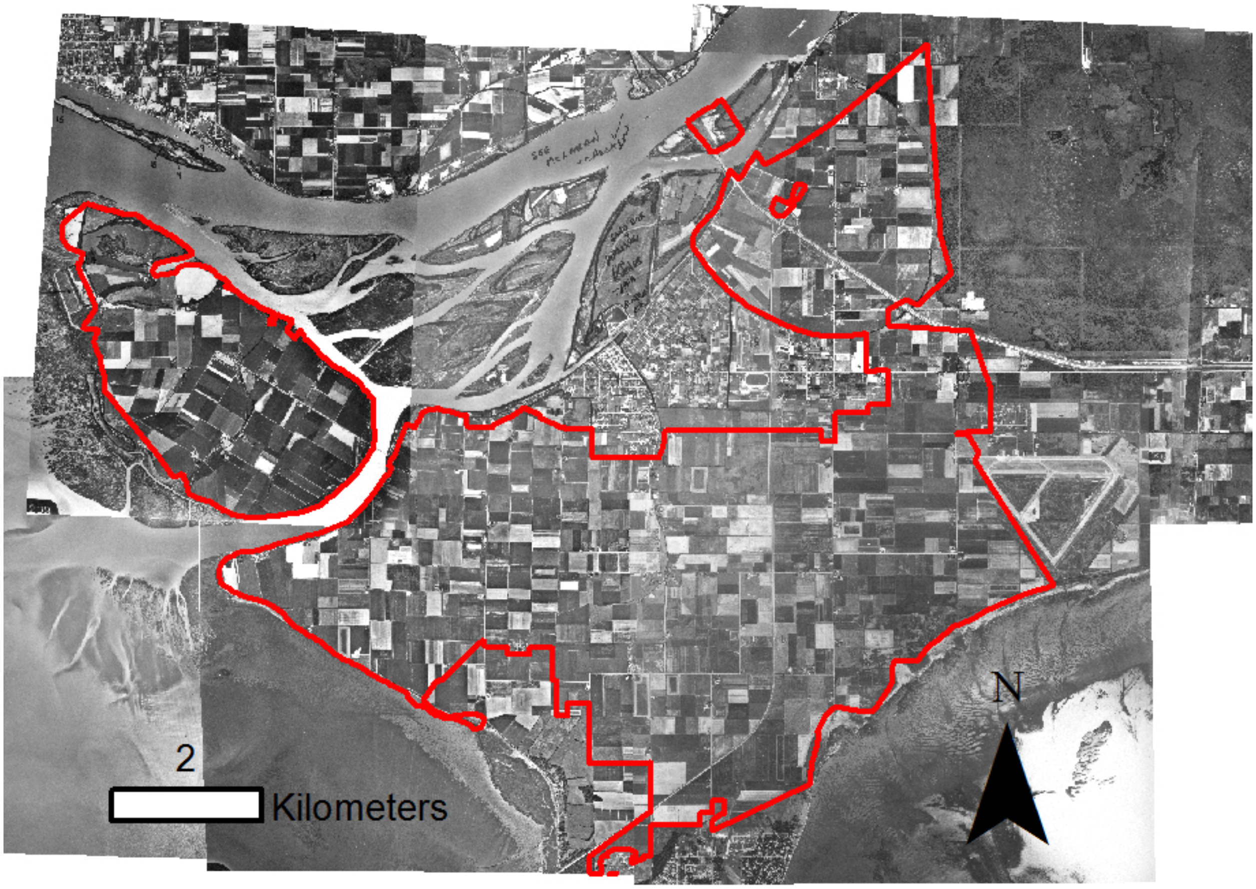

Figure 30. Scanned and mosaicked aerial photos from 1966. Red line indicates the boundary of the historical analysis area.

Our analysis of the 1966 mosaicked air photos determined that there were a total of 121 ha of woody habitat or 2% of the 5,928 ha region of our historical analysis area of the Delta's ALR (Figure 31). Of that woody habitat, 5 ha had been clearly planted and or managed intensively. Our analysis of the 1986 air photos (Figure 32) indicated that 25 ha of woody habitat were cut down reducing the total woody habitat to 96 ha or to 1.6% of the total historical analysis area (Figure 33). At the same time the number of hectares that were planted and or managed intensively increased to 11 ha. The decrease of total woody habitat and increase in planted area could be attributed to changes in land management, such as the expansion of agricultural land or urban development or possibly it could be attributed to the differences in resolution between the two sets of air photos (i.e. 1966's MMU = 0.015 ha and 1986's MMU = 0.005).

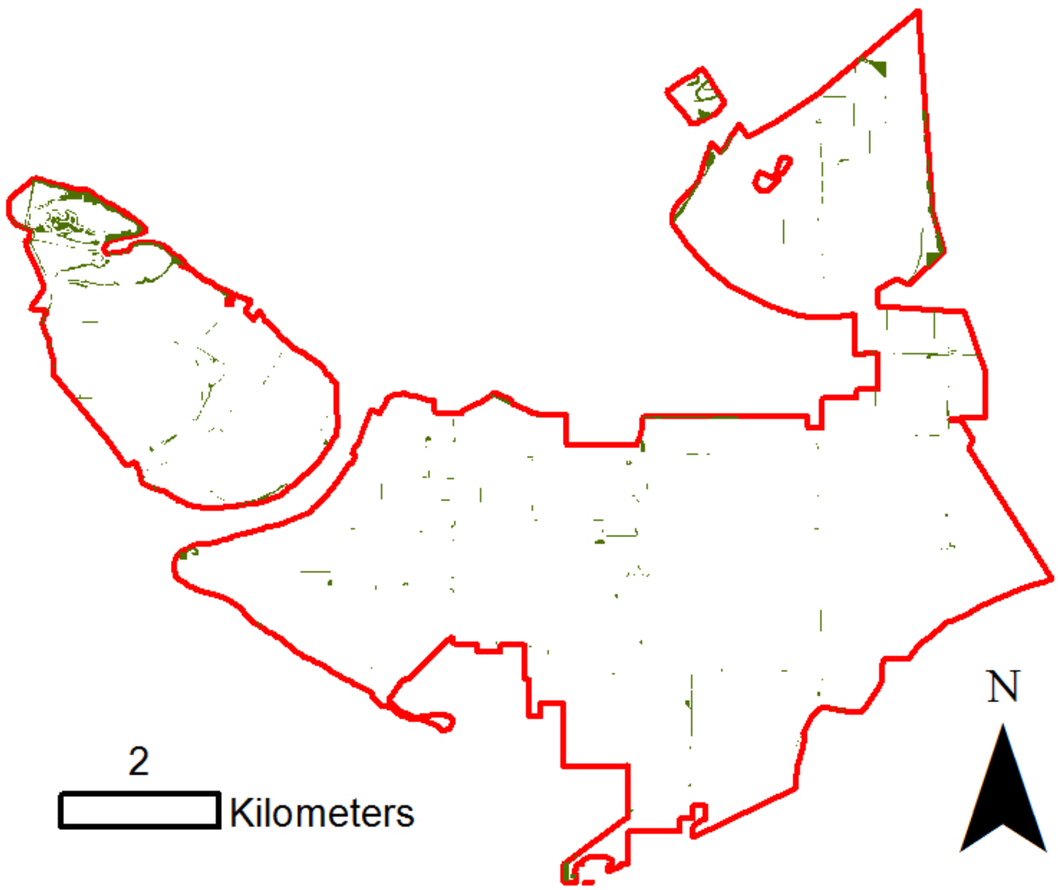

Figure 31. Analysis of woody habitat found within a subset of the Delta's agricultural land reserve in 1966.

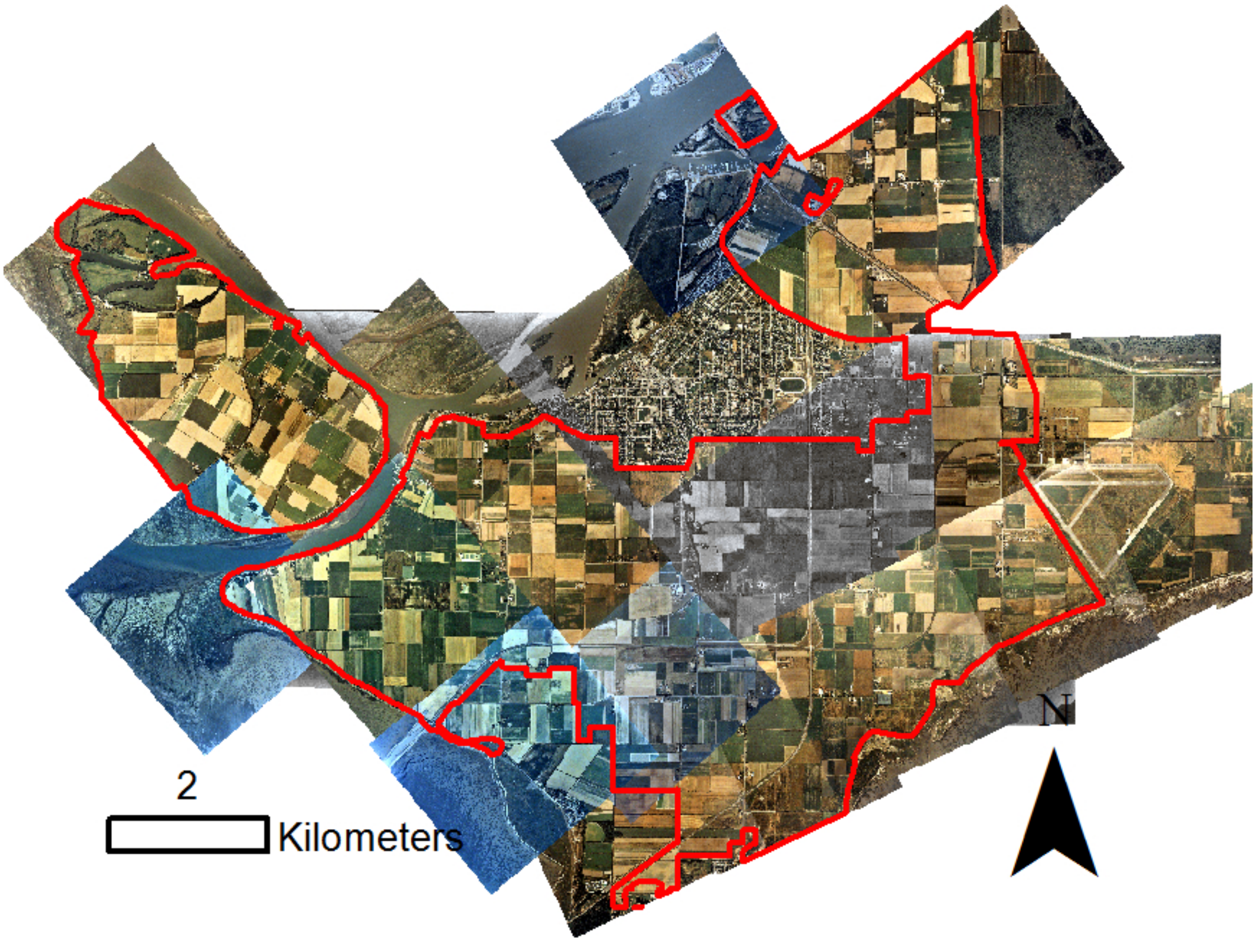

Figure 32. Scanned and mosaicked aerial photos from 1986. Red line indicates the boundary of the historical analysis area.

From 1986 to 2012 there was a substantial increase woody habitat (Figure 34). In 2012 we determined there was 131 ha of total woody habitat, 2.2% of the historical analysis area (Figure 35). Planted and managed woody habitat increased by 1 ha to 12 ha or 0.2% of the total historical analysis area (Figure 36). Some of the increase of woody habitat area from 1986 to 2012 could be again attributed to the differences in air photo quality. While the MMU is the same, the quality and consistency of colors and shadows is far better in the 2012 image enabling a more detailed determination of total woody habitat and the differentiation of what is managed and what is not. Regardless of error associated with our analysis methodology it is clear that there has been an increase in woody habitat from 1986 to 2012 (a difference of 0.6%) but it is unclear if the 0.2%

difference between 1966 and 2012 is due to an actual increase or due to differences in data quality and analysis methodology.

Even if there has been an increase in woody habitat over the last 50 to 80 years the current area of woody habitat is likely far less than what was there prior to European settlement. Surveys of the Delta done by the Royal Engineers from 1958 to 1880 indicated that 31% of the area was once woody habitat (Schaefer 2004). Butler and Campbell (1987) compared the 1880 survey to their estimates of habitat in 1985 and found that woody habitat had been reduced to only 10% of the landscape. While these numbers are not directly comparable to our analysis given that they are from a much larger area and use very different analysis methods, they indicate that even though woody habitat has increased recently, this is likely far from what might have been there in 1880.

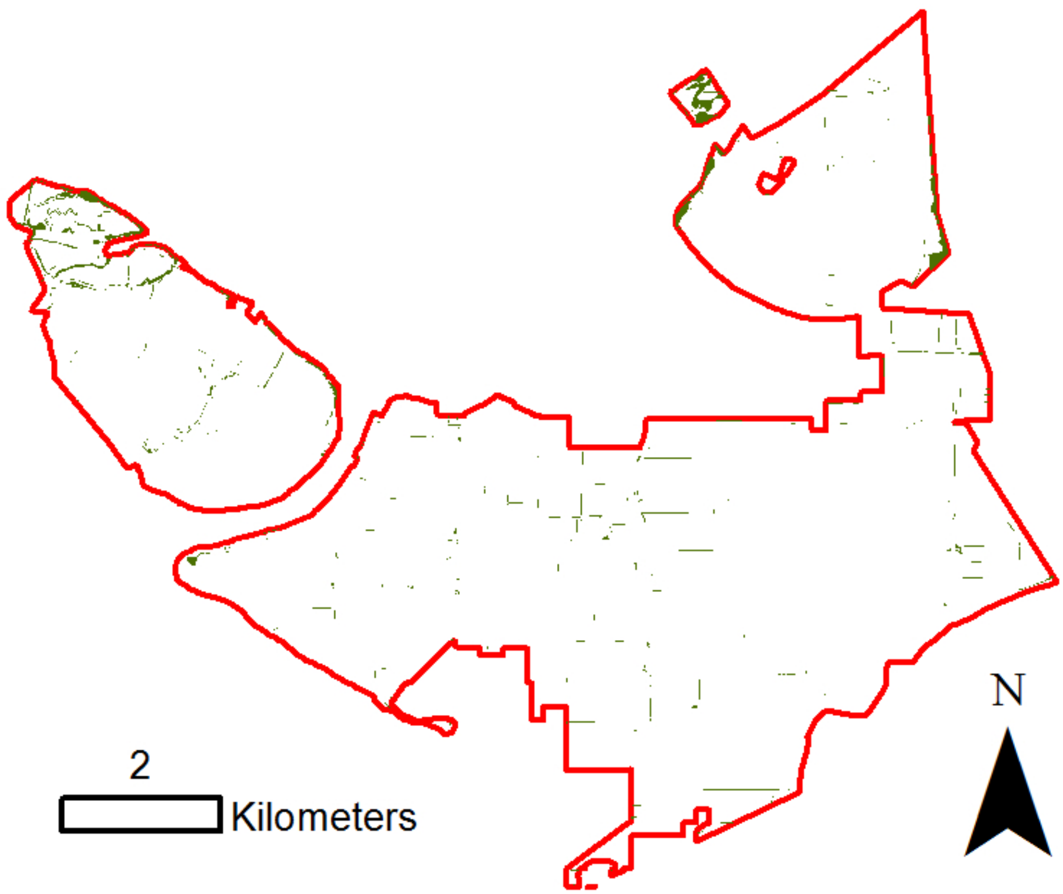

Figure 33. Analysis of woody habitat found within a subset of the Delta's agricultural land reserve in 1986.

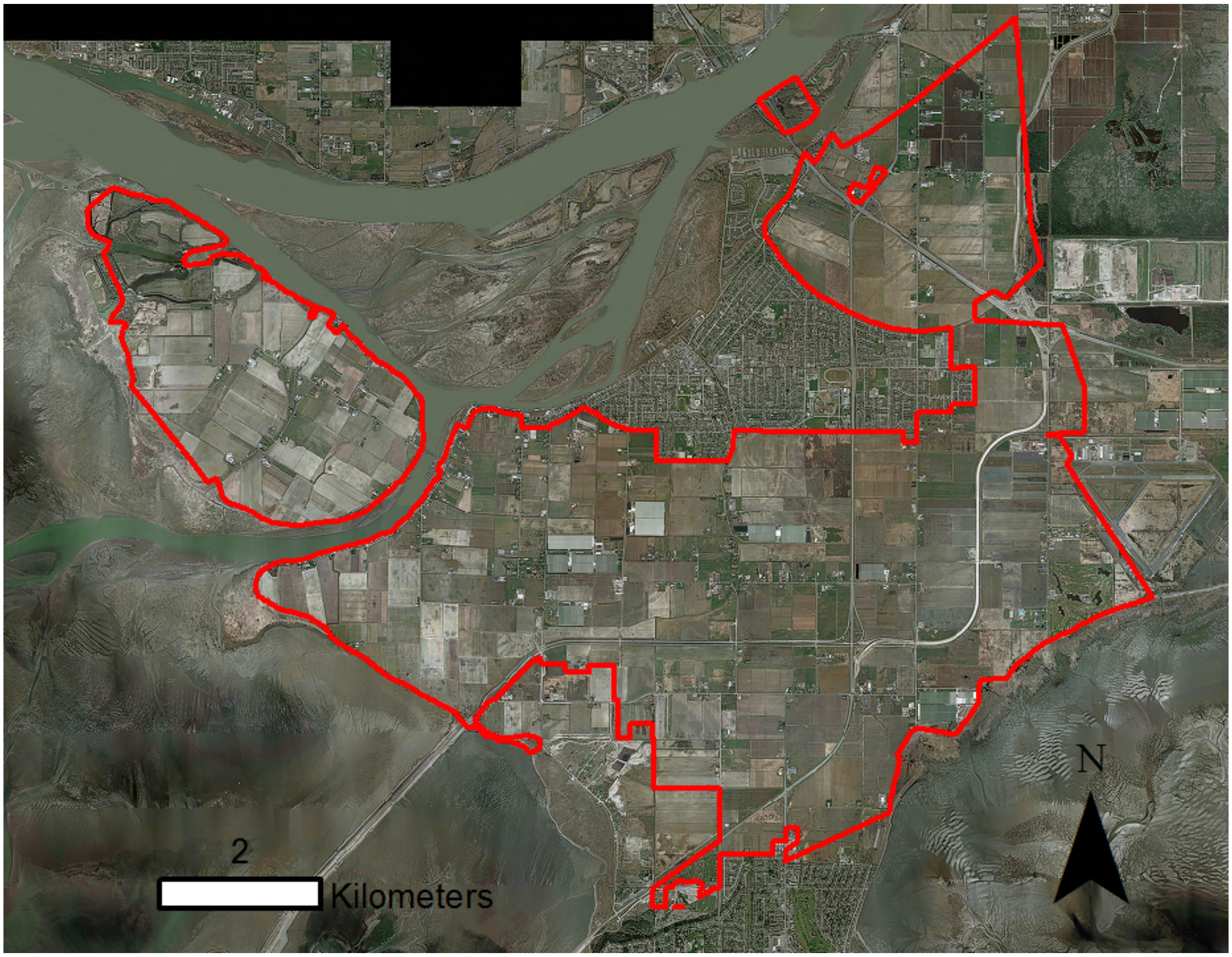

Figure 34. Aerial photo of 2012. Red line indicates the boundary of the historical analysis area.

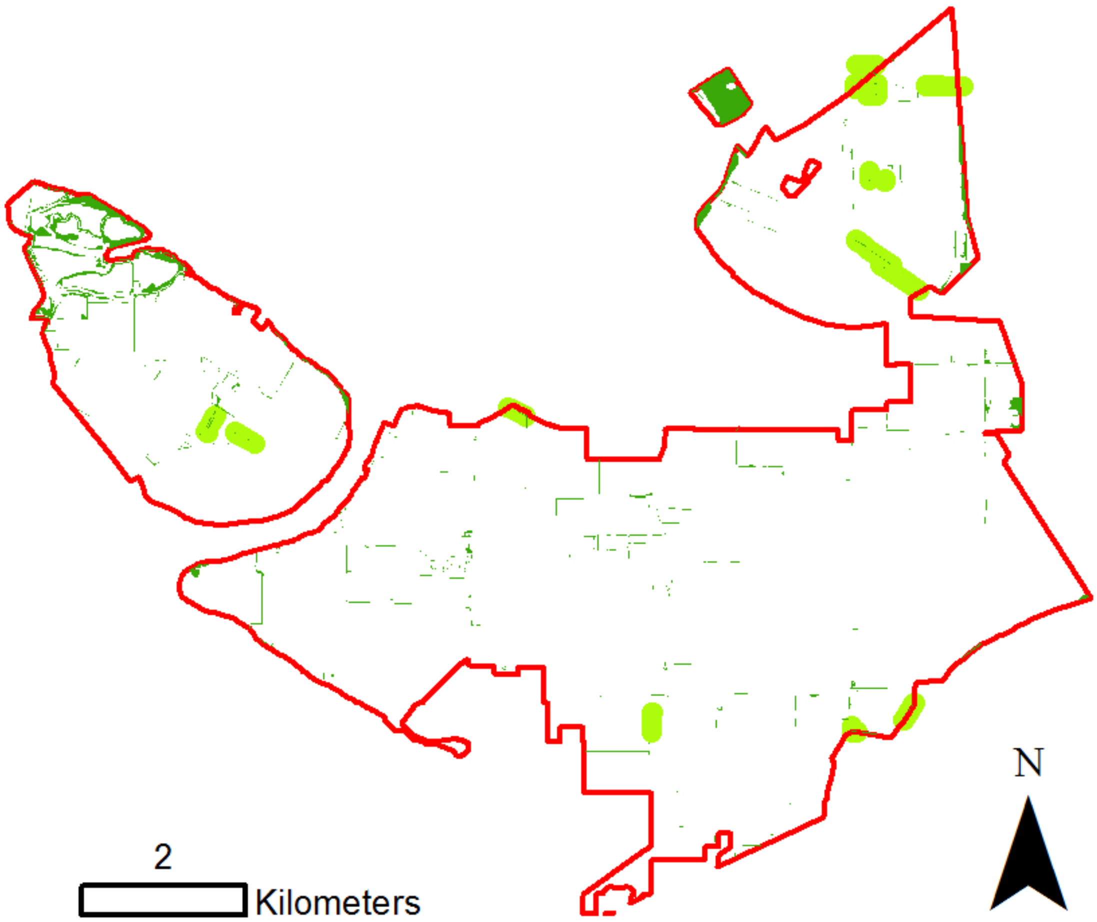

Figure 35. Analysis of woody habitat found within a subset of the Delta's agricultural land reserve in 2012. Light green highlighted areas indicate the distribution of the DF&WT hedgerows.

Since the programs inception in 1995, the DF&WT has been planting hedgerows on 430 m of farmland per year with an average area of 0.15 ha. By 2012 the program planted 15 hedgerows totaling 6 km and an area of 2.2 ha. The program's hedgerows are likely responsible for much of the change in woody habitat observed in the analysis area (Figure 36) and are at least offsetting any losses.

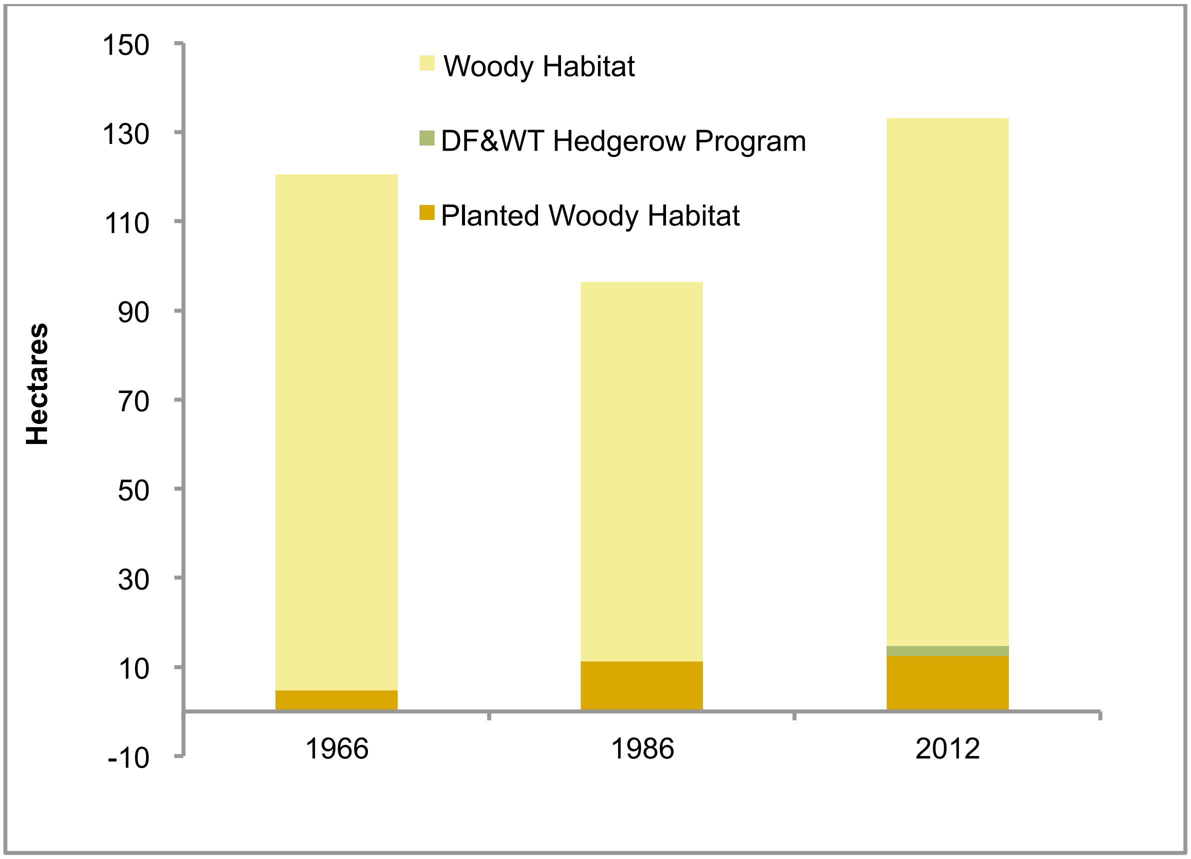

Figure 36. Analysis of the area of woody habitat in 1966, 1986 and 2012 and the area of woody habitat established by the DF&WT Hedgerow Program.

3.2.2 Land Use Land Cover 2013

The land use land cover (LULC) map developed from the analysis of the Rapid Eye satellite image differentiated agricultural land, bare land and other types of vegetation. The analysis was completed at two scales, at the scale of the *historical analysis* (5,928 ha) to compare to the results of the LULC change analysis and at the larger *project analysis* area (9,802 ha) to generate future scenarios for a more complete coverage of the Delta's ALR.

The *project analysis area* was dominated by 6,854 ha of agricultural land, followed by 1,931 ha of vegetation, and 1006 of bare land (Figure 37). *Bare land* included small patches of bare soil, roads, and built structures. When this analysis was compared to the historical analysis results it is clear that the *vegetation* class included far more than just woody habitat.

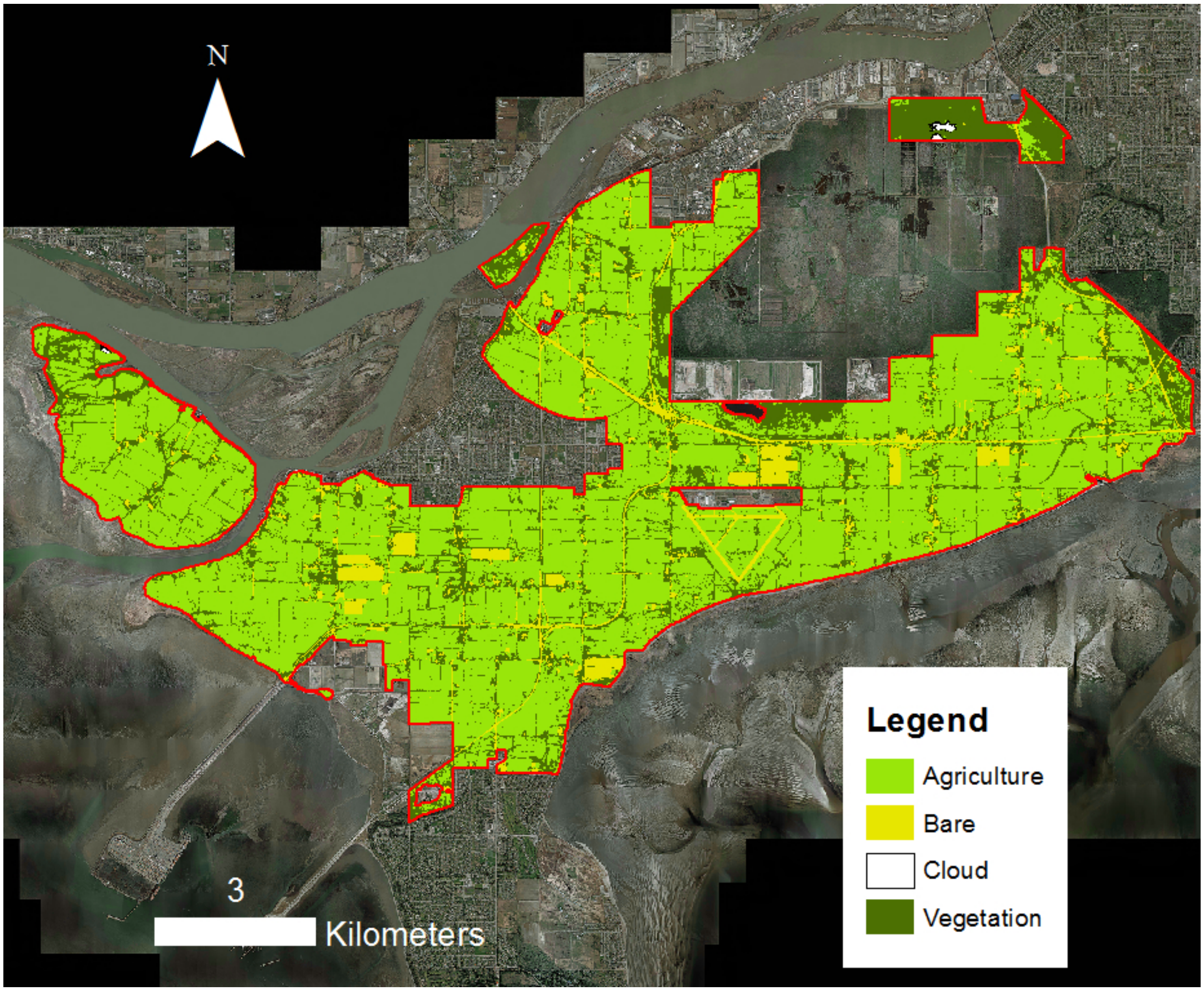

Figure 37. Land use/ Land Cover map of the agricultural land reserve in the Delta project area derived from Rapid Eye satellite imagery capture in 2013

The hand digitized woody vegetation in 2012 air photo (1m resolution) was only 2% of the analysis area while the automated analysis of the 2013 of the Rapid Eye satellite imagery (6m resolution), differentiated non-production vegetation as 18% of the entire landscape (Figure 38). When the analysis area is expanded to the entire *project area* the relative distribution of *vegetation* to other LULC types remains close to the same amount (20%).

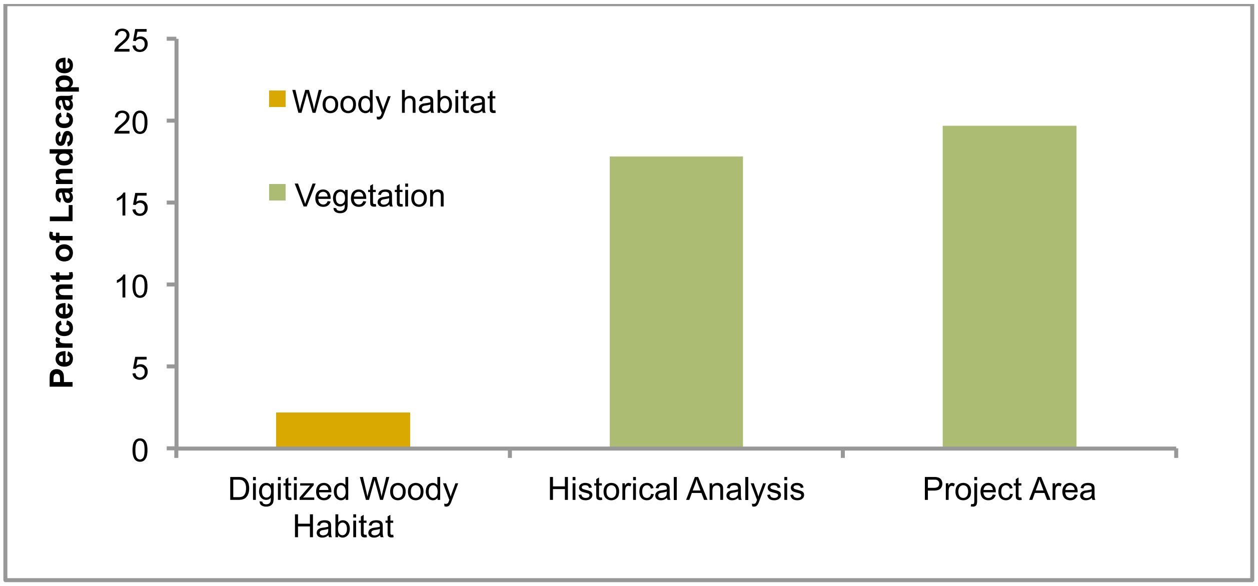

Figure 38. Digitized woody habitat in 2012 and vegetation identified in the remote sensing analysis of the Rapid Eye satellite image in 2013 in the historical analysis area (5,928 ha) and vegetation in the project area (9,802 ha) as a percent of the total area

The differences between the two analysis methods are substantial, illustrating the limitations of remote sensing and the need for cautious interpretation of the results. It is likely that hand digitizing underestimated the total area of woody habitat given that many trees and shrubs found across the landscape were not included because they did not meet the MMU criteria. Alternatively the *vegetation* LULC type derived from satellite imagery analysis is clearly an over estimate of woody habitat. The satellite imagery analysis would have captured many of the trees and shrubs that would not have met the MMU criteria but because of the imagery resolution (5m) the area of those trees and shrubs may have been determined to be larger than it would if digitized. For example if a 5m in diameter tree canopy (78m^2 in area) fell between two 5m pixels the diameter could be assesses as 10m or 314m^2 in area, an area four times that of the air photo analysis. The utility of using the medium resolution imagery is that large areas of landscape can be quickly analyzed and the methodology standardized between images enabling more comparable change over time. The air photo digitization process is extremely time consuming and can be very widely between technicians. The utility of medium resolution imagery, such as Rapid Eye may be limited for an area as small as our *historical analysis* area (~5000 ha) but may be more appropriate larger scales (>10,000 ha).

3.2.3 Landscape Environmental Function

The analysis of the three future scenarios for the Delta's ALR illustrated that maximizing the establishment of hedgerows in the region would have little impact on our indicators of environmental function but there would likely be substantial decline for all indicators should there be large scale agricultural expansion.

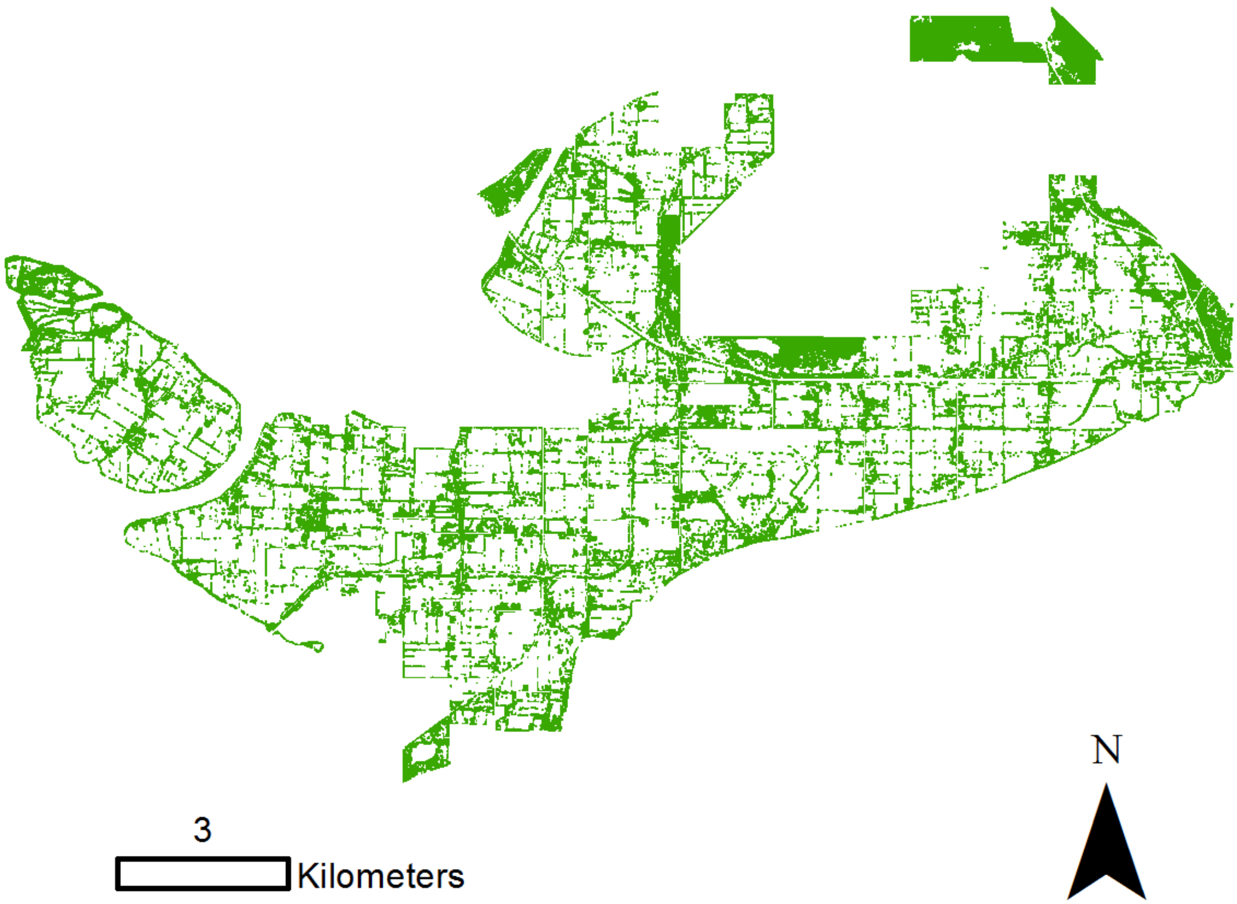

Figure 39. The distribution of non-production vegetation habitat in the "Business as Usual" scenario where the area of habitat in 2013 is kepMg Constant

Estimated values of landscape carbon stocks were 8% lower for the *Business as Usual* scenario (Figure 39) than the *Maximize Hedgerow* scenario (Figure 40) but these were not clearly distinguishable given the high variability associated with these estimates. The average values for these scenarios were however ten times greater than that of the *Agricultural Expansion* scenario (Figure 41). We calculated the *Maximize Hedgerow* scenario would result in 499,988 ± 105,301 Mg C landscape^{-1} while the *Business as*

Usual scenario would results in 458,417 ± 96,546 Mg C landscape^{-1}. Our estimate of agricultural expansion was only 47,816 ± 10,070 Mg C landscape^{-1}. The conversion of habitat to farmland would result in 150,000 metric tons of carbon dioxide lost to the atmosphere (Figure 42).

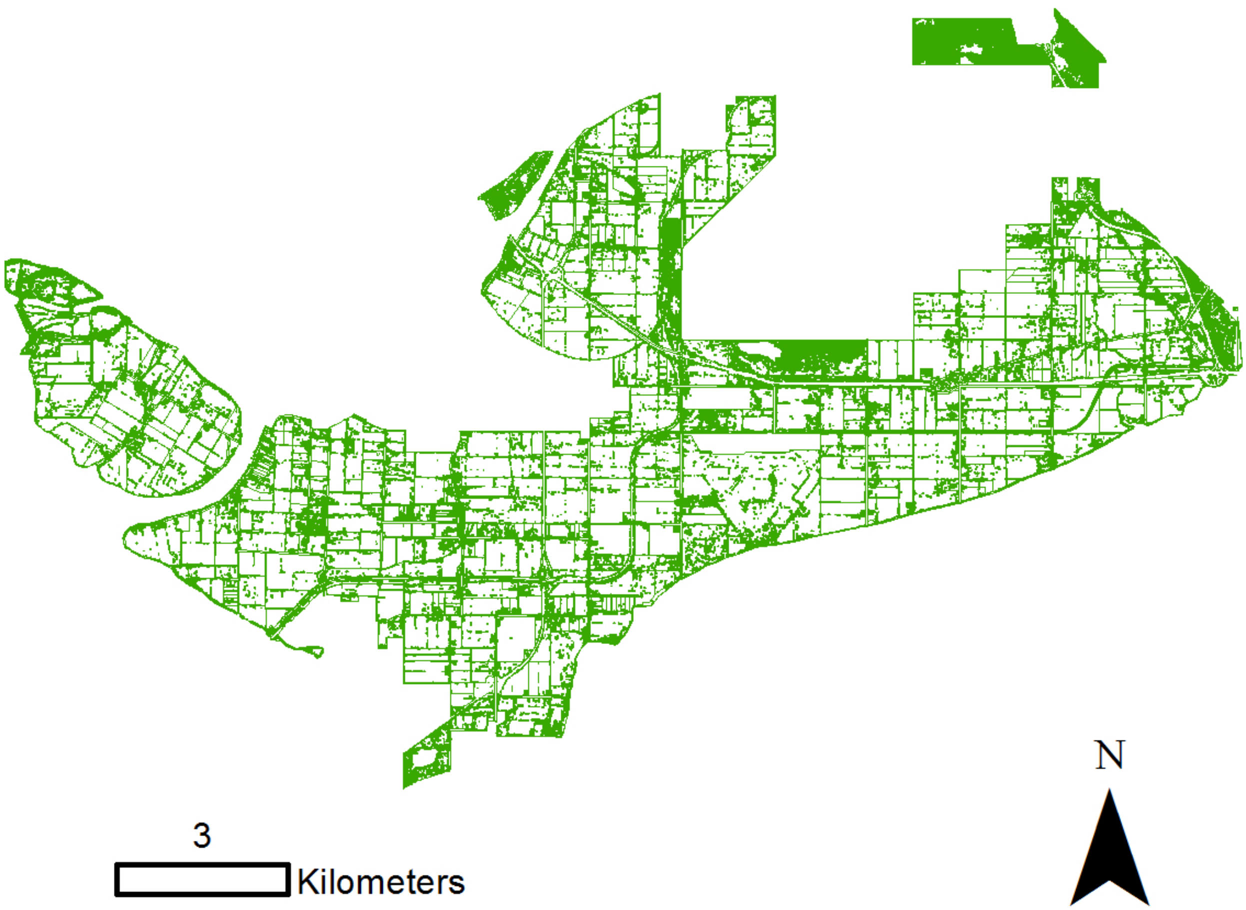

Figure 40. The distribution of non-production vegetation habitat in the “Maximize Hedgerow” scenario where all roadways and parcel edges are planted with hedgerows.

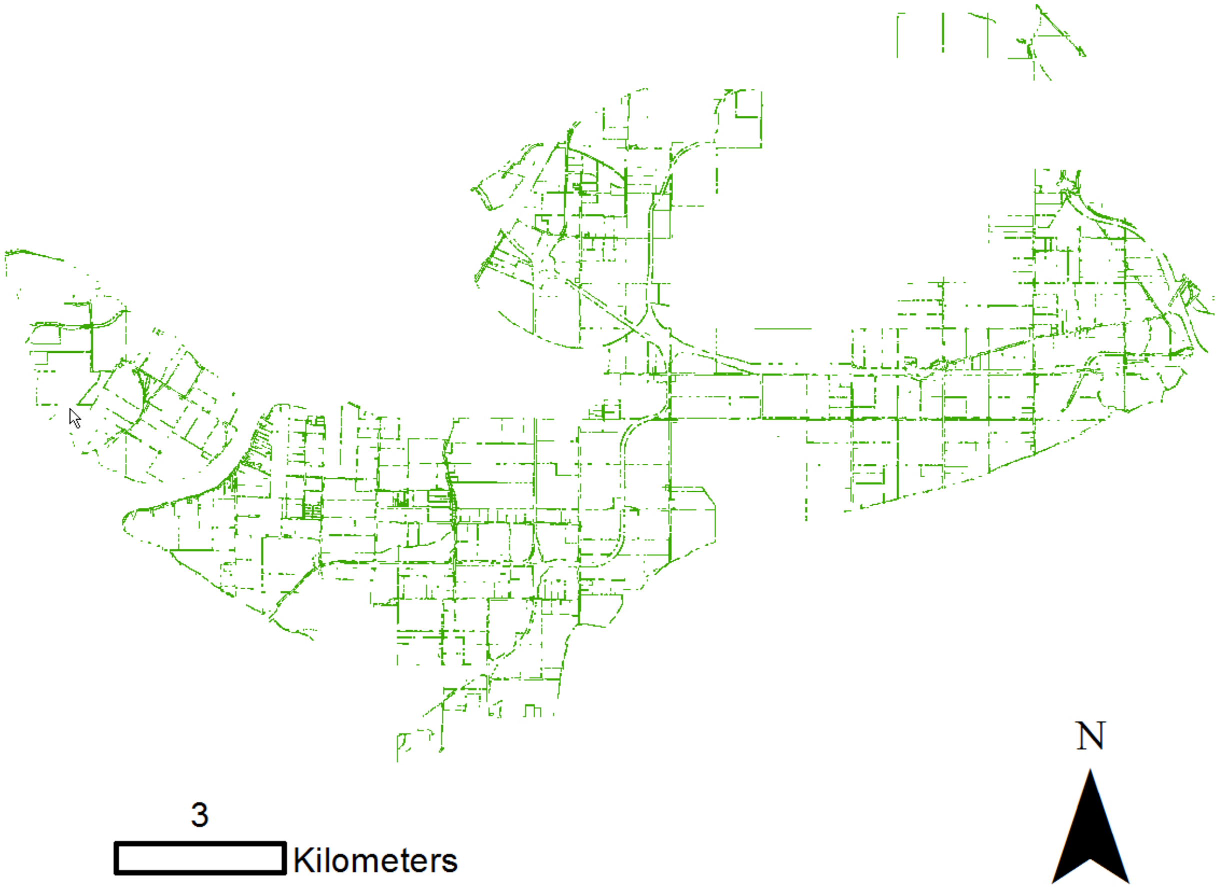

Figure 41. The distribution of non-production vegetation habitat in the "Agricultural Expansion" scenario where all habitat is converted to agricultural production except that bordering road and parcel edges

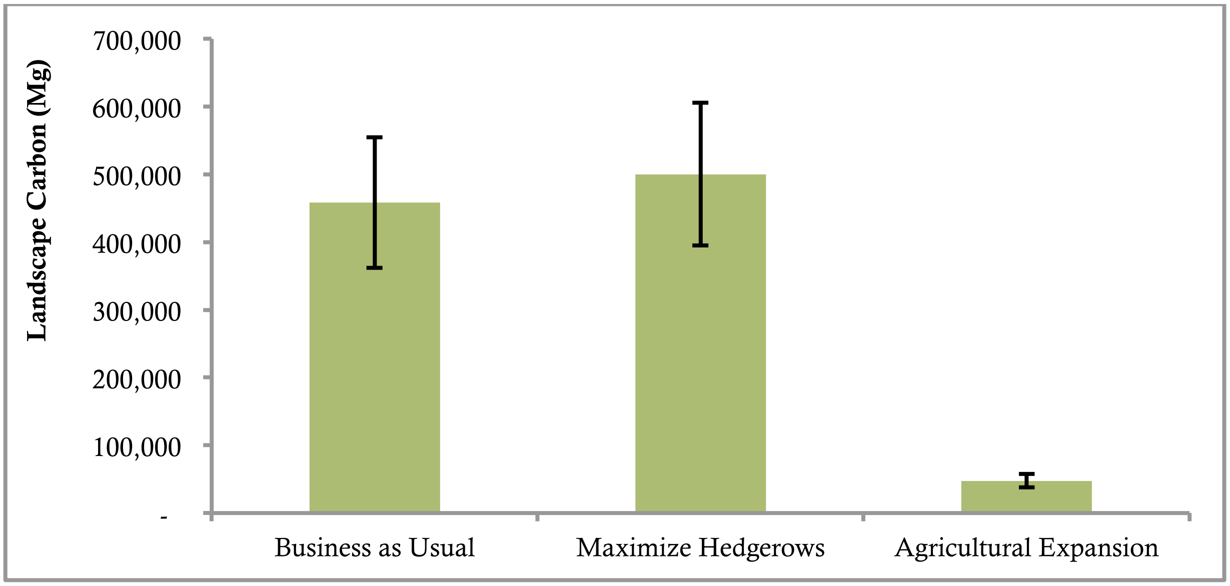

Figure 42. Expected landscape carbon (Mg C landscape^{-1}) for each of three future scenarios ("Business as Usual", "Maximize Hedgerows" and "Agricultural Expansion") for the Delta's ALR

Maximize Hedgerow scenario patch size was twice as large that for the *Business as usual* and almost ten times greater than that of the *Agricultural Expansion* scenario (Figure 43). Patch contiguity was however not distinguishable between the *Business as Usual,* and the *Maximize Hedgerow* scenario, or from the *Agricultural Expansion* scenario. *Business as Usual* scenario had a patch continuity of 0.9 ±0.14, the *Maximize Hedgerow* scenario 0.9 ± 0.10, and the *Agricultural Expansion* scenario 0.7 ± 0.26. These results illustrate that despite the much lower overall area of habitat, patch contiguity can be maintained through an extensive planting campaign. These however are just two of many metrics that can be used to assess habitat quality across a landscape.

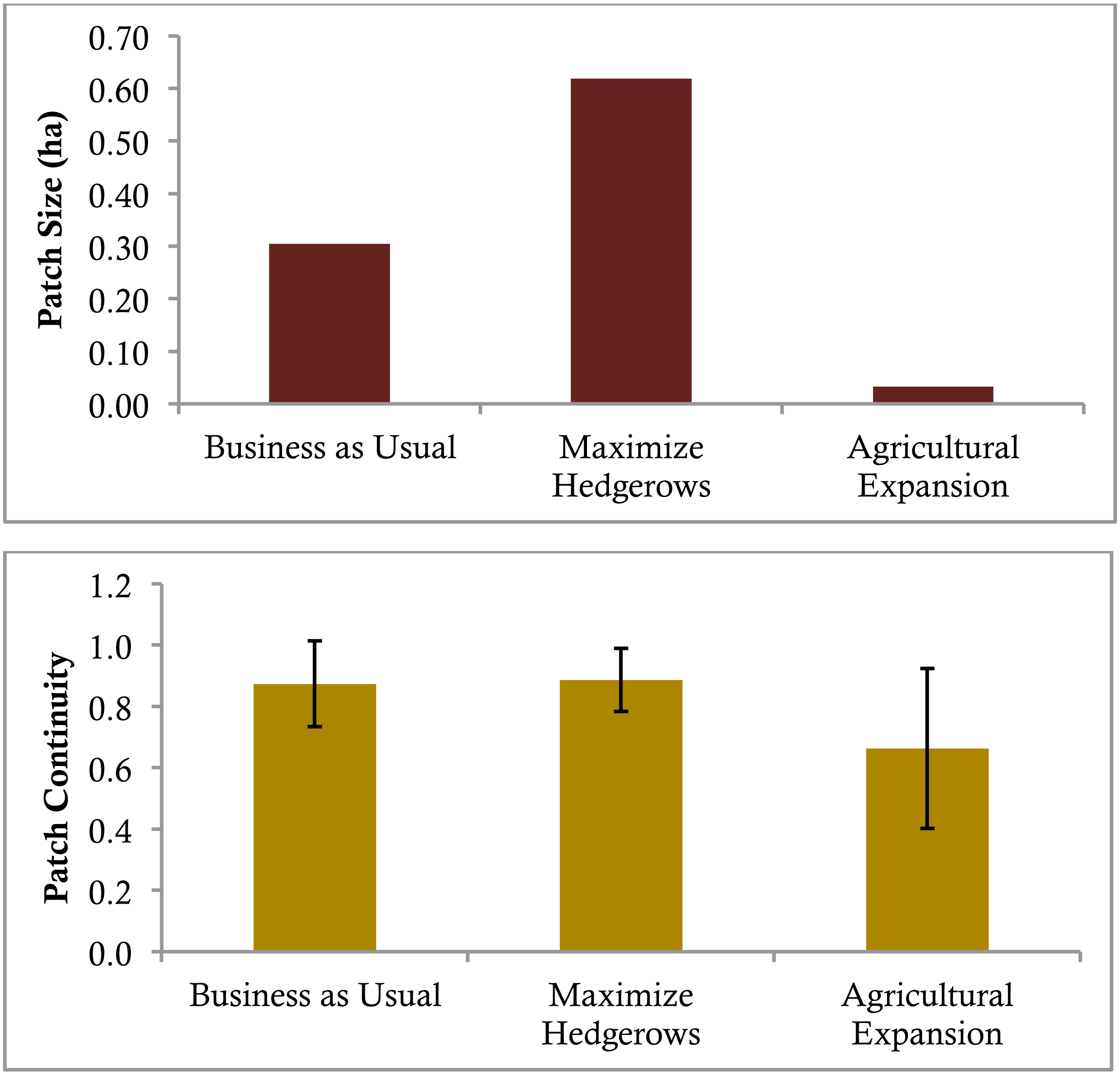

Figure 43. Expected habitat patch size and continuity for each of three future scenarios (“Business as Usual”, “Maximize Hedgerows” and “Agricultural Expansion”) for the Delta’s ALR

When comparing the three scenarios for contagion, a more comprehensive metric of landscape connectivity, again we see that the *Business as Usual,* and the *Maximize Hedgerow* scenario are similar but the *Agricultural Expansion* scenario has much higher index values indicating greater habitat dispersion. *Business as Usual* scenario had a contagion value of 61.6, the *Maximize Hedgerow* scenario 58.8, and the *Agricultural Expansion* scenario a value of 91.5 (Figure 44).

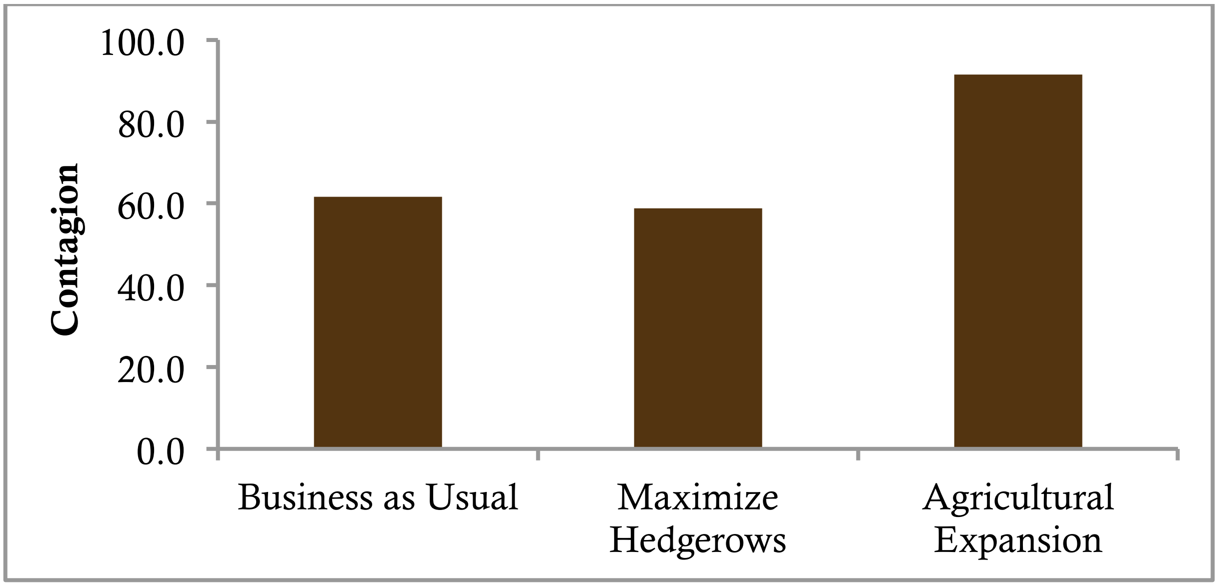

Figure 44. Expected habitaMg Connectivity for each of three future scenarios (“Business as Usual”, “Maximize Hedgerows” and “Agricultural Expansion”) for the Delta’s ALR

3.2.4 Cost Benefit Analysis

The costs for establishing and maintaining mature stands of perennial habitat were similar for both the *Business as Usual* and *Maximize Hedgerow* scenario but far lower for the *Agricultural Expansion* scenario. We estimated that the *Business as Usual* would cost $84 million, the *Maximize Hedgerow* scenario, $106 million and the *Agricultural Expansion* scenario $22 million over a 40-year project period.

While the net present costs for the *Business as Usual* and *Maximize Hedgerow* scenarios are far higher than the *Agricultural Expansion* scenario the costs per unit return in landscape C are far lower. For *Business as Usual* and *Maximize Hedgerow* scenarios costs per Mg of carbon was $183 and $212 Mg^{-1} respectively while the costs per Mg of carbon was more than double for the *Agricultural Expansion* scenario at $453 Mg^{-1} (Figure 45).

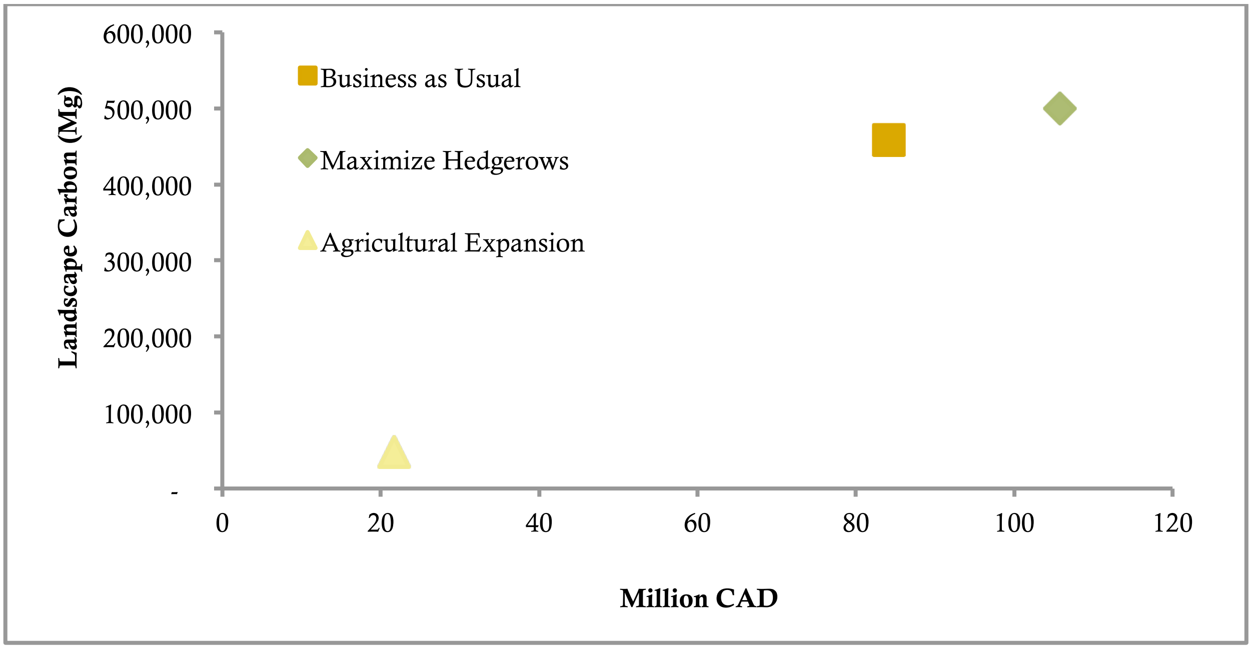

Figure 45. Net present costs (million CAD) for benefit of landscape carbon (Mg) for estimated for established mature stands of woody habitat in 2054 on the Delta's ALR for each of three future scenarios ("Business as Usual", "Maximize Hedgerows" and "Agricultural Expansion")

The benefits for woody habitat patch contiguity was similar for each of the three scenarios, therefore gives that the *Agricultural Expansion* scenario was a four fold lower investment it clearly has the best cost benefit ratio (Figure 46). *Business as Usual* and *Maximize Hedgerow* have lower contagion values than the *Agricultural Expansion* scenario but it is unclear how this compares to costs. Clearly the increase in contagion comes with reduced patch size and therefore a tradeoff for wildlife.

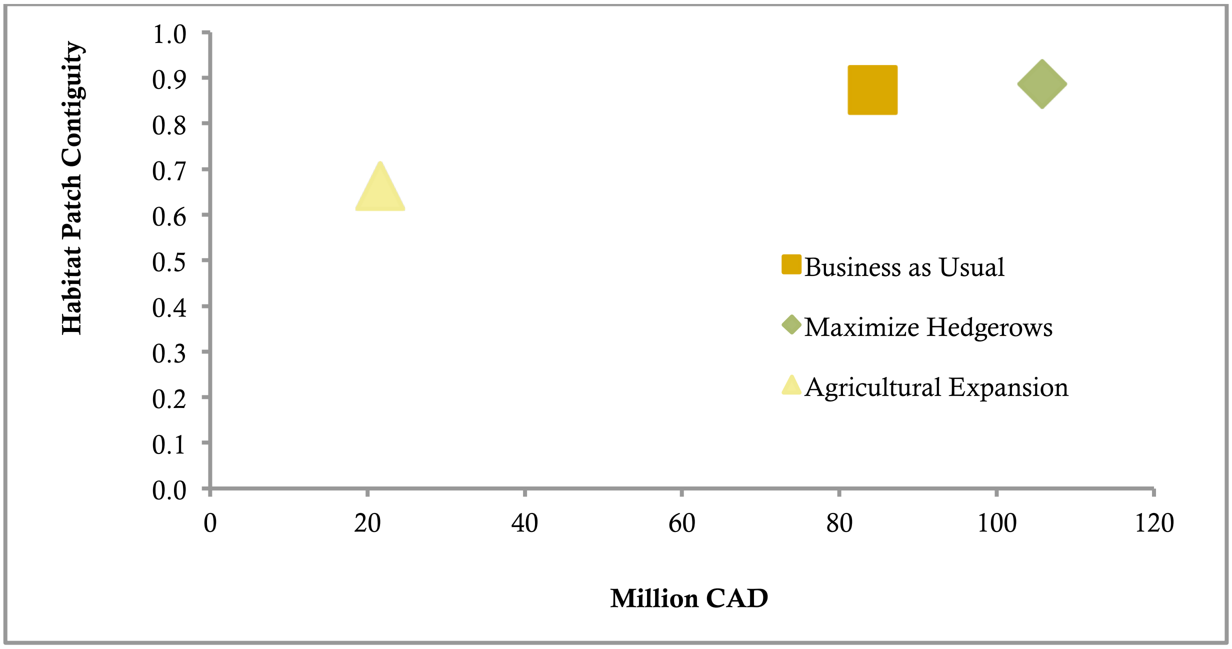

Figure 46. Net present costs (million CAD) for benefit of woody habitat patch continuity estimated for established mature stands of woody habitat in 2054 on the Detla's ALR for each of three future scenarios ("Business as Usual", "Maximize Hedgerows" and "Agricultural Expansion")

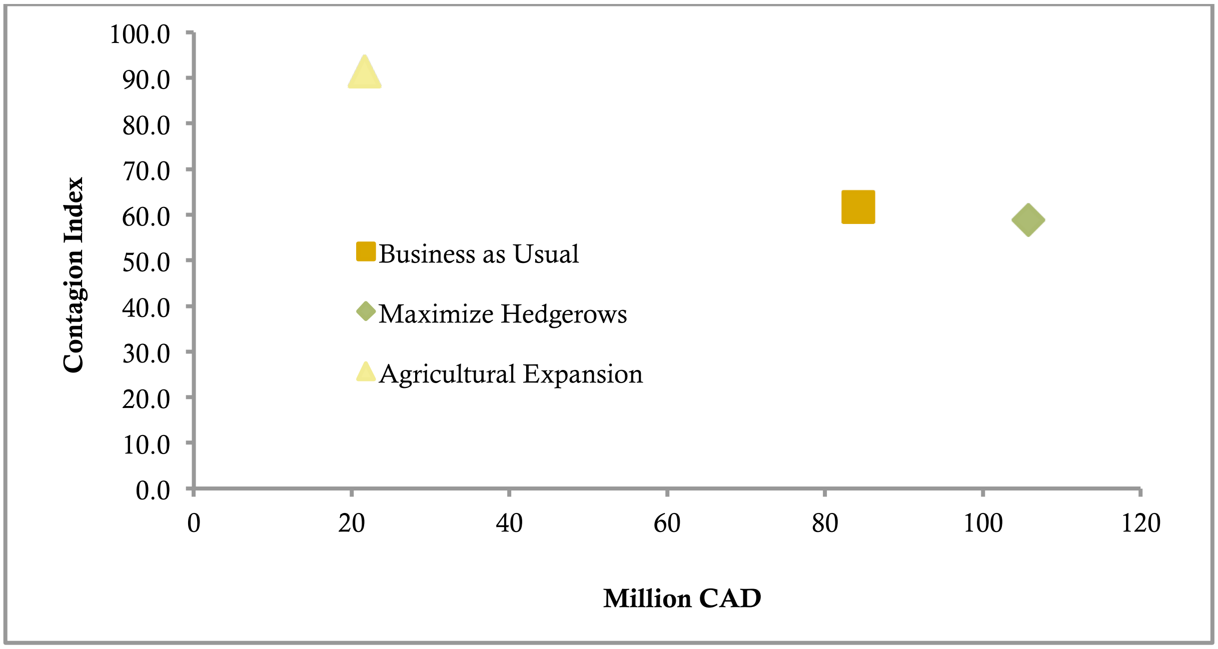

Figure 47. Net present costs (million CAD) for benefit of landscape continuity for estimated for established mature stands of woody habitat in 2054 on the Detla's ALR for each of three future scenarios ("Business as Usual", "Maximize Hedgerows" and "Agricultural Expansion")

4 CONCLUSION

This research provides some of the first quantifications of key ecosystem services provided by hedgerows in the Lower Fraser River Delta, and contributes to the small but growing global body of literature on hedgerows and the management of woody habitat on farms. The overarching goal of this research was to contribute to strategies to improve hedgerow management in the region to maximize positive environmental outcomes. Specifically we set out to answer the following questions about the DF&WT's Hedgerow Stewardship Program:

- Is the hedgerow-planting program offsetting the number of hectares of remnant hedgerows being cut down?
- Do planted hedgerows provide the same environmental function as remnant hedgerows?
- Could paying farmers to conserve remnant hedgerows under the existing DF&WT Hedgerow Program be a more cost effective way to ensure the availability of multiple environmental functions across the Delta region?

Through our data collection and analyses over the last year we have clearly answered each of these questions. Our analysis of historical air photos from three time periods, 1966, 1986 and 2012 showed that while there was initially a decline, overall the area of woody habitat has increased from 1966 to 2012. Despite anecdotal evidence that there is widespread removal of woody vegetation our analysis indicates that regrowth and new planting has not resulted in net losses and may have instead resulted in a small gain in woody habitat. The area of woody habitat has increased from 2.0% of the ALR in 1966 to 2.2% in 2012. We were not able to do a direct geographical assessment of land use change given that we could not align the photos from the different years with enough accuracy and therefore cannot report the relative change in loss vs. regrowth and planting, only the overall area. We thus know that DF&WT Hedgerow program is adding to the overall increase in woody habitat but cannot say how it compares with the rate it is being cut down.

In this study we documented clear differences in one key environmental function between hedgerows that were planted by the DF&WT and those that were remnant in the landscape before the Hedgerow Program's inception. Our analysis also indicated that for all other functions the two types of hedgerows could not be distinguished. We found no significant differences in species richness, biomass C, or GHG emissions between the two hedgerow types. We did however find that soil C was significantly higher in hedgerow habitats.

Our analysis of potential future scenarios for perennial habitat across the ALR in the Delta also shows mixed results. This scenario analysis indicated that even if the DF&WT were to maximize its program and plant hedgerows on every farm field and road edge there would be no distinguishable increase in key ecosystem functions or indicators of habitat connectivity compared to our baseline. Our analysis does clearly show that if agricultural or urban development were to expand on the ALR there would be substantial losses in both key ecosystem function and indicators of habitat even with hedgerows, indicating the importance of perennial habitat beyond farm edges. We examined the costs and benefits of these three potential future scenarios and again the results are mixed. The cost benefit ratio for landscape carbon indicates our *Business as Usual* scenario would be the best investment and *Agricultural Expansion the worst*, but for patch contiguity the result would be the opposite. For landscape continuity (contagion) it is unclear what the cost benefit ratio is given the challenges to ascribe a dollar value per unit of change in continuity.

This study quantifies some of key environmental benefits of hedgerows but there are other benefits and potential costs that need to be quantified in order to fully understand the potential environmental and production tradeoffs of establishing hedgerows on the edges of fields. In order to accurately calculate the CO_2 mitigation potential it would be important to replicate our study's greenhouse gas emissions collection over multiple years and quantify changes in C accumulation over time to establish net emissions vs. sequestration. Other functions that need quantification include how hedgerows impact water dynamics on the farm or compete with crops for nutrients. Further analysis of the quality of habitat might include more species-specific assessments and impacts to production. Better quantification of these relative tradeoffs and potential synergies between environmental outcomes and agricultural production will help to provide clearer management recommendation and policy incentives that optimize multiple beneficial outcomes from agricultural landscapes.

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