CARBON SEQUESTRATION POTENTIAL OF AGROFORESTRY SYSTEMS IN CANADA

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Major Advisor

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ABSTRACT

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Agroforestry is a land management system which integrates forest management practices with agriculture, often using high-value tree species planted alongside crops to increase profits. Agroforestry has the potential to increase carbon sequestration from the atmosphere within an area by increasing or maintaining land productivity through preventing soil erosion and binding carbon within the soils. As carbon dioxide is the most abundant greenhouse gas, sequestering carbon dioxide by any means will help to mitigate the degree of climate change. In this study, I compared the potential carbon sequestration capacity of shelterbelt agroforestry systems and silvopastoral agroforestry systems applicable to ecosystems within Canada against that of their adjacent pure agricultural systems. The results of this study indicated that silvopastoral systems sequester significantly more carbon dioxide within their soils than their adjacent agricultural counterparts while shelterbelt systems do not. Potential aboveground biomass productivity was also compared for hardwood and softwood tree species. The results indicated that there was no statistically significant difference between the two in aboveground biomass production potential. Based off these results, recommendations for resources and policies were made specific to Canada. The recommendations included developing a strategic framework for agroforestry in Canada, increasing the availability of grants for agroforestry in Canada, and changing property tax schemes to make agroforestry more financially appealing to land managers over single-use systems.

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INTRODUCTION

Since the beginning of the Industrial Era, human activities have been emitting excessive amounts of greenhouse gasses into the atmosphere. This was first recognized in 1896 by Svante Arrhenius, a Swiss scientist, who pioneered the idea that carbon dioxide (CO_2) released by the burning of fossil fuels has the potential to change the planet's climate (Nunez 2019). Although carbon dioxide is not the only greenhouse gas in the atmosphere, it is the most abundant and constitutes 65% of the total global greenhouse gas emissions (United States Environmental Protection Agency 2019). Carbon dioxide is emitted into the atmosphere primarily by anthropogenic activities, such as industrial activities, deforestation and other land-clearing activities, as well as soil degradation (United States Environmental Protection Agency 2019).

Just as human activities can emit excess carbon dioxide, we also have the ability to remove it from the atmosphere and sequester it. Both trees and soils have the potential to sequester carbon dioxide from the atmosphere (Natural Resources Canada 2016). In 1997, the Kyoto Protocol recognized the potential benefits of agroforestry, citing its ability to sequester carbon dioxide, conserve biodiversity and bring socioeconomic benefits to communities (Abbas *et. al* 2017). By properly managing our forests and agriculture activities to increase the capacity of our managed land to capture more carbon than it emits, we can mitigate the effects of carbon dioxide emissions on the global climate (Nair *et. al* 2010).

Currently, Canada has no guidelines or policies for agroforestry, and very little resources available on the subject. When compared to other countries, Canada's use of agroforestry systems is low (Gordon *et. al* 2008). The efficacy and potentials of agroforestry in Canada need to be studied in order to develop policies and programs for proper implementation. Currently, Canada is one of the top ten carbon-emitting countries in the world (Government of Canada 2019). To offset the country's greenhouse gas contributions, viable mitigation tactics, such as agroforestry practices, should be studied and implemented.

The objective of this study is to review the current agroforestry systems, and to compare the carbon sequestration potentials among them and with other land management systems. The amounts of carbon sequestered within soils (g/kg soil) and vegetation (kg/tree) have been included in this analysis, when possible. I have focused on species which grow in vegetation zones found within Canada as well as agroforestry systems which would be applicable in a Canadian context. Policies and programs were recommended according to the findings of the study and the potentials for agroforestry to aid in climate change mitigation were also discussed. I have tested the null hypothesis that agroforestry systems would not sequester significantly more carbon per hectare than other land management systems and that hardwood tree species would not sequester more carbon than softwood tree species.

LITERATURE REVIEW

Agroforestry is a land management system where agriculture is integrated with the cultivation of trees and has been used in many countries around the world, notably in South American and African countries (Mbow *et. al* 2014). In these areas, agroforestry is used to increase crop yield as suitable land becomes scarce and food security may be an issue (Mkonda & He 2017). Currently, some private landowners in the Canadian prairies use agroforestry practices to increase farmland profits by cultivating high-value timber tree species alongside crops (Agriculture and Agri-food Canada 2016).

Agroforestry is used by some private landowners in the temperate areas of Ontario and Quebec to cultivate hardwood tree species, such as *Acer* sp., to increase profits through sales of timber and non-timber products (Gordon *et. al* 2008). However, as mentioned previously, the use of agroforestry systems in Canada is still relatively low compared to other countries around the world (Gordon *et. al* 2008).

AGROFORESTRY SYSTEMS IN CANADA

Currently, there are five types of agroforestry systems classified for Canada; intercropping, windbreaks or shelterbelts, forest farming, integrated riparian systems, and silvopastoral systems (Hesselink & Thevathasan 2012).

Intercropping

Intercropping is a system popular in tropical regions of the world, with little use thus far in more temperate regions (Toor *et. al* 2012). In an intercropping system, trees and crop production are planted in alternating rows (Toor *et. al* 2012). These systems are used frequently in developing countries as crop production provides a constant flow of income while trees can take years to grow (Toor *et al.* 2012).

Windbreak/Shelterbelt

A windbreak, also known as shelterbelt, is a system of agroforestry which uses at least one row of trees or shrubs to protect crops from wind damage and soil erosion, and for protection of wildlife or farm animals (US Department of Agriculture n.d.a). In some occasions, this system is combined with intercropping to create an alleycropping system (US Department of Agriculture n.d.a). Windbreaks and alleycropping are frequently used in South American countries within coffee plantations (US Department of Agriculture n.d.a).

Forest Farming

Forest farming, also called multistory cropping, uses trees to protect high-value crop species grown underneath them (US Department of Agriculture n.d.b). Unlike windbreaks, the trees in a forest farming system are grown in a natural distribution pattern opposed to in rows (US Department of Agriculture n.d.b). This system is used mostly on private land in countries such as the United States to grow understory species such as *Panax quinquefolius* L., which is of high-value and requires shade (US Department of Agriculture n.d.b; Vaughan *et. al* 2011).

Integrated Riparian Systems

Integrated riparian systems use trees, shrubs and grasses to protect crop land from weathering and erosion by planting trees in once deforested riparian zones (Thevasathan *et. al* 2014). Implementation of integrated riparian systems also protect water quality, decrease flooding risk and increase biodiversity (Thevasathan *et. al* 2014). When trees and shrubs are planted in a riparian zone, they transpire excess water which prevents flooding, and bind soil with their roots which prevents erosion (Gregg 2008; Thevasathan *et. al* 2014). Decreased or lack of erosion leads to greater quality of water, as turbidity of the water decreases (Thevasathan *et. al* 2014).

Silvopastoral Systems

Silvopastoral systems consist of the use of grasses and/or grass-legumes for livestock grazing within a forested area. What differentiates a silvopastoral system from any forest stand with a grass-legume understory is that a silvopastoral system involves management and improvement of timber tree species and available forage (Angima 2009). In the majority of silvopastoral systems, livestock consists of cows and sheep (Angima 2009). Silvopastoral systems can be utilized in most parts of the world, including North America (Angima 2009).

CANADIAN POLICIES, PROGRAMS AND GUIDELINES

Canada has few resources and policies for agroforestry implementation and management. Aside from information on agroforestry systems applicable to Canada and suggestions for tree and shrub species for shelterbelt systems, as outlined in the later section, "Tree and Shrub Species used in Agroforestry" (p. 11), little guidance is provided by government agencies regarding the topic. Agencies such as Canadian Agroforestry/Afforestation Research Network (CAARN) have attempted to acquire funding for agroforestry research and development, however, thus far have failed (Van Rees 2008). Others, such as the Prairie Farm Rehabilitation Administration Shelterbelt Centre (PFRASC) in Saskatchewan, were only viable for a short period before ceasing operations (Wilson 2012). However, the Saskatchewan Research Council (SRC) currently aids land managers in Saskatchewan regarding agroforestry implementation (Johnston n.d.). The SRC will deliver services such as land area mapping, property assessment, land preparation and implementation of agroforestry systems (Johnston n.d.).

Funding from the federal government has been made available for agroforestry research by Agriculture and Agri-food Canada through the Agricultural Greenhouse Gasses Program and has been given to multiple Canadian universities since 2016 (Agriculture and Agri-food Canada 2019). A search for grants available for private landowners was conducted, however no grants were available in Canada specific to agroforestry outside of the mentioned grants for Saskatchewan landowners (AgPal 2020). However, grants specific to agriculture or farming may be applicable to certain situations, depending on how the land is being managed.

Canadian federal policy regarding agroforestry consists of only the Experimental Farms Act (1887). When this was enacted, governments were given the ability to use land for crop, livestock and tree experimentation. This opened the doors for agroforestry research and development in Canada (Jones 2013).

Property Tax Rates for Agroforests in Canada

In Ontario, under the Farm Property Tax Rate Program, eligible farmlands can have their property taxes reduced to 25% of their respective municipal or provincial property tax rate (Government of Canada 2015). In order to be eligible for this, the property must be considered "farmland" by the Municipal Property Assessment Corporation, have an income exceeding $7,000 annually, be majority owned by Canadian citizens or permanent residents, and hold a Farm Business Registration number (Government of Canada 2015).

Ontario assesses privately managed forest lands the same as farmlands, and as such, these lands are eligible for the property tax reduction received by farmlands (Government of Canada 2015). As well, privately owned forests are eligible for a tax credit under the Managed Forest Tax Incentive Program (MFTIP). To be eligible for this, there must be a 10-year management plan in place which has been approved by a qualified managed forest plan approver (MFPA) (Government of Canada 2015).

Managed lands which consist of both farmland and forest (agroforests) are eligible for the Farm Property Tax Rate Program as well as the MFTIP program. However, in these instances, the land does not have to be covered under a 10-year approved management plan to be eligible for the MFTIP program.

Agricultural Greenhouse Gasses Program

As mentioned previously, Agriculture and Agri-food Canada has provided funding to multiple Canadian universities and organizations for agroforestry research. This program provides funding for projects which cover one or more of the following areas: Livestock systems, cropping systems, agricultural water use efficiency and/or agroforestry.

Thus far, funding for agroforestry research has been awarded to the University of Alberta, University of Guelph, University of Waterloo, Eastern Townships Forest Research Trust, East Prince Agri-Environment Association, and University of Saskatchewan (Agriculture and Agri-food Canada 2019). During this study, no publications of the funded projects outlined by Agriculture and Agri-food Canada were found (University of Alberta 2020, University of Saskatchewan 2018).

INTERNATIONAL POLCIES AND GUIDELINES

Kyoto Protocol (1997)

As deforestation releases C02 into the atmosphere, it has the potential to contribute to the warming influence of greenhouse gases (Bala *et. al* 2007). The effects of deforestation on climate were recognized by the Kyoto Protocol in 1997. The Kyoto Protocol has recognized agroforestry a mitigation measure against climate change by sequestering carbon within soils (Abbas *et. al* 2017). The Kyoto Protocol recommends implementation of agroforestry for not only carbon sequestration, but for greater food security, increased biodiversity, and greater pollen availability (Abbas *et. al* 2017). Canada had ratified the Kyoto Protocol in 1997, however withdrew in 2011 as Canada was not likely to meet its emissions reduction goals (United Nations 2019). Another factor in Canada's withdrawal from the Kyoto Protocol was the fact that neither the United States nor China, the world's two largest emitters, were covered by it (Guardian News 2011). At the time, Canada's Environment Minister, Peter Kent, was quoted saying "The Kyoto Protocol does not cover world's largest two emitters…and therefore cannot work" (Guardian News 2011).

Paris Agreement, Article 5 (2016)

The Paris Agreement was set out in 2016 by the United Nations Framework Convention on Climate Change (UNFCCC). The end goal of the Paris Agreement is to limit the global rise in temperature to 1.5 degrees Celsius above pre-industrial temperatures through a cooperative plan between countries (United Nations 2019). Article 5 of the Paris Agreement calls for sustainable forest management and enhancement of carbon sinks, as these actions have the potential to aid significantly in climate change mitigation (Food and Agriculture Organization of the United States 2018). Article 5 also calls for the implementation of sustainable development goals, including sustainable agricultural practices which tackle food security and do not contribute to climate change (Food and Agriculture Organization of the United States 2018). Although agroforestry is not mentioned specifically within Article 5 of the Paris Agreement, the reported benefits of agroforestry shown in various countries align with the goals of the Article. Canada became signatory to the Paris Agreement on October 6, 2016 (United Nations 2019).

<u>Agroforestry Strategic Framework, United States (2019 – 2024)</u>

In the United States (USA), the United States Department of Agriculture (USDA) develops a five-year strategic framework for agroforestry within the country. The mission of the strategic framework is to "advance agroforestry knowledge, tools, and assistance for the benefit of landowners, communities and the Nation" (USDA 2019). Multiple objectives and strategies are outlined within the framework to achieve this mission, such as, providing training on agroforestry for natural resources professionals, advancement of agroforestry technologies, and undergoing "on-farm" research on agroforestry (USDA 2019). The Agroforestry Strategic Framework is implemented and carried out by multiple government agencies, including, United States Forest Service, United States Department of Agriculture, the Natural Resources Conservation Service, the Farm Service Agency, and Rural Development (USDA 2019).

<u>Goals on Climate Change and Carbon Emissions</u>

The Intergovernmental Panel on Climate Change (IPCC) has indicated that to stall the changing climate, we need to lower the average global temperature increase to 1.5 degrees Celsius by 2030 (Kolbert 2018). To do this, the world needs to move toward the use of negative emissions technologies and the removal of carbon from the atmosphere (Kolbert 2018). The IPCC estimates that to curb climate change, the world needs to remove at least 100 gigatons (GT) of CO2, and up to 1,000 GT of CO2, from the atmosphere by 2100 (Irfan 2018). According to the IPCC, 88 parts per million (ppm) of atmospheric CO2 can be attributed to improper land management (Irfan 2018).

TREE AND SHRUB SPECIES USED IN AGROFORESTRY

For the purpose of this research, only species which could be applicable in a Canadian context will be outlined. This includes species currently native or introduced to Canada, and non-invasive species which can grow and thrive in Canada.

In Canada, the government agency Agriculture and Agri-food Canada (2014) has outlined multiple tree and shrub species recommended for agroforestry practices. Each of the species outlined by Agriculture and Agri-food Canada are recommended for use in shelterbelt systems only. The recommended species can be seen in Table 1 below, along with their respective hardiness zones.

Table 1. *Tree species recommended for shelterbelt agroforestry systems in Canada* (Agriculture and Agri-food Canada 2014, Farrar 1995).

Binomial	***Common Name***	***Con./Dec./Shrub***	***Hardiness Zone(s)***
Acer negundo	Manitoba Maple	Deciduous Tree	2a - 3b
Caragana arborescens	Caragana	Deciduous Shrub	3a - 8b
Cornus serica	Red-osier Dogwood	Deciduous Shrub	2a – 2b
Crataegus spp.	Hawthorn	Deciduous Shrub	4a - 7b
Fraxinus pennsylvanica	Green Ash	Deciduous Tree	1a - 2b
Hippophae rhamnoides	Sea Buckthorn	Deciduous Shrub	3a - 3b
Larix sibirica	Siberian Larch	Coniferous Tree	2a - 3b
Malus baccata	Siberian Crab-apple	Deciduous Tree	2b
Picea glauca	White Spruce	Coniferous Tree	5a - 7b
Picea pungens	Colorado Spruce	Coniferous Tree	1a - 7b
Pinus sylvestris	Scots Pine	Coniferous Tree	0a - 6b
Populus deltoides	Cottonwood	Deciduous Tree	4a - 7b
Populus tremuloides	Trembling Aspen	Deciduous Tree	0a - 9b
Populus x *hybrid*	Hybrid Poplar	Deciduous Tree	0a - 9b
Prunus pensylvanica	Pincherry	Deciduous Tree	0a - 9b
Prunus virginiana	Choke Cherry	Deciduous Shrub	0a - 9b
Quercus macrocarpa	Bur Oak	Deciduous Tree	3a - 8b
Rosa x *hybird*	Hedge Rose Hybrid	Deciduous Shrub	2a
Salix acutifolia	Acute Willow	Deciduous Tree	2a - 2b
Salix alba var. *sericea*	Silverleaf Willow	Deciduous Tree	3a - 3b
Salix amygdaloides	Peachleaf Willow	Deciduous Tree	1a - 7b
Sambucus racemosa	Red Elder	Deciduous Shrub	0a - 5b
Shepherdia argentea	Silver Buffaloberry	Deciduous Shrub	2a
Symphoricarpus occidentalis	Snowberry	Deciduous Shrub	1a - 7b
Syringa villosa	Villosa Lilac	Deciduous Shrub	3a - 7b

SOCIOECONOMIC BENEFITS OF AGROFORESTRY

The potential socioeconomic benefits of agroforestry have been studied widely in developing areas such as Haiti, India and some African countries. A study completed on agroforestry systems of farmers in India concluded that all agroforestry systems studied were more profitable than their agricultural counterparts alone (Kareemulla *et al*. 2004).

Agroforestry has been recognized as a tool for food security enhancement at individual and community scales (Mbow *et. al* 2014). In developing countries especially, changing climates, fossil-fuel prices and conflicts have led to decreased food security (Mbow *et. al* 2014). Agroforestry has been shown to increase crop productivity and livestock health, as well as provide added income from timber and non-timber product sales (Abbas *et. al* 2017; Mbow *et. al* 2014).

In Canada, where the majority of agroforestry systems utilized are shelterbelt, protection provided from trees decreases farm operating costs and livestock and crop loss. Farm operators can also sell timber and non-timber products for added income, as with all agroforestry systems (Hesselink & Thevathasan 2012). As climate change increases risk of extreme weather events, shelterbelt systems could be a key method of protecting livestock and crops (Hesselink & Thevathasan 2012).

ECOSYSTEM SERVICES PROVIDED BY AGROFORESTRY

Agroforestry implementation has the potential to provide many ecosystem services, aside from sequestering carbon. These services include biodiversity enhancement/conservation, wildlife habitat creation, pest control, erosion control, seed dispersal, soil enrichment, water quality improvement and air quality improvement (Jose 2009; Plaza *et. al* 2011).

Proper implementation of agroforestry systems has the potential to conserve biodiversity at local, landscape and global scales as well as provide habitat for wildlife (Jose 2009; Kumar & Ramachandran 2011). Species composition plays an important role in biodiversity conservation through agroforestry, as does tree and shrub density, harvesting frequency, and management of course woody debris (Jose 2009). The type of agroforestry system implemented does not significantly impact biodiversity conservation (Jose 2009). However, for the provision of wildlife habitat, silvopastoral systems have shown to have the greatest impact (Kumar & Ramachandran 2011). For biodiversity conservation, a diverse species composition is needed as well as a high density of trees/shrubs (Jose 2009). Additionally, any harvesting of trees or shrubs should be minimal and emulate natural disturbance patterns and leave behind snags and coarse woody debris for wildlife habitat (Jose 2009).

Air and water quality have the potential to be improved by agroforestry implementation, specifically through windbreak and shelterbelt systems (Jose 2009). Through windbreak systems erosion from wind is minimized, therefore protecting the quality of nearby water systems (Jose 2009). As well, both shelterbelt and windbreak systems can minimize dust and debris in the air through erosion control and the trapping airborne particles, which can enhance both air and water quality (Jose 2009).

MATERIALS AND METHODS

A thorough examination of publications pertaining to agroforestry was conducted. These publications included refereed journal articles, student theses, books, conference proceedings, government publications and any other resources which synthesize completed and reviewed studies on the carbon sequestration potential of agroforestry systems. Emphasis was placed on systems applicable to Canada. As the areas where agroforestry is utilized the most are outside of Canada, international studies were examined for data as well as any available studies within Canada. Data was extracted from a set of the most applicable, and reliable sources which synthesize agroforestry and carbon sequestration studies (Abbas *et al.* 2017; Baah-Acheamfour *et al.* 2014; Dhillon *et al.* 2017; Gordon *et al.* n.d.; Kort & Turnock 1999; Kumar & Ramachandran 2011; Mkonda & He 2017; Nair *et al.* 2010; Peichl *et al.* 2006; Wang *et* *al.* 2014). The data extracted consisted of grams of carbon per kilogram of soil and kilograms of carbon sequestered per tree or shrub within shelterbelt and silvopastoral agroforestry systems. For consistency and accuracy, only data which was expressed in grams of carbon per kilogram of soil or kilograms of carbon per tree within the original study used. For comparison, publications outlining the carbon sequestration potentials of agricultural systems alone (adjacent fields) were examined, and data was extracted from them, when available (Abbas *et al.* 2017; Baah-Acheamfour *et al.* 2014; Dhillon *et al.* 2017; Gordon *et al.* n.d.; Kort & Turnock 1999; Kumar & Ramachandran 2011; Mkonda & He 2017; Nair *et al.* 2010; Peichl *et al.* 2006; Wang *et al.* 2014). Data pertaining to the carbon levels of adjacent agricultural fields were also used only if expressed in grams of carbon per kilogram of soil. All published data are the intellectual property of the authors and are under copyright of their respective publishers. Permission has been obtained to use the data in this study.

Data extracted from these reviews and studies was analyzed and tested for statistical significance, which was not previously conducted within any of the studies used. To test for a significant difference in carbon sequestration potentials, a t-test was conducted using Microsoft Excel with a p-value of 0.05 (Table 3, Table 5 and Table 7). The comparisons completed consisted of testing the difference between an agroforestry system and adjacent fields of another management system for each dominant species and between different species within the same system. Within the studies used for this analysis the following sample counts were found: Six samples for carbon within the soils of shelterbelt agroforests, six samples for carbon within the soils of purely agricultural fields adjacent to shelterbelt agroforests, two samples for carbon within the soils of silvopastoral agroforests, and two samples for carbon within the soils of purely agricultural fields adjacent to silvopastoral agroforests (Abbas *et al.* 2017; Baah-Acheamfour *et al.* 2014; Dhillon *et al.* 2017; Gordon *et al.* n.d.; Kort & Turnock 1999; Kumar & Ramachandran 2011; Mkonda & He 2017; Nair *et al.* 2010; Peichl *et al.* 2006; Wang *et al.* 2014).

A review of the available literature on agroforestry, tree species used in agroforestry, carbon sequestration potentials of agroforestry systems and their adjacent field as potentially pertaining to Canada yielded reliable, usable information only for the shelterbelt system and the silvopastoral system. Information was found for the following species in shelterbelt systems: *Fraxinus pennsylvanica, Acer nugundo, Populus* sp. (hybrid), *Picea glauca, Pinus sylvestris* and *Caragana* sp. For silvopastoral systems, data could be obtained only for *Populus* sp. (hybrid) and *Picea glauca* dominated agroforests. Publications were researched and analyzed regarding aboveground carbon sequestration of all potential species used in shelterbelt and silvopastoral agroforestry systems in Canada, however reliable, peer reviewed information was only found for five species: *Fraxinus pennsylvanica, Acer negundo, Populus* sp. (hybrid), *Picea glauca,* and *Pinus sylvestris* (Abbas *et al.* 2017; Baah-Acheamfour *et al.* 2014; Dhillon *et al.* 2017; Kort & Turnock 1999; Kumar & Ramachandran 2011; Mkonda & He 2017; Nair *et al.* 2010; Peichl *et al.* 2006; Wang *et al.* 2014). For all included silvopastoral agroforestry systems, the main use of these areas was pasture for animal grazing.

From the results of this study and information found during the literature review, recommendations were made for programs and resources to effectively implement agroforestry practices in Canada on a wider scale, as the practice has been recognized as a viable way to mitigate climate change (Abbas *et. al* 2017; Agriculture and Agri-food Canada 2016; Agriculture and Agri-food Canada 2019; Government of Canada 2015; Hesselink & Thevathasan 2012; Kareemulla *et al*. 2004; Kumar & Ramachandran 2011; Manley 2009; Mbow *et. al* 2014; USDA 2019).

RESULTS

SHELTERBELT AGROFORESTS

In shelterbelt systems, *Populus sp.* dominated agroforests had the greatest difference between the amount of carbon sequestered in their soils and the carbon sequestered in the soils of adjacent purely agricultural fields with 9.26g more carbon per kilogram of soil, however the greatest percent change was seen in *P. sylvestris* dominated agroforests with a 37.26% increase (Table 2, Figure 1). The smallest difference between carbon sequestered in a species' agroforest and its adjacent agricultural field was shown to be within *A. negundo* dominated agroforests with only 0.30g carbon/kg of soil difference; this species' agroforest also showed the lowest percent change with an increase of 1.57%.

Table 2. *Mean carbon sequestered (g/kg of soil) in soil of shelterbelt agroforests and their adjacent agricultural fields by dominant tree species with associated differences*

Binomial	**Common Name**	**Mean Soil Carbon Agroforest (g/kg soil)**	**Mean Soil Carbon Adjacent Field (g/kg soil)**	**Difference (g/kg soil)**
Fraxinus pennsylvanica	Green Ash	33.08	30.38	+2.70g/8.89%
Acer negundo	Manitoba Maple	19.43	19.13	+0.30g/1.57%
Populus sp.	Hybrid Poplar	37.00	27.74	+9.26g/33.38%
Picea glauca	White Spruce	33.52	27.48	+6.04g/21.98%
Pinus sylvestris	Scots Pine	28.18	20.53	+7.65g/37.26%
Caragana sp.	Caragana	15.53	12.00	+3.53g/29.41%

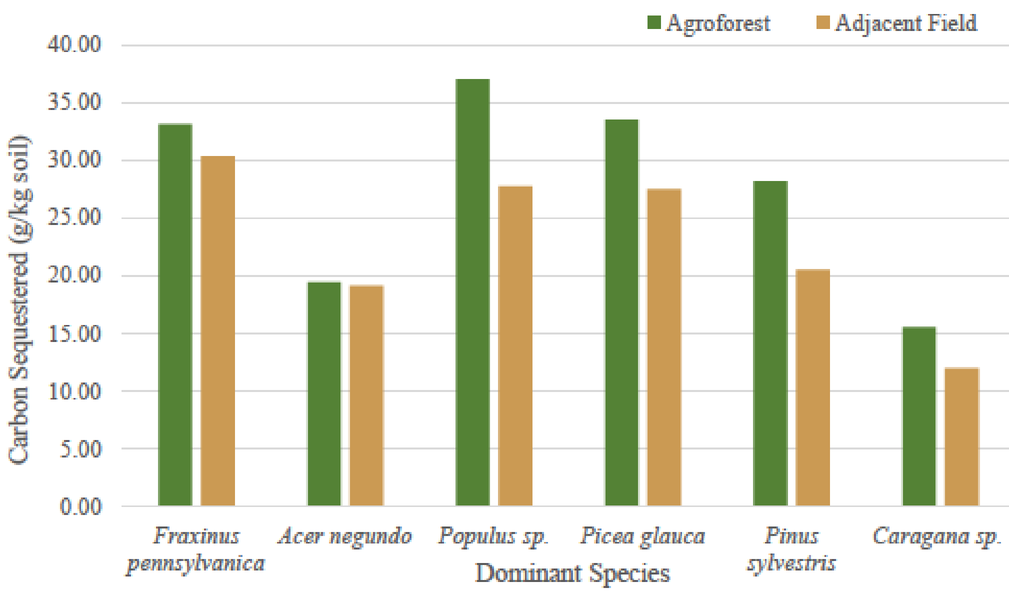

Figure 1. *Mean carbon sequestered (g/kg of soil) in soil of shelterbelt agroforests and their adjacent fields by dominant tree species*

When amounts of sequestered soil carbon were compared, shelterbelt agroforestry systems did not sequester a significantly different amount of carbon than adjacent purely agricultural fields ($p = 0.30$) (Table 3).

Table 3. *Test of significant difference results for soil carbon (g/kg of soil) in shelterbelt agroforestry systems compared to their adjacent purely agricultural fields*

	Adjacent Field	Agroforest
Mean	22.87	27.79
Variance	47.79	73.23
Observations	6	6
Hypothesized Mean Difference	0	
df	10.00	
t Stat	-1.09	
P(T<=t) one-tail	0.15	
t Critical one-tail	1.81	
P(T<=t) two-tail	**0.30**	
t Critical two-tail	2.23	

SILVOPASTORAL AGROFORESTS

Silvopastoral agroforestry systems dominated by *Populus* sp. showed an increase of 24.4 g of carbon/kg of soil or 44.20% over their adjacent purely agricultural fields, and *Picea glauca* dominated agroforests showed an increase of 25.1 grams of carbon per kilogram of soil or 48.93% over their adjacent purely agricultural fields (Table 4, Figure 2).

Table 4. *Mean carbon sequestered (g/kg of soil) in soil of silvopastoral agroforests and their adjacent purely agricultural fields by dominant tree species with associated differences*

Binomial	Common Name	Mean Soil Carbon Agroforest (g/kg soil)	Mean Soil Carbon Adjacent Field (g/kg soil)	Difference (g/kg soil)
Populus sp.	Hybrid Poplar	79.6	55.2	+24.4g/44.20%
Picea glauca	White Spruce	76.4	51.3	+25.1g/48.93%

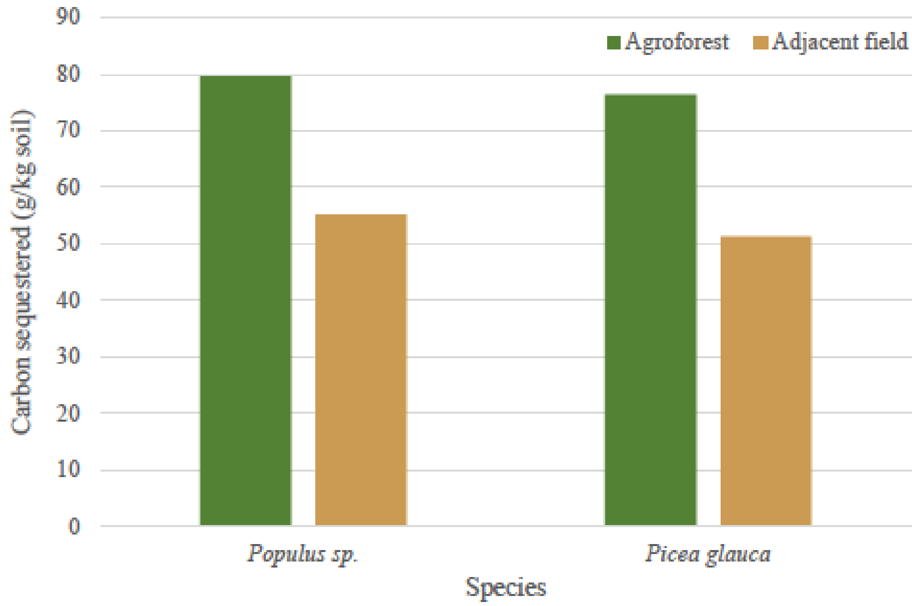

Figure 2. *Mean carbon sequestered (g/kg of soil) in soil of shelterbelt agroforests and their adjacent purely agricultural fields by dominant tree species*

When comparing amounts of sequestered soil carbon, shelterbelt agroforestry systems did sequester a significantly different amount of carbon than adjacent purely agricultural fields ($p = 0.01$) (Table 5).

Table 5. *Test of significant difference results for soil carbon (g/kg of soil) in silvopastoral agroforestry systems*

	Adjacent Field	Agroforest
Mean	53.25	78
Variance	7.61	5.12
Observations	2	2
Hypothesized Mean Difference	0	
df	2	
t Stat	-9.81	
P(T<=t) one-tail	0.01	
t Critical one-tail	2.92	
P(T<=t) two-tail	**0.01**	
t Critical two-tail	4.30	

ABOVEGROUND CARBON

Populus sp. has the greatest amount of aboveground carbon sequestered per tree with 161.80kg/tree stored (Table 6, Figure 3). The least amount of carbon sequestered per tree was found to be by *F. pennsylvanica* with 79kg/tree stored.

Table 6. *Mean aboveground carbon sequestered per tree (kg/tree) by tree species used in shelterbelt and silvopastoral agroforestry systems*

Binomial	**Common Name**	**Type**	**Mean Aboveground Carbon (kg/tree)**
Fraxinus pennsylvanica	Green Ash	Hardwood	79
Acer negundo	Manitoba Maple	Hardwood	86
Populus sp.	Hybrid Poplar	Hardwood	161.80
Picea glauca	White Spruce	Softwood	105.67
Pinus sylvestris	Scots Pine	Softwood	82

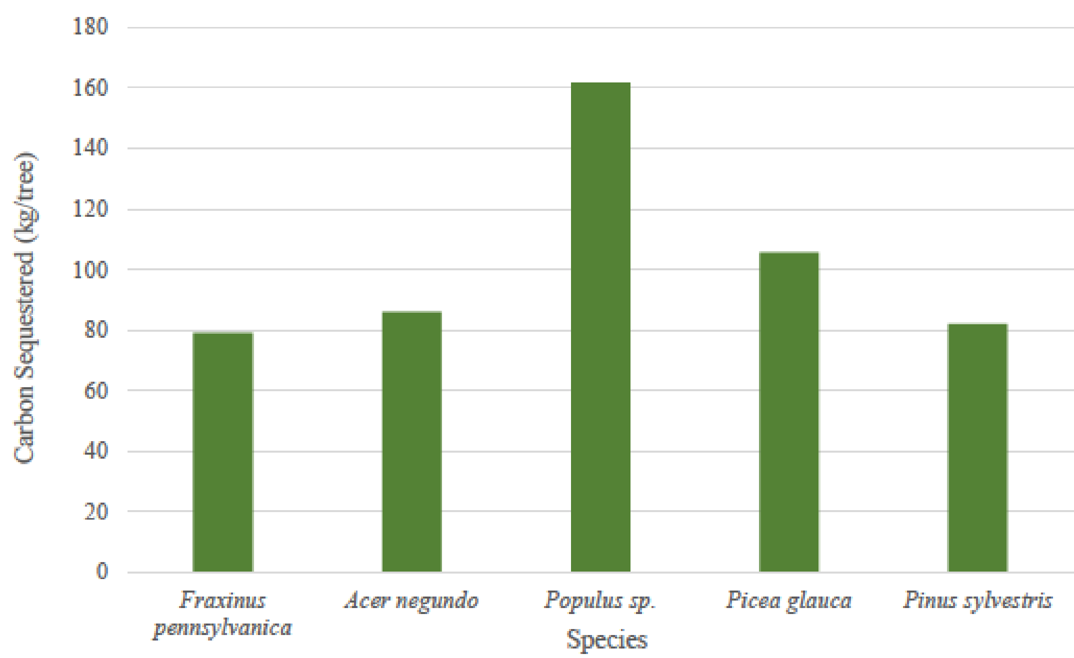

Figure 3. *Mean aboveground carbon sequestered per tree (kg/tree) by species used in shelterbelt agroforestry systems*

When comparing amounts of aboveground carbon sequestered, hardwood tree species did not sequester a significantly different amount of aboveground carbon than softwood tree species ($p = 0.64$) (Table 7).

Table 7. *Test for significant difference between aboveground carbon (kg/tree) sequestered between softwood and hardwood species*

	Softwood	**Hardwood**
Mean	93.83	108.93
Variance	280.06	2108.41
Observations	2	3
Hypothesized Mean Difference	0	
df	3	
t Stat	-0.52	
P(T<=t) one-tail	0.32	
t Critical one-tail	2.35	
P(T<=t) two-tail	**0.64**	
t Critical two-tail	3.18	

DISCUSSION

DIFFERENCES IN CARBON SEQUESTRATION POTENTIALS

The results indicate that shelterbelt systems did not have a significantly greater amount of carbon in the soil than their adjacent agricultural fields. However, silvopastoral agroforestry systems did sequester a significant amount of carbon over their adjacent agricultural fields. When comparing aboveground carbon sequestered by hardwood tree species and softwood tree species, hardwood species did not sequester a significant amount of carbon over softwood tree species. Although when comparing carbon sequestration potentials of agroforestry systems and their respective adjacent agricultural fields shelterbelt systems did not show a significant difference, silvopastoral systems did. These results suggest that agroforestry systems can sequester significantly more carbon than their pure agricultural systems. These results also indicate that both hardwood and softwood tree species can sequester a comparable amount of carbon, and therefore both can be used in agroforestry systems where carbon sequestration is a goal.

A study by Feliciano *et al.* (2018) supports the statement that silvopastoral agroforestry systems will have a significantly higher carbon content within their soils than their adjacent land management systems as well as other agroforestry systems. Through a review of 86 peer reviewed publications, Feliciano *et al.* (2018) indicated that silvopastoral systems can sequester up to 278% more soil carbon than purely agricultural fields. As well, the results indicated that silvopastoral systems can sequester up to 242% more soil carbon than other agroforestry systems such as shelterbelt, forest farming, and fallow systems.

Silvopastoral agroforestry systems may have greater carbon density in the soil than pure agricultural fields because of long-term livestock grazing (Hewins *et. al* 2018; Wang *et. al* 2014). All data pertaining to silvopastoral agroforests used were derived from areas which the primary use was pasture for animal grazing. Studies on the effects of livestock grazing on soil carbon have shown that grazed areas have a significant increase of carbon within the first 15 cm of mineral soil compared to non-grazed areas of the same vegetation type (Hewins *et. al* 2018; Wang *et. al* 2014). Specific management activities which may contribute to silvopastoral systems having an increased amount of carbon sequestered include stocking rate management and enclosures (FAO United Nations n.d.). Managing the stocking rate of grazing animals to ensure that carrying capacity is not reached has been shown to increase soil carbon levels (FAO United Nations n.d.).

The results of this study indicate that the carbon sequestration capacity of the tree component in an agroforestry system was similar between hardwood tree species and softwood tree species (108.93 kg/tree versus 93.83 kg/tree). According to Unruh *et al.* (1993), the ideal density for trees in agroforests is between 50 and 200 trees per hectare. This means that at a density 50 trees per hectare, hardwood dominated, and softwood dominated agroforests will sequester 5446.5 kilograms and 4691.5 kilograms of aboveground carbon per hectare, respectively. At a density of 200 trees per hectare, hardwood agroforests would sequester 21,786 kilograms of aboveground carbon per hectare and softwood agroforests would sequester 19,766 kilograms of aboveground carbon per hectare when considering results from this study.

There has been a considerable amount of studies completed on the carbon content of hardwood and softwood tree species, and many of these studies show conflicting results. Lamlom and Savidge (2003) compared the aboveground biomass within hardwood and softwood tree species and found that softwood tree species have a significantly higher carbon content than softwood tree species (55.2% versus 49.97%). Lamlom and Savidge (2003) concluded that the difference is due to the higher lignin content within softwood trees. This is supported by a study completed by Hoover (2013) on old growth forests in the northern United States. Hoover (2013) found that softwood old growth forests hold 25% more carbon than their hardwood counterparts. Inversely, Cannell (1999) indicates that hardwood trees have a greater carbon content than softwood trees. Cannell (1999) showed that hardwood trees have 195% greater carbon content than softwood trees (62 tC ha-1versus 21 tC ha-1).

TREE SPECIES SELECTION

This study has shown that hardwood and softwood trees do not sequester a significantly different amount of carbon. As well, other studies have shown conflicting results when comparing the amount of carbon within the two tree types. As such, emphasis should be placed on economic value when selecting tree species for use in agroforestry. In Canada, economic value of saw logs from individual tree species will differ between provinces, and as such these differing prices should be taken into consideration when selecting tree species. According to British Columbia's Ministry of Forests, Lands, Natural Resource Operations and Rural Development (MOF) (2020), the current value of softwood species averages at $84.94/m3 for saw logs. British Columbia's MOF indicates that currently, cedar species are the highest valued softwoods at $148.34/m3 for saw logs and spruce/pine/fir species are the lowest valued softwoods at $80.88/m3 for saw logs. British Columbia's MOF (2020) values saw logs from hardwood species from $40.45/m3 for cottonwood to $55.81/m3 for maple. In Ontario and Quebec, hardwood species are of greater value than softwood tree species with the average value of maple species being $117.95/m3 and $65.95/m3 for spruce/pine/fir species (Government du Quebec 2016; Ontario Woodlot Association 2001). The difference in timber values between these provinces are stark and should be considered when choosing a dominant species for agroforests in Canada to maximize total revenue (ie. Hardwoods should be chosen in Ontario/Quebec and softwoods should be chosen in British Columbia).

POTENTIAL OF AGROFORESTRY IN CLIMATE CHANGE MITIGATION

Although this study's results have shown that a silvopastoral system was the only agroforestry system which could sequester significantly more carbon than other land management systems, there is still potential for all agroforestry systems to aid in climate change mitigation. To curb climate change, 100 GT to 1000 GT of carbon needs to be removed from the atmosphere (Abbas *et. al* 2017). This study determined that silvopastoral agroforests hold significantly more soil carbon than their adjacent purely agricultural fields with an average of 78.00 grams of carbon per kilogram of soil and up to 21,786 kilograms of aboveground carbon per hectare. In Canada, the average plot of agricultural land is 294.61 hectares (Statistics Canada 2014). This means that at a maximum 21,786 kilograms of aboveground carbon per hectare, one plot of land could hold up to 15,860,208 kilograms of aboveground carbon alone, or 0.00000159 GT of the 100 GT minimum needed to curb climate change. Although this amount may seem negligible, if agroforestry were implemented on a wider scale than it is currently, it may be able to aid in climate change mitigation.

Supporting this, the Kyoto Protocol has recognized agroforestry a potential mitigation measure against climate change (Abbas *et. al* 2017). Agroforestry is recognized as a potential climate change mitigation measure as it is a method of afforestation (Abbas *et al.* 2017). Deforestation has had a large contribution to climate change, with 24% of all anthropogenic carbon emissions coming from the removal of forests (Schoene & Netto n.d.). The United Nations has recognized the need to restore industrial and agricultural land to aid in climate change mitigation and has said that 900 million hectares of this land around the world could be restored using agroforestry

(Majendie & Parija 2019). The United Nations has indicated that if this land were to be restored by 2030, it would have a significant positive impact on climate change (Majendie & Parija 2019). Implementation of agroforestry not only has the potential to mitigate climate change, but to ease the effects of climate change on humans (Toppo & Raj 2018). As the climate changes, food security, income and the health of land will be threatened around the world. Agroforestry can increase food security, protect from erosion, restore already degraded soils, and increase the income of landowners, among other benefits (Abbas *et. al* 2017; Mbow *et. al* 2014; Toppo & Raj 2018). In the face of climate change, agroforestry has many benefits beyond the sequestration of carbon.

POLICY RECOMMENDATIONS

Resources and Strategic Framework

Currently, Canada only has accessible resources for land managers available for shelterbelt agroforestry systems. It is recommended that Canadian governments invest time and resources into developing programs and educational materials for land managers to implement any applicable agroforestry system, with emphasis on programs for silvopastoral systems. Although silvopastoral agroforestry systems are mostly implemented in temperate regions of the world, their use in Canada would still show a positive impact. Aside from sequestering a significant amount of carbon in their soils compared to their adjacent agricultural fields, silvopastoral systems have also been shown to have the greatest provision of wildlife habitat compared to other agroforestry and land management systems (Kumar & Ramachandran 2011). Silvopastoral systems also have a positive socioeconomic impact. Managers of silvopastoral agroforests can use livestock as a source of income and to ensure food security (Mbow *et. al* 2014, Abbas *et. al* 2017). Income is also made available through sale of timber harvested from agroforests (Hesselink & Thevathasan 2012). These benefits are not secluded to temperate regions and would be seen in within properly implemented and managed silvopastoral systems anywhere.

Educational materials and resources should encourage private land managers to use silvopastoral agroforestry systems, but also highlight the benefits of all agroforestry systems, as silvopastoral systems would not be applicable to all land managers. At the time of this study, no grants were found outside of Saskatchewan in Canada specific to agroforestry for landowners (AgPal 2020). It is recommended based on the results of this study that Agriculture and Agri-food Canada, and similar government organizations, develop and make grants available for agroforestry across Canada. To encourage the use of silvopastoral systems to increase the net carbon sequestration within Canada, an additional amount should be given to land managers implementing this system over other systems. As there is no statistically significant difference between the amount of carbon sequestered aboveground in hardwood and softwood trees, emphasis should be placed on selecting either the most economically valuable native species, depending on location (Manley 2009). Native species should be preferred as their use will benefit wildlife and reduce the risk of the spread of a potentially invasive species (Manley 2009).

It is also recommended that Canada develop and implement a strategic framework for agroforestry, as developed in the United States. As with the United States' strategic framework, Canada's would outline the mission and individual goals for implementing agroforestry more widely across the country and would be delivered by

Agriculture and Agri-food Canada. Development and implementation of grants and resources would be outlined in the strategic framework as goals. Once developed, they would remain in the strategic framework as deliverable resources available for landowners. Reduction of property tax rates, which is outlined in the following section, would also be included within the strategic framework for agroforestry in Canada.

Property Tax Rates

When developing resources for land managers in Canada to implement silvopastoral systems (or other agroforestry systems), we should look to other areas of the world such as New Zealand and to provinces within Canada such as Ontario, for guidance (Gordon *et. al* 2008). During the 1990's, New Zealand saw a sweep of policy changes regarding land use and associated taxation (Gordon *et. al* 2008). At this time, property taxation across multiple land uses became equal, as subsidies were eliminated for purely agricultural lands (Gordon *et. al* 2008). As costs to operate agriculture-only land increased, agroforestry became a more appealing land management system. As land managers shifted toward silvopastoral agroforestry for added income, international and domestic markets for high-value timber species began to surge due to increased timber production (Gordon *et. al* 2008). As well, managers of many New Zealand's silvopastoral agroforests reported decreased erosion during the rainy season and increased livestock health (Gordon *et. al* 2008). In Ontario, land managed as both farmland and private forest land (agroforests) are eligible for the Farmland Program as well as the Managed Forest Tax Incentive Program (MFTIP). These lands are eligible for MFTIP without a 10-year approved management plan, unlike private forest land without incorporated farmlands.

It is recommended that Canadian governments (federal and provincial) modify property tax schemes to make agroforestry a more accessible and appealing land use system following the examples of New Zealand and the province of Ontario, Canada. Tax rates for multiple-use land (agroforests) should be the same as or lower than the rates for pure agricultural land or pure forest production land. This would encourage land managers to move toward agroforestry instead of single-use land management systems. This, in conjunction with educational materials and programs promoting the use of agroforestry could increase silvopastoral agroforestry's rate-of-use in Canada, and therefore, could decrease Canada's overall carbon emission contribution through sequestration of carbon within soils.

POTENTIAL SOURCES OF ERROR

There are multiple potential sources of error which may have affected the results of this study. As with all scientific analyses, there is a potential for systematic and random errors, as well as errors in calculation (Carlson 2002). Regarding this research, it is possible that errors may have occurred during the original studies which were reviewed and/or during this study itself. A major source of error for this study may have been the fact that publications researched had varying methods of data collection, data analysis, data expressions and measures of experimental design between them.

Systematic errors which may have affected this study could have occurred during either the reviewed studies or during the review of the studies (this research), if having occurred at all. Examples of systematic errors which may have affected this study include miscalibration of equipment, misreading of information from instruments by users, and poorly maintained instruments, which may have occurred during the reviewed studies (Carlson 2002). As well, information biases may have occurred during either the reviewed studies or during this study. It is possible that selected individual trees for analysis of aboveground carbon were used due to their accessibility and did not result in a truly random sample. If individual trees analyzed for aboveground carbon content were not from a random sample set, the data may have been inaccurate (Lavrakas 2008).

Additionally, a bias of information may have occurred during this study. As discussed in the results of this study, there were issues with access to reliable information to be analyzed; usable information was only found for shelterbelt and silvopastoral systems, and information for each tree species used in either system was not available. It is possible that additional information has been published in journals, books and other formats which were not accessible at the time of this study and therefore were not included in the data, potentially resulting in inaccurate results. Additionally, acquisition of quality data was made difficult by inconsistencies in quantifying carbon levels within studies. For this study, publications quantifying carbon levels in grams/kilogram of soil were used as this was the most frequent quantifier for all systems. Studies were found for agroforestry systems other than shelterbelt and silvopastoral, however the quantifier for carbon levels in soil or aboveground carbon were not consistent with other studies and levels were not able to be accurately converted into grams/kilogram of soil and/or did not have control numbers (adjacent field data) for comparison.

Calculation errors may have occurred during any of the reviewed studies or this study. Precision errors may have occurred during the reviewed studies with instruments used for measuring parameters (Carlson 2002). Additionally, similar errors may have occurred during this study with the use of programs used for analyzing the results of the review (Carlson 2002).

CONCLUSION

In conclusion, silvopastoral agroforestry systems were the only system studied which show a statistically significant increase in carbon sequestration potentials over their adjacent purely agricultural fields. However, all agroforestry systems have socioeconomic and environmental benefits which make them preferable over other land management systems. There was shown to be no significant difference between the aboveground biomass within hardwood trees and softwood trees. As such, emphasis should be placed on the use of native tree species with the greatest economic value in agroforests over hardwood or softwood species specifically. This will ensure that wildlife habitat is provided within the agroforest and will ensure the greatest economic returns for land managers. Currently, Canada does not have adequate, accessible resources for land managers to implement agroforestry practices. More resources, including grants applicable across Canada and a strategic framework for agroforestry, need to be developed. As well, property tax schemes should promote the use of agroforestry over agriculture, or other single-use land management systems.

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