Quantifying past, current, and future forest carbon stocks within agroforestry systems in central Alberta, Canada

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Abstract
Information about regional-level carbon (C) stocks in agroforestry systems (AFS), as well as the annual loss of agroforests and associated C stocks, is scarce, limiting our capacity for increasing C sequestration through establishing, retaining, and enhancing these systems. This study quantified regional-level C stocks and the associated incremental economic value in the forest land-use component of three common AFS (hedgerows, shelterbelts, and silvopastures), estimated the annual loss of hedgerow and silvopasture forests and the associated C, and assessed the potential to enhance C storage through the expansion of shelterbelts in central Alberta, Canada, using publicly available satellite imagery, previously collected field data and the Google Earth Engine platform. Results showed that forests in the three AFS stored 699.9 million tons (Mt) C across 9.5 million hectares (Mha) of land in central Alberta and were valued at $102.7 billion based on the 2021 Canadian C tax rate of $40 t⁻¹ CO₂-equivalent. Silvopasture forests in the studied region had the highest C stocks, which were 14.2 and 67.2 times that found in hedgerow and shelterbelt forests, respectively. Between 2001 and 2020, forests in hedgerows and silvopastures declined at rates of 468.1 and 1957.1 ha year⁻¹, respectively, leading to an 8.4 Mt decline in total C storage over the 20 years. However, there is potential to establish new shelterbelts at many road/field margins, which could increase C stocks by 2.3 times the current C stocks in shelterbelt forests. These results highlight the importance of retaining existing and establishing new AFS for increasing C sequestration, emphasizing the impact of agroforest loss on reducing C storage within agroecosystems. The development of policies that assist or reward landowners for providing the ecosystem service of C storage by retaining, establishing, and enhancing agroforests as part of existing agroecosystem management should be encouraged for mitigating climate change.

Keywords
agroforestry systems, carbon sequestration, carbon storage, carbon tax, forest loss, Google Earth Engine
1 | INTRODUCTION

Changes in C storage in agroforestry systems (AFS) will affect the role those systems play in mitigating climate change. Quantification of C stocks in AFS is essential to understand the capacity of agroforests for C sequestration and climate change mitigation. However, C sequestration studies with respect to AFS in Canada (and in other regions) are often limited to a small number of plots, selected C pools, or certain AFS (e.g., shelterbelts) within specific regions (Abbas et al., 2017; Amichev et al., 2020; An et al., 2021). Furthermore, limited studies have reported on the current C storage status (Shi et al., 2018), past loss of C stocks (Mosquera-Losada et al., 2012), and future potential for C gains by expanding AFS (Albrecht & Kandji, 2003) across the larger landscape, particularly in Canada, limiting our understanding of where and to what extent AFS may be an effective C sequestration strategy.

Temperate agroforestry in North America plays a crucial role in C sequestration (Thevathasan et al., 2018), with the forested component (referred to as ‘forest’, hereafter) of AFS being estimated to store 46.1 and 36 t ha⁻¹ more C in plant biomass (Ma et al., 2020) and soil (Shi et al., 2018), respectively, than adjacent cropland. In Canadian agroecosystems, hedgerows (legacy trees, usually found along field margins), shelterbelts (planted trees along field margins), and silvopastures (widely-spaced trees or dense patches of trees across grasslands) are critical for increasing C sequestration (Amichev et al., 2016; Lim et al., 2018; Oelbermann et al., 2004). Specifically, the Canadian Prairies have a vast agricultural area, and expansion of AFS could increase C sequestration (Baah-Acheamfour et al., 2014; Kort & Turnock, 1998). For example, shelterbelt systems comprising 6 million trees could store 0.4 million tons (Mt) of additional C annually across the agricultural landscape of the Canadian Prairies (Kort & Turnock, 1998), helping to offset increases in atmospheric CO₂ (Pankiw & Piwowar, 2010). The province of Alberta, for example, may have a large potential to increase C sequestration by establishing new AFS, as Alberta has the second largest agricultural land area in Canada, consisting of ~20.6 million hectares (Mha), or 31.7% of Canada’s agricultural land (Statistics Canada, 2014).

Although the importance of AFS in C sequestration and climate change mitigation has been recognized, incentives are lacking for landowners to invest in the development of AFS. By incentivizing the private sector, C sequestration can be increased through innovation in technology, conservation vegetations, and substitution to other energy sources (Carbon Tax Center, 2014). Many regions and countries are imposing C taxes to disincentivize C emissions from anthropogenic sources as a means to mitigate climate change. Canada announced its initial C tax ($20 t⁻¹ CO₂-equivalent; all dollar values reported herein are in Canadian dollars) in 2019. The C tax would increase at a rate of $10 per year until it reaches $50 t⁻¹ CO₂-equivalent in 2022, and will thereafter further increase by $15 per year until it reaches $170 t⁻¹ CO₂-equivalent by the year 2030 in Canada (Urban & McElhone, 2021). Determining the incremental economic value of current AFS compared with traditional agricultural land-use types (i.e., cropland and grassland), as well as the loss of C stocks due to deforestation of the previous AFS, is critical for conserving and promoting AFS for C sequestration and climate change mitigation.

The objectives of this study were to: (1) quantify the regional-level C stocks in the forest land-use component of three common AFS (hedgerow, shelterbelt, and silvopasture) and the associated economic value of the C stock, (2) estimate the annual loss of C and the associated C from hedgerows and silvopastures, and (3) assess the potential to increase C storage through the expansion of shelterbelts and estimate the associated incremental economic value of such an expansion in central Alberta, Canada.

2 | MATERIALS AND METHODS

2.1 | Study area and sources of datasets

This study focuses on agricultural land within the central Alberta region (52° 20’–55° 15’ N, 110° 0’–116° 39’ W; 9.5 Mha) in Canada. The study area has a humid continental climate and includes the Central Parkland, Central Mixedwood, and Dry Mixedwood natural subregions of Alberta (Environment & Parks, 2006). The annual total precipitation and temperature of the region range from 474 to 432 mm and 1.6 to 2.5°C, respectively, for the period of 1980–2020, in a north to south transect in the study region (Environment Canada, 2020). The region is characterized by having Gray Luvisolic and Dark Gray Chernozemic soils (based on the Canadian system of soil classification) in the north, and Black Chernozemic and Dark Brown Chernozemic soils in the south (Soil Classification Working Group, 1998).

The extent of agricultural land was based on the shapefile “Organic Matter Content of Cultivated Soils” in the Alberta Open Government Program (Alberta Agriculture & Forestry, 2016), in which the total area under cultivation was provided. This dataset also allowed for the differentiation of AFS across the study area (Table 1). However, due to the considerable time investment required to map each agroforestry system for the whole study area, 50 randomly selected large-scale plots (details below) were chosen to manually map each agroforestry system present in the
TABLE 1 List of data sources used in the current study

| Data source                                           | Usage                                                                 | Web link (all accessed on January 14, 2022) |
|-------------------------------------------------------|-----------------------------------------------------------------------|---------------------------------------------|
| Bing Aerial Imagery                                   | Differentiation of agroforestry systems in selected plots             | https://www.bing.com/maps/                  |
| Environmental Systems Research Institute (ESRI Satellite Imagery) | Differentiation of agroforestry systems in selected plots             | https://www.arcgis.com/apps/mapviewer/      |
| Google Satellite Imagery                              | Differentiation of agroforestry systems in selected plots             | https://www.google.ca/maps/                |
| Alberta Biodiversity Monitoring Institute (ABMI) 3 × 7 km Sample-based Human Footprint Data | Selection of plots and differentiation of agroforestry systems in selected plots | https://abmi.ca/home/                      |
| ABMI Wall-to-Wall Human Footprint Inventory           | Determination of land area under grazed grassland and cultivated cropland within selected plots | https://abmi.ca/home/                      |
| Organic Matter Content of Cultivated Soils            | Determination of agricultural land and agroforestry systems           | https://open.alberta.ca/dataset/            |
| Alberta Satellite Land Cover                          | Validation of the land area under agroforestry in selected plots      | https://open.alberta.ca/dataset/            |
| Central Parkland Vegetation Inventory (CPVI) Polygons  | Validation of the land area under agroforestry in selected plots      | https://open.alberta.ca/opendata/           |
| Global Forest Change (2000–2020) v1.8                 | Extraction of forest area gain and loss information                    | https://data.globalforestwatch.org/documents/ |

region (Figure 1). The "3 × 7 km Sample-Based Human Footprint Data" released by the Alberta Biodiversity Monitoring Institute (ABMI) provided a selection of pre-defined plots, each 21 km² in size (Alberta Biodiversity Monitoring Institute, 2017; Table 1). As ABMI plots in central Alberta were not uniformly distributed across the region and some areas had no ABMI plots available (Figure 1), 35 of the ABMI 3 × 7 km plots were randomly selected, and added an additional 15 randomly placed plots were across the areas where no ABMI plots were available. The randomization of plots was achieved using the R software (R Core Team, 2018). After the randomization, the results were checked carefully to ensure that the selected plots covered all types of land-uses in the study area. The final 50 plots covered a total area of 0.105 Mha, representing 1.9% of central Alberta.

Detailed descriptions of the vegetation and soil physical characteristics of forests associated with hedgerow, shelterbelt, and silvopasture systems in central Alberta can be found in Baah-Acheamfour et al. (2014) and Lim et al. (2018). Briefly, hedgerow forests, which are linear boundary features in the landscape, were dominated by naturally occurring broadleaf deciduous trees (e.g., *Betula papyrifera* and *Populus tremuloides*, with an average tree age of 28 years), along with various shrubs (e.g., *Prunus virginiana* and *Amelanchier alnifolia*) and herbaceous understory vegetation (e.g., *Bromus inermis*) at field edges (Baah-Acheamfour et al., 2014; Lim et al., 2018). They were typically non-uniform and had varied colors and spacing in satellite images. Shelterbelt systems, which are also linear boundary features, are comprised of planted trees (e.g., *Picea glauca* or *Caragana arborescens*, with an average tree age of 34 years) and therefore appeared uniform, with similar color and width of the planted tree belts in satellite images. Silvopasture forests consisted of patches of trees (e.g., mostly *Populus tremuloides* and *P. balsamifera*, with an average age of 30 years) among grasslands grazed by livestock (Baah-Acheamfour et al., 2014; Lim et al., 2018). As silvopasture forests were not linear, tree coverage was manually determined (after delineation of each silvopasture) by mapping each patch of trees. Forests associated with the shelterbelt, hedgerow, and silvopasture systems were identified in the 50 plots (Figure 2) using Bing Aerial Imagery, Environmental Systems Research Institute (ESRI) Satellite Imagery, and Google Satellite Imagery. The extent of land area under grazed grassland and cultivated cropland within the plots (Figure 3) was derived from the "Wall-to-Wall Human Footprint Inventory" (Alberta Biodiversity Monitoring Institute, 2018) and cross-validated with the "Alberta Satellite Land Cover" (Alberta Agriculture & Forestry, 2018), "Central Parkland Vegetation Inventory (CPVI) Polygons" (Environment & Parks, 2012), Bing Aerial Imagery, ESRI Satellite Imagery, and Google Satellite Imagery (Table 1).
The past forest loss was estimated using the Google Earth Engine. Our assumption was that the loss of forests from croplands and perennial grasslands was attributed to removing natural boundary hedgerow forests and silvopasture forests, respectively. Annual forest loss data of hedgerows and silvopastures from the cultivated land area (based on the extent of cropland and grassland in the study area, respectively) between 2001 and 2020 was extracted from "Global Forest Change (2000–2020) v1.8" (Hansen et al., 2013; Table 1). Non-forested road/field...
margins were marked as potential areas for expanding or establishing shelterbelts (Figure 2). Delineation of the forests within each agroforestry system and the potential area for shelterbelt forest expansion was done using QGIS 3.12.0 (QGIS Development Team, 2018) and ArcGIS Pro 2.7 (Esri Inc, 2020), with “NAD83/Alberta 10-TM (Forest)” as the source coordinate reference system. All map outputs were created in ArcGIS Pro 2.7.

2.2 | Carbon density in different AFS

For the purpose of this study, C density is defined as the mass of C stored per unit land area (e.g., t ha⁻¹), while C stocks refer to C inventories quantified over broader spatial scales (e.g., central Alberta). Carbon stock estimation in this study was based on previous field data of average C density from 36 locations associated with three different AFS (12 sites for each hedgerow, shelterbelt, and silvopasture systems, with average tree age >20 years; Lim et al., 2018). The average ecosystem C density in the forests of hedgerow, shelterbelt, and silvopasture systems was 369.0, 392.5, and 368.4 t ha⁻¹ (Lim et al., 2018; Ma et al., 2022), respectively. These values included C densities in aboveground vegetation (Ma et al., 2022), roots, litter, and partially decomposed litter and humus, as well as mineral soil organic C densities to 75 cm depth (Lim et al., 2018).

In contrast, C densities within the cropland and grazed grassland land-use components of the AFS were 198.9 and 191.8 t ha⁻¹, respectively (Table 2; Lim et al., 2018; Ma et al., 2022). These C density data were combined with the spatial data in the current study and applied to each corresponding land-use type at the plot scale for current areal C stock estimation and computation of aggregate C stock changes over time. This process assumed that the observed C densities at the 36 locations (Lim et al., 2018; Ma et al., 2022) were representative of the entire study area in central Alberta.

2.3 | Calculations

The calculations of land-use areas and C stocks, both current and past, in each of the 50 plots were extrapolated across the central Alberta region. The processes involved in studying past, current, and future carbon stocks in the current study are shown in Figure 4. Total C stocks within the forests associated with the shelterbelt, hedgerow, and silvopasture systems were obtained by multiplying the area within each forest type by the corresponding C density. Regional C stock size was calculated using the following equation:

\[
\text{Regional C stock} = C_{\text{Cropland}} + C_{\text{Grassland}} + C_{\text{AFS}}
\]  

(Figure 3) The areal extent of cultivated land used within the Google Earth Engine to derive information on annual forest loss. The cultivation extent includes the combined area of managed grassland and cropland.
where \( \text{CCropland, CGrassland, and CAFS} \) represent C stocks in cropland, perennial grassland, and forest land-use types in AFS (sum of hedgerow, shelterbelt, and silvopasture forests). The C loss in the hedgerow and shelterbelt systems was estimated using the following equations:

\[
\text{Hedgerow C loss} = \left( \text{Density - hedgerow} - \text{Density - cropland} \right) \times A_1 \times \text{W hedgerow} \times L \times A_1 \times W \times L
\]

\[
\text{Shelterbelt C loss} = \left( \text{Density - shelterbelt} - \text{Density - grassland} \right) \times A_2 \times \text{W shelterbelt} \times L \times A_2 \times \text{W} \times L
\]

\[
\text{Silvopasture C loss} = \left( \text{Density - silvopasture} - \text{Density - grassland} \right) \times A_3 \times \text{W silvopasture} \times L \times A_3 \times \text{W} \times L
\]

\[
\text{C stock change} = \text{Density - shelterbelt} \times \text{W shelterbelt} \times \text{L shelterbelt}
\]

3 RESULTS

3.1 Current C stocks and their valuation in AFS in central Alberta

### Table 2 Estimated C stocks, the relative contribution of C stocks, land areas occupying different land-uses, and the incremental C values comprising different land-uses, found in various agricultural land-uses across 50 study plots and the greater study region of central Alberta, Canada. All valuations are in Canadian dollars

| Land-use               | Carbon densitya (t ha\(^{-1}\)) | Sample of 50 plots | Central Alberta region |
|------------------------|---------------------------------|---------------------|-----------------------|
|                        | Estimated total C (Mt)          | Percent of C stocks in various agricultural lands | Incremental C valueb ($ ha\(^{-1}\)) | Estimated total C (Mt) | Percent of C stocks in various agricultural lands | Incremental C value (total $ billion) |
| Shelterbelt forests    | 392.5                           | 0.1 0.5            | 0.3 28,421            | 9.6 0.5 0.3 0.9       |
| Hedgerow forests       | 369.0                           | 0.5 2.3            | 1.5 24,971            | 45.3 2.3 1.5 2.9      |
| Silvopasture forests   | 368.4                           | 7.1 32.9           | 21.0 25,925           | 645.0 32.9 21.0 45.1  |
| Grassland             | 191.8                           | 4.0 18.5           | 23.1 n.a.             | 364.5 18.5 23.1 n.a.  |
| Cropland              | 198.9                           | 9.9 45.8           | 54.1 n.a.             | 898.0 45.8 54.1 n.a.  |
| Total                 | n.a                             | 21.6 100%          | 100% n.a.             | 1962.4 100% 100% n.a. |

Abbreviations: Mt, million tons; n.a., not available.

aThe C stocks included aboveground vegetation C stock, roots, litter, and partially decomposed litter and humus, and soil C to 75 cm depth.

bThe percent of the total agricultural land area did not include urban-industrial, water, etc.

cThe incremental C value is calculated based on $40 ton\(^{-1}\) CO\(_2\)-equivalent.
(relative to adjacent croplands or grasslands), was estimated to be $28,421, $24,971, and $25,925 ha$⁻¹, respectively (Table 2).

Applying the data from the 50 plots to the broader central Alberta region, the forests associated with the three common AFS were estimated to occupy 24,390 (shelterbelt), 122,888 (hedgerow), and 1,750,791 ha (silvopasture; Table S1). The total C stock in the forests of the three AFS in central Alberta was estimated to be 699.9 Mt C (Table 2), worth an estimated value of approximately $102.7 billion (B) based on the 2021 C tax rate. Silvopasture forests stored the largest amount of C with 645 Mt C, followed by hedgerow and shelterbelt forests with 45.3 and 9.6 Mt C, respectively (Table 2). Grassland and cropland stored 364.5 and 898.0 Mt C, respectively (Table 2). The total length of shelterbelt forests (21,264 km) and hedgerow forests (85,228 km) was 106,492 km in central Alberta (Table S1). The economic value of additional C storage within the forests of shelterbelts, hedgerows, and silvopastures (relative to adjacent croplands or grasslands), was estimated to be $0.9, $2.9, and $45.1 B, respectively (Table 2).

3.2 | Past loss of forests and associated C in AFS in central Alberta

The area occupied by forests in the agricultural region of central Alberta declined between 2001 and 2020, with a mean forest loss rate of 2425 ha year$^{-1}$ (Figure 5). Annual forest loss peaked in 2016, slowed down thereafter to a low of 770 ha in 2020 (Figure 5). The total forest area lost over the 20 years was 48,503 ha, of which silvopasture forests represented over 80% of the decline. The estimated C stock loss ranged from 0.1 to 1.0 Mt C year$^{-1}$, with a mean loss rate of 0.4 Mt C year$^{-1}$ over the 20 years (Figure 5). Land-use change from AFS to solely cropland and grassland resulted in the loss of 1.6 and 6.9 Mt C in hedgerows and silvopastures, respectively, for a net decline of 8.5 Mt C (Figure 5). This represents a loss of $1247.8 M (based on the 2021 C tax rate) in sequestered C across the agricultural landscape of central Alberta between 2001 and 2020.

3.3 | Projected C stock changes with shelterbelt expansion in central Alberta

The total length of non-forested road/field margins potentially available to plant shelterbelt forests is 46,285 km (Table S2), a 230% increase compared to the current length of shelterbelt forests. Should this shelterbelt expansion occur, the estimated increase in C storage over time is projected to be 21.8 Mt C (Table S2), or 2.3 times the C stock currently held in shelterbelt forests.

4 | DISCUSSION

4.1 | Current, past, and projected C stocks in AFS in central Alberta

Our results showed that there is a substantial amount of C (including above- and belowground plant biomass C and soil organic C to 75 cm depth) stored in the agricultural landscape of central Alberta, Canada. Importantly, forests
within the three AFS stored a disproportionately large amount of this C relative to the area of land that they occupy, storing 35.8% of the regional C but represented by only 22.8% of the total land area. The amount of C stored in the forests of the AFS was around two times the C stored in grasslands (18.5% of the regional C), despite occupying a similar amount of land area. This suggests that both the retention of existing forests (averted C loss) and planting of trees into the agricultural landscape (expanding the existing AFS) could be very effective in achieving long-term C sequestration and climate change mitigation in the region (Amichev et al., 2015, 2016; Ha et al., 2019; Kort & Turnock, 1998; Piwowar et al., 2016).

The loss of forests in AFS and associated C in the study region due to the conversion of forests to cropland and grassland over the past 20 years was substantial, totaling 8.5 Mt C. Most of the removed deciduous trees were likely burned rather than salvaged for alternate uses (Rudd et al., 2021), releasing the sequestered C into the atmosphere. Our results highlight the urgency to protect hedgerow and silvopasture systems for their ecological services, including C sequestration. Annual C loss due to forest removal in the agricultural landscape of central Alberta varied substantially from 2001 to 2020. However, loss of forests and associated C within hedgerow and silvopasture systems began decreasing dramatically in 2017, possibly due to reductions in cropping activities and wood trade profitability during this time or, alternatively, an improving recognition of the importance of trees.

Many factors influence landowner attitudes toward trees in the agricultural landscape. Although the ecological benefits provided by AFS are substantial, factors such as shortage of labor to plant and maintain shelterbelts, reduction in space for maneuvering large agricultural equipment due to trees, and tree aging and death likely caused the reduction in the area maintained as AFS (Rempel, 2013; Rempel et al., 2014). Additionally, trees within AFS may be considered harmful because they can harbor pests, disease-causing pathogens, and competitive weedy plants (Gordon et al., 2009) that can negatively influence crop yield and make landowners want to remove them. It should be noted that time lags are not considered of C loss with deforestation and assumed that C stock changes occurred in sync with land-use change when evaluating past C loss. On the contrary, trees incorporated into agricultural land provide other essential ecosystem services such as reducing soil erosion, water conservation and flood mitigation, wind protection, and biodiversity conservation (Aznar-Sánchez et al., 2018; Jose, 2009), all of which increase agroecosystem sustainability and may promote net increases in crop yield over time.

There is substantial potential to increase C storage across the agricultural landscape in central Alberta by establishing new shelterbelt systems or expanding tree coverage at road/field margins. Over time, the C stored in current shelterbelt forests could be increased 2.3-folds by adding trees to agricultural lands, with an associated value of approximately $3200.3 M for central Alberta. However, newly planted shelterbelt forests may take decades to reach their maximum estimated valuation, with a potential annual median soil organic C accrual rate of 0.7 t ha\(^{-1}\) year\(^{-1}\) (Dhillon & Van Rees, 2017). Of course, increasing C sequestration in agroecosystems is not solely dependent on adding trees. Proper management practices in croplands are also vital to enhance C sequestration. For example, the use of cover crops, no-till, and manure,
as well as biochar amendments, can further increase C storage in AFS (Gross et al., 2022; Stavi & Lal, 2013). Considering the size of agricultural land areas on a global scale [~1.5 B ha (Bruinsma, 2003)], management practices (e.g., fertilization, crop diversification, use of perennial tree crops) that promote the development of AFS could retain and/or increase biological C stocks worldwide.

4.2 Contribution of forests to the value of AFS in central Alberta

Using the current C taxation rate of $40 t^{-1} CO_2$-equivalent the total value of C stored within agricultural lands in the study area was $288.1$ B. The economic value of additional C storage within the forests of shelterbelts, hedgerows, and silvopastures (relative to adjacent croplands or grasslands) was estimated to be $102.7$ B. Notably, our valuation only accounted for C sequestration and did not include the value of other ecosystem services provided by forests within AFS. It is also noted that the C tax rate in Alberta will increase annually for the foreseeable future (Energy Rates, 2021). Therefore, the incremental economic value of additional C storage within the forests of AFS is expected to substantially grow in the future. Although the area of tree cover was only 22.8% of the total land area, the associated C stock was 35.7% of the total, highlighting the significant C storage potential of AFS (Lorenz & Lal, 2014; Pandey, 2002). Our work highlights the potential for climate change mitigation through shelterbelt establishment and expansion, which is consistent with findings in Zhang et al. (2021), who found that the construction of Three North Shelterbelt could bring huge ecological and economic benefits with the shelterbelts being a C sink in the future; furthermore, even if trees are added only to small areas at road/field margins, the estimated potential increase in C storage in the region is substantial (21.8 Mt C).

Although establishing AFS is an effective means to balance the need for environmental conservation and agricultural production (Porro et al., 2012; Santos et al., 2019), many of the ecological benefits of AFS are not fully understood by the public (Torralba et al., 2016); this lack of awareness limits people’s interest in AFS practices and thus may affect the valuation of the services that are provided by AFS. In addition, the ability for AFS to provide services as mentioned earlier is also dependent on the status of the current land-use, and the level and duration of funding for the implementation of AFS is often less than that for afforestation projects (Torralba et al., 2016). Quantification of the economic and ecological benefits of AFS will help to promote AFS as a sustainable land-use system to the public and to attract more funding to support the development of AFS. Providing economic incentives in the form of C credits or payments for C sequestration help promote AFS among landowners (Van Noordwijk, 2020).

4.3 Limitations and recommendations

Remote sensing is a readily available and effective tool for determining the areal extent of AFS over a study area. However, some image tiles used in this study may not have been current due to delays in updating them by the provider, reducing the accuracy of the C stock estimates. Additionally, information on forest gains was not updated annually and was only available for 2000–2012. The available information indicated that only a total of ~970 ha of forest gains occurred over this period, while there was over 2200 ha of forest lost at the same time in central Alberta. Furthermore, no other dataset was readily available for estimating annual forest gain in the region. Timely collection of forest gain and loss information in the future will help us to better estimate C storage in AFS in the studied region.

In estimating shelterbelt expansion, road/field margins were only used as the potential areas for tree planting, as tree planting along road/field margins is the most common practice for establishing AFS in central Alberta. However, trees can also be added in the middle of croplands or grasslands if there is sufficient space available. Given our modest approach, our results are likely an underestimation of the potential of tree cover expansion in the form of shelterbelts to enhance C stocks across the agricultural landscape in central Alberta.

The calculation of C stocks in the three AFS across the study area was based on the average C density values at 36 AFS locations with an average tree age of 20 years (Lim et al., 2018). Previous work indicates that many factors, including tree size, tree species composition, tree age, and ecosite type, can influence C stocks in AFS (Ma et al., 2020) and planted forests in Alberta (Sun et al., 2015). For example, younger trees of newly established shelterbelts may result in initial soil organic C losses during the development of the AFS and may require decades of growth to achieve net increases in soil organic C stocks (Arevalo et al., 2011; Dhillon & Van Rees, 2017). Furthermore, the historical expansions in hedgerow were not considered and silvopasture forests due to fire suppression may have occurred on grassland soils with high C density (Bailey & Wroe, 1974), and prolonged tree establishment may lead to the loss of a portion of this grassland-originated legacy soil organic C (Dormaar & Lutwick, 1966). Similarly, management
practices (e.g., tillage, irrigation, fertilizer, and herbicide application) may influence the total C stocks in AFS. The absence of specific management practice influences on the observed and extrapolated C stocks in our study limits our more nuanced understanding of the factors regulating C sequestration within the three AFS studied (Amichev et al., 2021). Therefore, the estimated C stocks in this study should be used cautiously and interpreted as an assessment of the overall potential for AFS to contribute to ecosystem C storage.

In the future, more detailed information about factors influencing C stocks in different AFS should be collected, and further efforts should be put into calibrating and validating predictive models of C gain and loss in AFS (Kröbel et al., 2020). Such improvements should help us gain a better understanding of C dynamics in such agroecosystems. While the addition of trees to agricultural lands is key in enhancing C stocks both above- and belowground, attention should also be paid to often-ignored C pools in AFS, such as C in the understory vegetation (Hubau et al., 2019) and litter layer (Ma et al., 2022). Additionally, future studies should also assess natural increases in the hedgerow and silvopasture forests, such as increases related to ongoing fire suppression (Bailey & Wroe, 1974; Bork et al., 1997), to further elucidate the dynamics of agroforestry land-uses and associated C stocks.

5 | CONCLUSIONS

Our analysis of current C stocks, past C losses, and potential future C stock gains within three AFS across a 9.3 Mha of land in central Alberta, Canada, indicates that hedgerows, shelterbelts, and silvopastures provide substantial C storage in this region. Moreover, there is potential to expand shelterbelts to increase C stocks in central Alberta by more than two-fold relative to the current areal extent of shelterbelt forests. Our work shows that forest loss from hedgerow and silvopasture systems led to a considerable loss in ecosystem C storage in the region. Both the ongoing risk of C loss due to the loss of forests within AFS to cropland or grassland and the opportunities to increase C stocks through tree retention and planting have significant implications for climate change mitigation. Policies should be implemented to promote the retention, expansion, or establishment of AFS. Further research is needed to improve our understanding of the value of AFS, including the assessment of a more complete suite of ecosystem services provided by agroforests and how ongoing forest losses and gains influence the value of these services. Our assessment of C sequestration and valuation shows that the benefits of retaining, expanding, and establishing AFS in central Alberta are substantial. It was recommended that the additional C stored in AFS be monetized to provide landowners with the incentive to utilize these systems.

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CONFLICT OF INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are openly available in figshare at https://doi.org/10.6084/m9.figshare.19200257.v1.

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