Growing our future: Assessing the outcome of afforestation programs in Ontario, Canada

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ABSTRACT

The United Nations Framework Convention on Climate Change (UNFCCC) requires its signatories, including Canada, to estimate and report their annual greenhouse gas (GHG) emissions and removals. Forests are an important natural resource as they slow the accumulation of atmospheric carbon through the process of carbon sequestration. Due to the role of forests as carbon sinks, governments consider afforestation projects as feasible climate change mitigation strategies. This article outlines a spatially-explicit approach to validating afforestation data in Ontario, Canada. Validation is a user-supervised process that uses satellite imagery, remote sensing tools, and other auxiliary data to confirm the presence of seedlings planted through Forests Ontario's 50 Million Tree program. Of the 12 466 hectares assessed, 83% is identified as afforested, 6% is not afforested and 10% is not determined. The area classified as successful afforestation is used as input for the Generic Carbon Budget Model (GCBM), to simulate afforestation effects on carbon stocks. Our findings show the afforestation activities will create a small carbon sink by 2060. From this project, it is evident that spatial validation of afforestation data is feasible, although the collection of additional standardized auxiliary data is recommended for future afforestation projects, if carbon benefits are to be reported.

Keywords: afforestation, carbon sequestration, CBM-CFS3, climate change mitigation

RÉSUMÉ

La Convention cadre des Nations Unies sur les changements climatiques (CCNUCC) exige que ses signataires évaluent et déclarent annuellement leurs émissions et annuelles de leur absorption de gaz à effet de serre (GES). Les forêts constituent une ressource naturelle importante, car elles ralentissent l'accumulation de carbone atmosphérique grâce au processus de séquestration du carbone. Considérant le rôle que jouent les forêts comme puits de carbone, les gouvernements voient les projets de boisement comme des stratégies viables pour la séquestration du carbone. Ce article décrit un approche spatialement explicite pour valider les données de boisement en Ontario, au Canada. La validation est un processus supervisé qui s'appuie sur l'imagerie satellitaire, les outils de télédétection et d'autres données accessoires pour confirmer la présence de semis plantés par l'entremise de *Forests Ontario's 50 Million Tree program* (programme de 50 millions d'arbres de Forêt Ontario). Des 12 466 hectares qui ont été évalués, 83 % sont considérés comme boisés, 6 % ne sont pas boisés et 10 % ont un statut indéterminé. La superficie qu'on catégorise comme bien boisée sert à alimenter le modèle générique du bilan de carbone (*Generic Carbon Budget Model - GCBM*) pour modéliser le rôle du boisement sur les stocks de carbone. Nos résultats laissent voir que les activités de boisement créeront un petit puits de carbone d'ici à 2060. On en déduit qu'il est possible de faire une validation spatiale des données de boisement, bien qu'on recommande la prise d'autres données normalisées pour les prochains projets de boisement si l'on souhaite rapporter les retombées en matière de carbone.

Mots-clés: boisement, séquestration du carbone, CBM-CFS3, atténuation des changements climatiques.

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Introduction

Land-use changes and natural resource extraction alter not only Canada's physical landscape, but also affect carbon stocks (Kurz *et al.* 2013). Forest ecosystems can be both a carbon sink, when they remove and store carbon from the atmosphere, or a carbon source when they release carbon back into the atmosphere (Kurz and Apps 2006). Forests account for up to 80% of carbon in global above-ground biomass stores, and forest soils account for 70% of below-ground stores. Therefore, it is essential that countries incorporate carbon dynamics and modeling into land-use planning and forest management regimes (Laganière *et al.* 2010).

Canada is a signatory to the international treaty, The United Nations Framework Convention on Climate Change (UNFCCC) (Environment and Climate Change Canada [ECCC] 2020b). The UNFCCC requires reporting of annual greenhouse gas (GHG) emissions and removals (UNFCCC 2002). To meet this reporting requirement, Canada estimates its annual carbon stocks and carbon stock changes under the Intergovernmental Panel on Climate Change's (IPCC) 2006 Guidelines for national GHG inventories. Under the Paris Agreement, Canada has also committed to emission reduction targets for 2030 and net-zero emission targets for 2050 (ECCC 2020a). Net-zero emissions require both reductions of emissions from fossil fuels and enhancements of forest sinks in the land sector (IPCC 2018).

Definitions

Under the definitions and parameters agreed to in the Marrakesh Accords (UNFCCC Decision 11/CP.7), Canada adopted the following definition of afforestation: "the direct human-induced conversion of land that has not been forested for a period of at least 50 years, to forested land through planting, seeding and/or the human-induced promotion of natural seed sources" (IPCC 2006). In contrast, reforestation is largely considered human-induced regeneration or the planting of trees on non-forested land, but without the 50-year requirement (e.g., planting after forest harvest) (IPCC 1997). Canada defines forest as an area of at least 1 hectare (ha), with a crown closure of 25% and the ability to reach a minimum tree height of 5 meters at maturity *in situ* (Government of Canada 2007). Sites with a previous use of forest, tree plantation or orchard are not considered afforested as they either do not adequately meet the afforestation definition, or they can be considered forested prior to tree planting.

Afforestation can lead to an increase in carbon stocks through the addition of above-ground biomass (i.e., branches and foliage) and below-ground biomass (i.e., roots), as well as providing an array of other ecosystem services such as flood mitigation and air purification (IPCC 2006). Due to forests ability to sequester carbon, afforestation has become recognized as a nature-based solution to mitigate climate change (White and Kurz 2005; Metsaranta 2019; Seddon *et al.* 2019).

Project objectives

Ontario has a long history of implementing tree planting programs to reforest and restore degraded cropland and abandoned agricultural lands (Trees Ontario 2012; Metsaranta 2019). During the 20th century, these programs occurred mostly in southern Ontario on private land, where ownership ranged from individual landowners to conservation groups and communities and were managed by a third party under an Agreement Forest Program (Borczon 1982; Teitelbaum and Bullock 2012; Metsaranta 2019). In the '90s, Trees Ontario, now known as Forests Ontario (FO), was formed to support large-scale afforestation efforts on private land across the province (Dominy *et al.* 2010). FO is a non-profit, charitable organization focused on afforestation, stewardship, education, and awareness. With funding from all levels of Government and private sponsors, FO works with a network of planting partners including conservation authorities, stewardship groups, forestry professionals, First Nations, municipalities, and local nurseries to build capacity and essential infrastructure related to large-scale tree planting. In 2003, the Canadian Forest Service (CFS) allocated funding to implement the federal Forest 2020 Plantation Demonstration and Assessment Initiative (F2020) (Dominy *et al.* 2010). This afforestation program occurred from 2004–2005 and included the planting of small-scale tree plantations across Canada. FO partnered with CFS to implement the federal program in Ontario (Dominy *et al.* 2010).

FO's "50 Million Trees Program" (50 MTP), provides monetary and planning assistance to planting partners. Their objective is to encourage landowners to plant trees on their property to increase above and below ground carbon stores and improve ecosystem values such as wildlife habitat, soil quality and recreational opportunities (Forests Ontario 2019a). The 50 MTP has been responsible for planting over 31 million trees since 2008 (Forests Ontario 2019b). In 2009 Parker *et al.* estimated the potential carbon storage and offsets of afforested sites, if 50 million trees (27 326 ha of land) were to be planted through the 50 MTP from 2008–2020. For modeling purposes, the study assumed only two tree species were planted, red pine (*Pinus resinosa* Ait.) and white spruce (*Picea glauca* (Moench) Voss.) (Parker *et al.* 2009). FO provided data for 5456 spatial polygons (afforestation sites) from the 50 MTP database to CFS for our analysis.

This project assesses the establishment and presence of afforested seedlings four to thirteen years after planting, through the development of a user-supervised, systematic process. The process was based on the mapping methods of the National Deforestation Monitoring System (Dyk *et al.* 2015). Validated data were provided as input for the Generic Carbon Budget Model (GCBM) developed by the Canadian Forest Service to evaluate the impact of afforestation activities on carbon stocks and fluxes in the area of interest (AOI). Through carbon modeling, one can gain a better understanding of the potential for afforestation projects to help meet climate change related goals such as the reduction of GHG emissions and enhancement of GHG removals (Metsaranta 2019). The information can also contribute to the Land Use, Land-Use Change and Forestry (LULUCF) sector of Canada's national GHG inventory that is submitted annually to the UNFCCC (ECCC 2020b). This project is timely following the Government of Canada's announcement to implement tree planting as a climate change mitigation strategy (Government of Canada 2020). This article quantifies the outcome of afforestation efforts, estimates carbon implications, summarizes operational lessons learned, and makes recommendations relevant to tree planting initiatives such as the Two Billion Trees Commitment.

Materials and methods

Study area

The tree planting analyzed within this project occurs in Ontario, Canada. Most sites are located in southern Ontario in the Mixedwood Plains ecozone, although a few sites are found to the north, in the Boreal Shield ecozone (Fig. 1) (Agriculture and Agri-Food Canada 2013).

ArcMap™ is the spatial interface used to assess the 5456 digitized afforestation events (12 466 ha) provided by Forests Ontario, that were planted from 2007–2016. Google Earth Pro™, (GE), Google Street View™, BING™ Maps, and Land Information Ontario's (LIO) South Central Ontario Orthophotography (SCOOP) 2018 imagery were used to visually assess each polygon for the presence of planted trees. Through combining fields from the original database with new categorized fields, an attribute table is generated. This table is used to record essential data associated with each afforestation event.[1]

Validation process

Events are manually validated by the analyst in descending order, beginning with the largest polygon. A topology rule: "Must Not Overlap" was carried out to highlight the individual polygons that overlap with one another. This rule makes it easier to identify polygon-related errors. Layers are converted to KML files and then uploaded to GE. When overlaid with imagery in GE, the analyst can use the time slider function to assess the area at different dates and identify the presence or absence of planted trees. The analyst will also classify their confidence level of each assessment, assign a site (stem) density class to the polygon, and if applicable, identify why the site is not afforested. The site preparation, planting method, previous use of land[2], polygon-related errors[3], information related errors[4], occurrence and date of refill planting, soil order[5], soil organic carbon, and the severity of errors are also recorded, based on a standardized domain as a drop-down list. Data for soil order and soil organic carbon were obtained from Soil Landscapes of Canada version 3.2 (Soil Landscapes of Canada Working Group 2010).

Site density

When assigning the site density class, the analyst can choose between three classes:

- <6% (very low density)
- 6–50% (low density)
- 51–100% (high density)

These classes are based on crown closure; crown closure (expressed as a percentage of the total polygon area) refers to the ground area covered by a vertical projection of tree crowns onto the ground for each afforestation polygon (IPCC 2006). Most trees in the imagery are young (1–14 years old); it is difficult to apply crown closure density classes to seedlings; therefore, stem density is used as a proxy for crown closure density. The site density class is based on the area of the actual afforestation event (it is not based on the entire polygon if there was a digitization or major commission error). The crown closure guide (Fig. A-VII-1) on page 62 of the Alberta Vegetation Inventory Interpretation Standards was used as a visual guide for determining the site density classes (Alberta Sustainable Resource Development 2005). If the analyst can identify tree planting rows or the presence of seedlings, but the image resolution is too low to accurately assess the site density class, it will be assigned based on the calculated site density (total number of trees planted/ size of the polygon). The calculated site density may not be accurate as it is based on the number of seedlings planted, not how many seedlings survived. Furthermore, the polygon area may be incorrect (i.e., commission or omission error). The calculated stem density will be assigned to the corresponding density classes (B.C. Ministry of Forests 1999).

- 0–499 stems/ha (<6% class)
- 500–1499 stems/ha (6–50% class)
- 1500 stems/ha or > (51–100% class)

The Generic Carbon Budget Model

The Carbon Budget Model of the Canadian Forest Sector (CBM-CFS3) (Kurz *et al.* 2009) is the core model of Canada's National Forest Carbon Monitoring Accounting and Reporting System (NFCMARS). This model is used to calculate forest carbon stocks and carbon stock changes in tree biomass and dead organic matter (DOM) pools (Kull *et al.* 2016). CBM-CFS3 adheres to the guidelines of the IPCC and is used to calculate GHG emissions and other carbon estimates that Canada is required to report annually under the UNFCCC (Kull *et al.* 2016). In addition to reporting purposes, this model is used by researchers, land and forest managers, and policymakers. The CBM-CFS3 uses growth and yield curves and various parameters including, but not limited to, climate, tree species, age-classes, and disturbance events (i.e., harvest, insect, and fire) to track the effects of past land-use changes on carbon and create simulations showing carbon stock changes at a stand and landscape level (Kull *et al.* 2016).

The new spatially-explicit Generic Carbon Budget Model (GCBM) uses the science of the CBM-CFS3 (Kurz *et al.* 2009) and a new computing platform. The GCBM is built on the Full Lands Integration Tool (FLINT), an open-source platform developed by an international group of experts that are contributing to the moja global initiative. Moja global was formed to develop and support open-source scientific software for the improvement of GHG emission and removal estimates in the land sector[6].

The GCBM was applied to the AOI consisting of 4279 polygons afforested under 50 MTP. The total area included in the simulation was 10 390 ha. Input data such as spatially-explicit polygon level afforestation variables and polygon-level yield curves were used to simulate tree growth and predict the carbon stock changes as a result of afforestation in Ontario, Canada.

Tree type and species composition

Tree species, stock type, and how many trees of each species, were recorded for each site. This project uses four-letter species codes based on Canada's National Forest Inventory (2014) Tree Species List. Species are identified as softwood

[1]Supplementary material, Table S1.

[2]Supplementary material, Table S2.

[3]Supplementary material, Table S3.

[4]Supplementary material, Table S4.

[5]Supplementary material, Table S5.

[6]http://moja.global

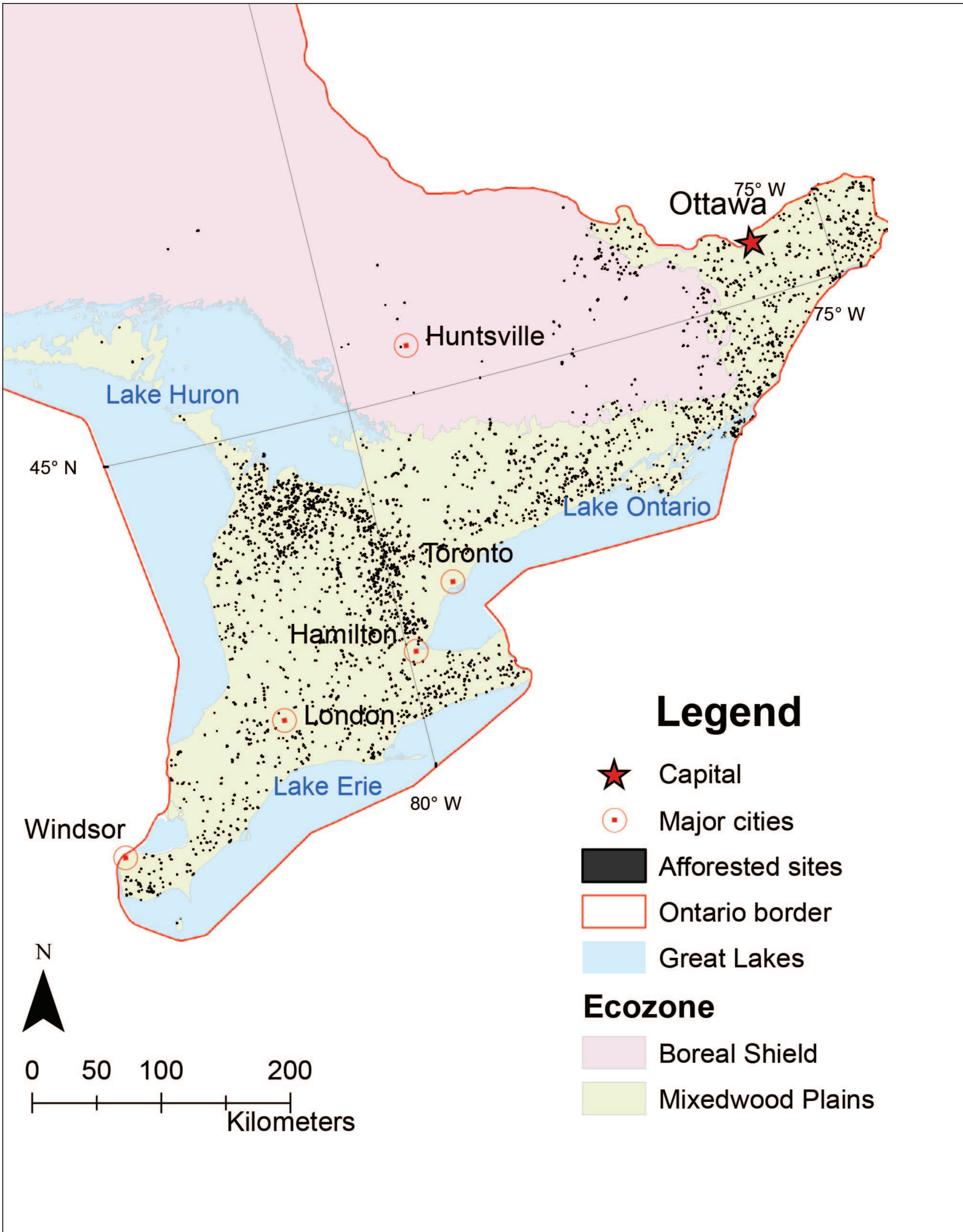

Fig. 1 Map of the confirmed Forests Ontario afforested sites within southern Ontario, Canada, overlaid with relevant terrestrial ecozones (Agriculture and Agri-Food Canada 2013); a small amount (<0.5%) of the afforested area is outside the region shown on the map.

(SW) (coniferous) or hardwood (HW) (broadleaf) and the composition is calculated and linked to the GIS attribute data. The HW and SW composition is recorded as a percentage but does not always sum to 100% as not all records included species information. It is important that the SW, HW composition is calculated as the GCBM takes into account the living biomass carbon pools for HW and SW species separately (Kurz *et al.* 2009). The species composition is also calculated separately (number of trees in one species/total number of trees). This allows species-specific growth and yield curves to be modeled at a polygon-level using the Forest Vegetation Simulator for Ontario ($FVS^{Ontario}$) (Lacerte *et al.* 2006). $FVS^{Ontario}$ is a tree growth model used for simulating future forest conditions from the bare ground conditions at the time of afforestation (as well other data collected under the 50 MTP such as densities, leading species, etc.). Of the trees planted, 80% are SW and 16% are HW (4% are unknown). Based on the number of seedlings planted, the leading species is eastern white pine (*Pinus strobus* L.), followed by white spruce (*Picea glauca* (Moench) Voss.) (Fig. 2). The most common hardwood species planted are red oak (*Quercus rubra* L.) and silver maple (*Acer saccharinum* L.) (Fig. 2).

Results

The afforested sites were validated via satellite imagery, 4 to 13 years after planting. Of the 5456 records (afforestation events) validated, 78% of records are confirmed as "afforested" (Table 1). This is equivalent to 10 390 ha or 83% of the total 12 466 ha of land that was analyzed (Table 1 and Fig. 3). The majority of tree planting occurred between 2008 and 2016 (Fig. 3). Furthermore, 6% (783.8 ha) of the total assessed area is identified as "not afforested" and 10% (1292.5 ha) is classified as "not determined" (Table 1). Out of the confirmed afforested sites, 91% of the area is classified with a high user-confidence level (Table 1).

93% of the 10 390 ha afforested land was previously used for agricultural purposes (i.e., abandoned farmland, crop, pasture, fallow etc.) (Table 2). 54% of the "not afforested" land is classified as such because the land is still currently used for various agricultural activities (Table 3). 28% of the "not afforested" area is classified as having the previous use of orchard, tree plantation, or natural forest (Table 3).

GCBM results

One of the motivations for this project was to quantify the carbon (C) balance of the afforested sites within the AOI. The individual bars in Figs. 4 and 5 represent the carbon flux averaged over all sites planted up to the respective year. The cumulative CO_2e removal in the 10 390 ha study area over the 54-year period from 2007 to 2060 was 2.24 Mt CO_2e which averaged to an annual removal of 41.52 kt $CO_2e\ yr^{-1}$ (Figs. 4 and 5). This removal is reflected in the ecosystem C stock increase over the length of the simulation period. Figure 6 shows the evolution of per-hectare C stocks over time for each of the five IPCC-defined carbon pools, for all sites planted in 2009. Figure 6a shows C stocks for each pool independently, and Fig. 6b shows the relative contributions of each pool to the overall C stocks.

The GHG balance for the afforested polygons within the AOI in Ontario represents a small C sink. However, no disturbances (i.e., wildfire emissions or harvesting) were considered during the length of the simulation period (2007 to 2060). Furthermore, the potential effects of climate change on tree growth rates, survival and mortality were not considered in the projection of carbon stocks.

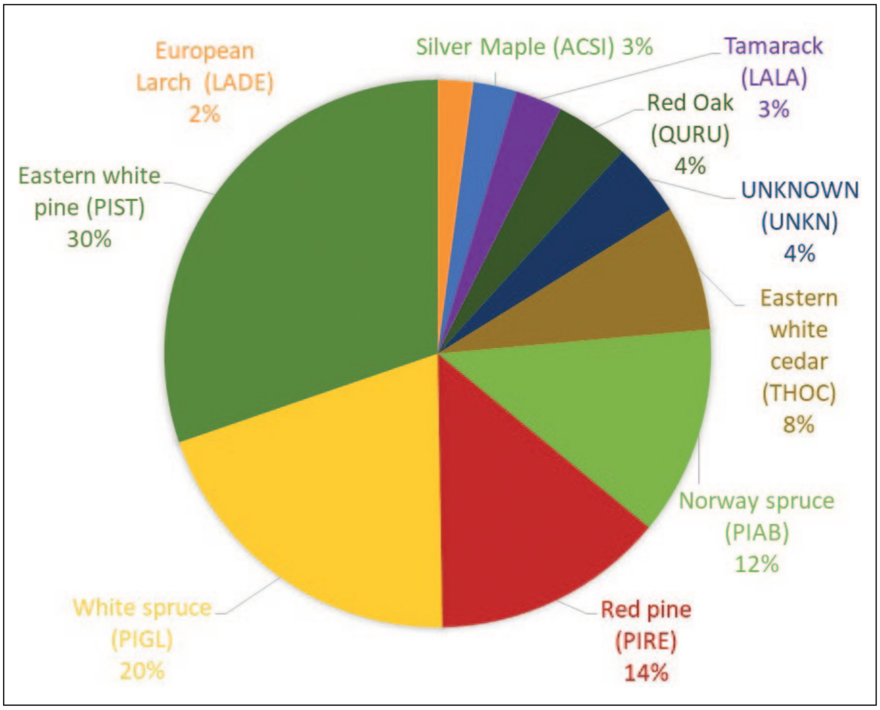

Fig. 2 Top ten tree species (%) based on the number of seedlings planted by Forests Ontario 2007–2016 (Unknown included as a species)

Discussion

Data validation

This study explores the process of spatial validation of afforestation data 4 to 13 years after planting in Ontario, Canada. Our results display that the majority of sites are capable of being spatially validated by a user, and of those validated sites less than 10% are classified as "not afforested" (Table 1). Similar to past studies, our results show the bulk of afforestation in Ontario occurs on abandoned, marginal, and/or less productive farmland (Table 2) (McKenney *et al.* 2000; White and Kurz, 2005; Voicu *et al.* 2017). Furthermore, the majority of "not afforested" sites are categorized as such because the land continues to be used for agricultural

Table 1. Primary queries conducted using structured query language (SQL) on the afforestation dataset to derive basic results (afforested or not afforested)

SQL	Results (records)	%	Results (ha)	%	User-confidence (high)
Afforestation = “yes”	4279/5456	78%	10 389.9 ha /12 466.2 ha	83%	91%
Afforestation = “no”	391/5456	7%	783.8 ha/12 466.2 ha	6%	83%
Afforestation = “unknown”	786/5456	14%	1292.5 ha /12 466.2 ha	10%	N/A

purposes (Table 3). In some instances, seedlings were never planted and in others, the planting failed or there was a possible landowner change and the site was converted back to agriculture. Afforestation events occurring on land that is originally an orchard or a plantation (i.e., failed plantation, nursery, or Christmas tree farm) that are cleared and then replanted, are considered “not afforested” because the original land-use meets the technical definition of forest[7] (UNFCCC 2002). In these cases, no land-use change from non-forested to forested land has occurred, and thus for the purposes of national GHG reporting, the sites will not be included in the afforestation related estimates. Similarly, it is not considered afforestation if seedlings are planted onto land that is already a natural forest (UNFCCC 2002). Although the orchard, Christmas tree, forest, and plantation sites do not meet the formal criteria used for this project and in national GHG reporting, seedlings may still have been successfully planted and thus contributed to carbon sinks (ECCC 2020a). Lastly, if the site is another land-use such as a rocky outcrop, wetland, or industrial area, the record will be classified as “not afforested” due to a lack of planted trees (Table 3).

[7]Canada defines forest as an area of at least 1 hectare (ha), with a crown closure of 25% and the ability to reach a minimum tree height of 5 meters at maturity *in situ* (Government of Canada 2007).

Challenges

The process of validation is best completed by a user as opposed to artificial intelligence, as there are many unique situations and decisions that must be made on a case-by-case basis. Sites classified as “not determined” have neither been confirmed as “afforested” or “not afforested”, often due to lack of current or high-resolution imagery. Further challenges include identifying seedlings in riparian areas and fallows, where there is a high shrub, grass, and understory competition. Similarly, without GE street-view™ it can be difficult to identify young deciduous seedlings from aerial imagery. Sites planted from seed were often left as “not determined” because not enough time had elapsed for seedlings to be seen from the air. Finally, there is a level of user subjectivity associated with analyzing imagery, especially when determining and assigning site density classes.

A limitation of this project is the inability to quantify tree height and size, which impedes the process of determining carbon stock changes because tree height and diameter at breast height (DBH) are used to estimate individual tree biomass. This information is critical because it is used to develop stand-level volume-to-biomass models (Kurz *et al.* 2009). Furthermore, site preparation activities such as prescribed burns, mowing, brushing, plowing, disking, and invasive species removal can affect carbon sequestration and car-

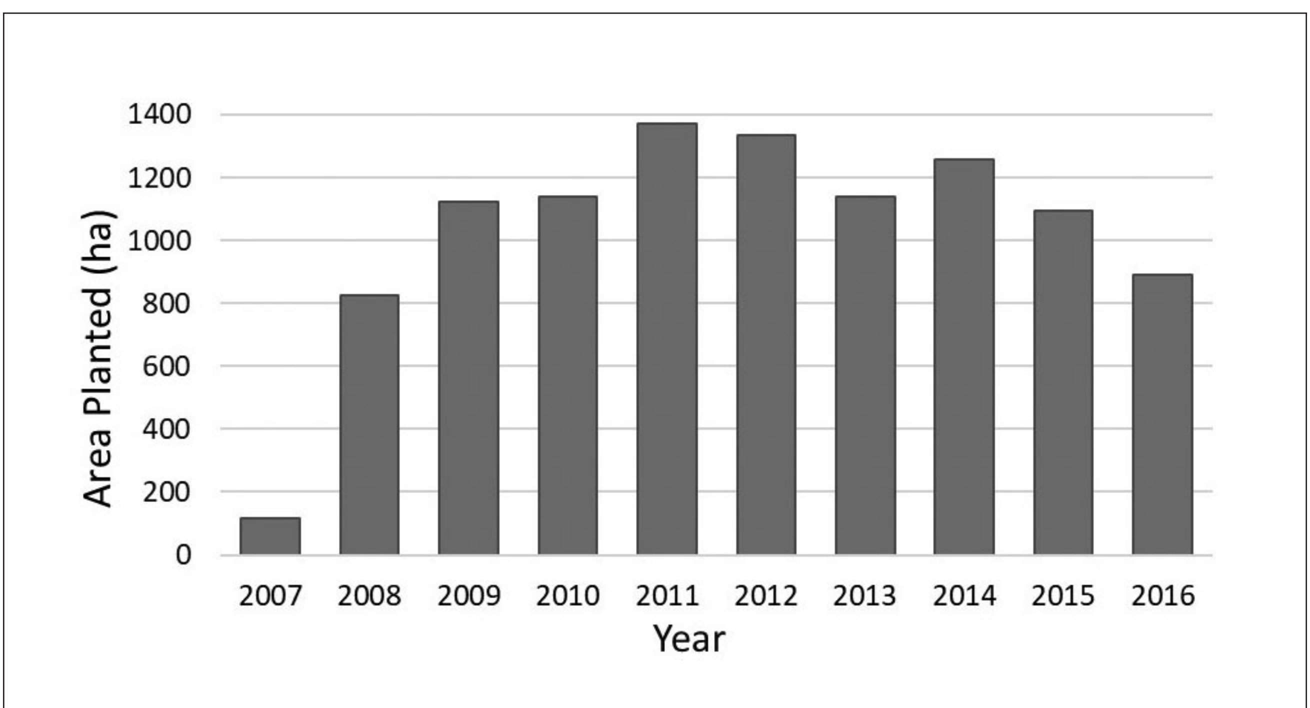

Fig. 3 Confirmed annual afforested area (ha) planted through Forests Ontario's 50 Million Tree Program from 2007–2016

Table 2. Top three previous uses of the successfully afforested sites

Previous use	Results (records)	%	Results (ha)	%
Agriculture[1]	3966/4279	93%	9495.6 ha/12 466.2 ha	76%
Open field[2]	102/4279	2%	232 ha/12 466.2 ha	2%
Residential[3]	63/4279	1.5%	55.2 ha/12 466.2 ha	0.4%

[1]Agriculture is defined as pasture, hay production, rotational crops, forage crop, fallow, and windbreaks, marginal, abandoned and less productive farmland
[2]Open field is defined as non-agricultural field(s): large grass openings, lawn/yard, meadows, and parkland
[3]Residential is defined as urban or rural residential area

Table 3. Standardized options for why the site was not classified as afforested

Reason[1]	Description	Results (record)	%	Results (ha)	%
Orchard (previous use)	The previous use is listed as an orchard by the landowner/planters.	23/391	6%	37.4 ha/778.8 ha	5%
Tree plantation[2] (previous use)	The previous use is listed as a tree plantation, Christmas tree farm, or nursery by the landowner/planters.	45/391	12%	86.9 ha/778.8 ha	11%
Forest[3] (previous use)	The previous use is listed as forest by the landowner/planters.	36/391	9%	94.3 ha/778.8 ha	12%
Agriculture (current use)	Post-planting date imagery shows the land is still being used for agriculture or has been converted back to agriculture.	219/391	56%	423.97 ha/778.8 ha	54%
No trees[4] (other land use)	There are no new trees on the land base.	66/391	17%	135.8 ha/778.8 ha	17%
Duplicate	The polygon is clearly a duplicate.	2/391	0.50%	5.5 ha/778.8 ha	0.70%

[1]If the previous use was incorrectly recorded or not supplied from the tree planting survey, it will be identified by the user using available satellite imagery.
[2]Forest stands established by planting or/and seeding (IPCC 2006). Failed plantation, nursery, or Christmas tree farms fall into this category.
[3]Canada defines forest as an area of at least 1 hectare (ha), with a crown closure of 25% and the ability to reach a minimum tree height of 5 meters at maturity in situ (Government of Canada 2007).
[4]Other land use is usually a rocky outcrop, construction/industrial site, residential home or wetland

bon stocks through soil disturbance (Wang *et al.* 2016; Mayer *et al.* 2020). Our project did not include analysis of the carbon implications of site preparation activities (i.e., prescribed burning), and the transition from original biomass conditions (i.e., shrub cover) to post-plant site conditions. Overall, the most common types of site preparation carried out on FO sites include mowing, seeding cover crops, herbicide application, invasive species removal, and to a lesser extent, non-native tree removal and site cultivation such as plowing or tilling. Prescribed burns on sites prior to planting was a rare site preparation activity and only occurred on ten of the afforested sites (29 ha).

Similarly, there is also evidence that the type of agricultural land use is important when calculating carbon stocks; afforestation of cropland may lead to higher carbon sequestration compared to afforestation on pastures or fallow lands (Mayer *et al.* 2020). This project does not differentiate between agricultural land-use types when defining the site's previous use. It is important for future afforestation projects to break down the agricultural domain further into standardized sub-categories: pasture, cropland, and fallow/abandoned/marginal farmland (Dyk *et al.* 2015).

Throughout the validation process, some records were identified as potential refill events. These records should not have been counted as separate, individual events, but rather included as refills within the original record, in order to lower the risk of overestimating the area of land that is afforested. FO has since recognized this issue and made the appropriate changes in the database to ensure accurate recording of refill plantings on sites. Lastly, data from the initial planting date were used in this analysis; ideally, data from five-year survival surveys should also be included in future afforestation validation analysis.

Carbon implications

The GCBM and the validated afforestation data for 10 390 ha were used to complete spatially-explicit modeling of the carbon dynamics and removals within the AOI. Our results show that an average of 41.52 kt CO_2e will be removed annually and over the span of 54 years, a total of 2.24 Mt CO_2e is estimated be removed from the atmosphere assuming forests will continue to grow undisturbed (Figs. 4 and 5). In contrast, in 2018 alone Ontario's GHG emissions were a total of 165 Mt CO_2e (ECCC 2020b). While Ontario's emissions have decreased by 38 Mt per year compared to 2005 (ECCC 2020b), the cumulative carbon sink from afforestation is comparatively small. The sites afforested from 2007 to 2016 are a small carbon source in 2020 (10 577 t CO_2e) but will become a small sink (-189 209 t CO_2e) by 2030 (Fig. 5). Afforestation alone will not make meaningful contributions to reducing emissions by 2030, only in combination with other strategies such as greener buildings, cleaner electricity and the electrification of transportation will it help Ontario progress towards its 2030 reduction target of 30% below 2005 levels (Ministry of the Environment, Conservation and Parks 2018). Ultimately, it is crucial to recognize that trees planted today will not result in a carbon sink immediately, but the sink strength will increase over time. Tree planting in Canada is not an immediate solution but a proactive

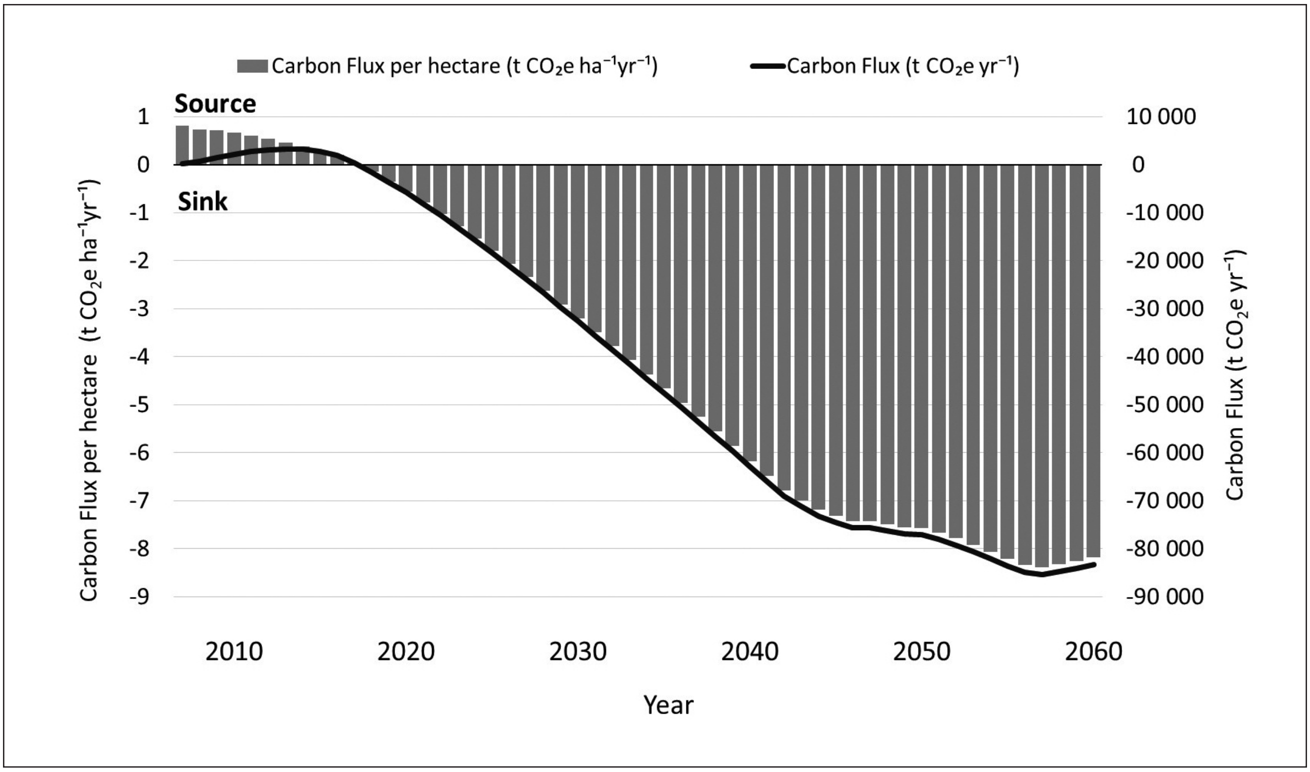

Fig. 4 GHG removals (sink is negative) and emissions (source is positive) displayed as the carbon flux per hectare (t CO_2e $ha^{-1}yr^{-1}$) and the total annual carbon flux (t CO_2e yr^{-1}) within the 10 390 ha of the confirmed afforested area; individual bars represent the carbon flux averaged over all sites planted up to the respective year

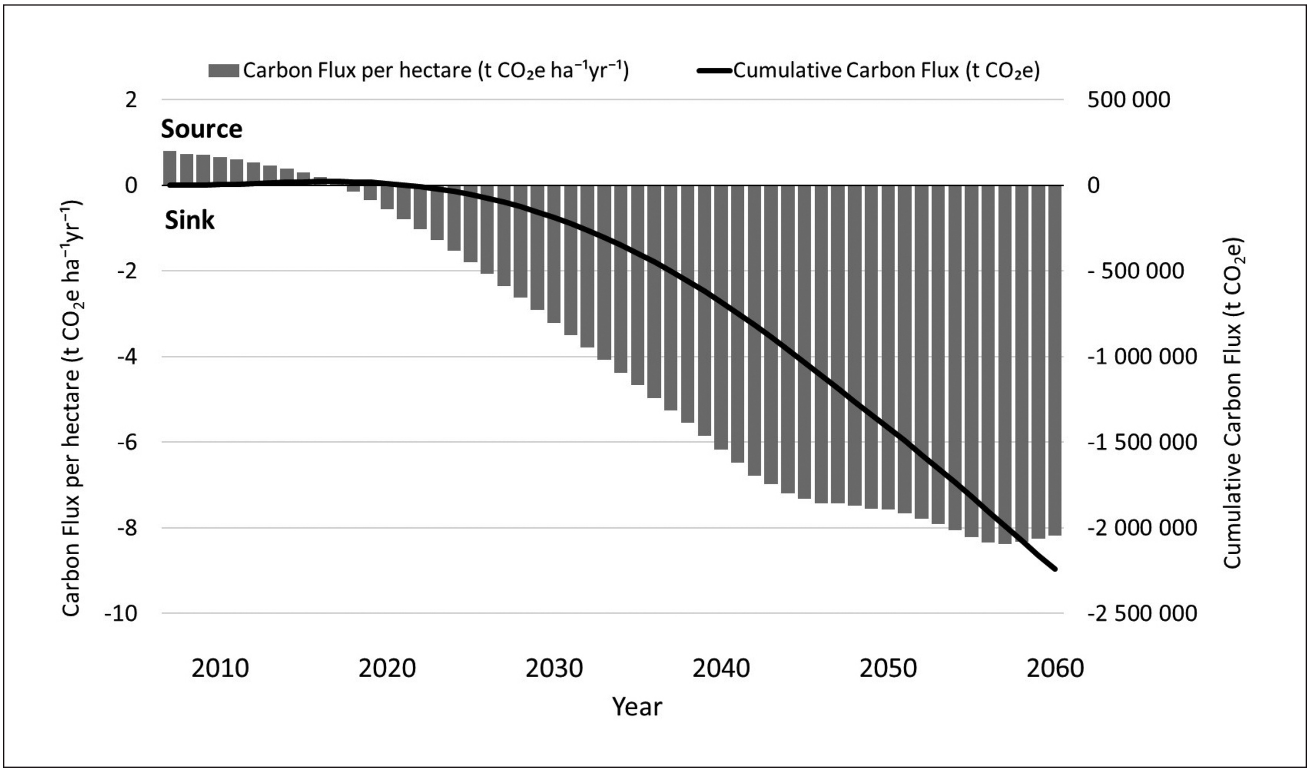

Fig. 5 GHG removals (sink is negative) and emissions (source is positive) displayed as carbon flux per hectare (t CO_2e $ha^{-1}yr^{-1}$) and cumulative carbon flux (t CO_2e), within the 10 390 ha of the confirmed afforested area; individual bars represent the cumulative carbon flux averaged over all sites planted up to the respective year

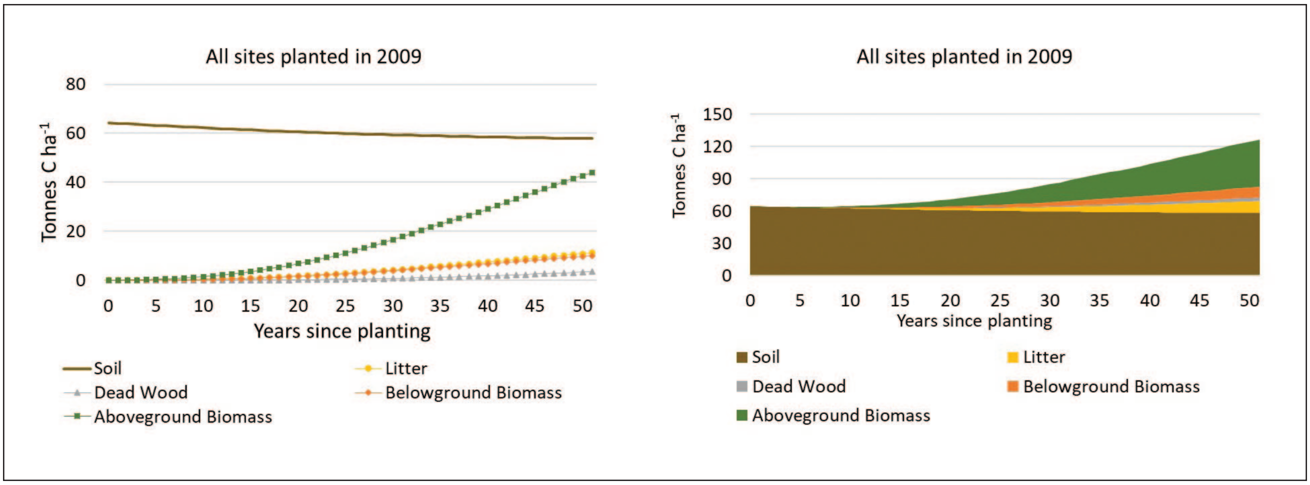

Fig. 6 Evolution over time of per-hectare carbon stocks (t C ha^{-1}) for all sites planted in 2009 for each IPCC carbon pool, **(a)** independently and **(b)** collectively

one; if we hope to see benefits in the long-term (i.e., 2050 targets), we must start to plant trees today.

The GCBM estimates of net emissions in the first years after afforestation represent the ongoing carbon losses from decomposition of soil and other organic matter carbon and the small carbon removals by the recently planted or seeded trees. While these estimates are uncertain, a small source estimate is qualitatively in the right direction because emissions from site preparation are not included in the estimates. Afforestation is always recognised as a carbon sink that will increase over time and make larger contributions to targets in 2050 and beyond, when net zero or net negative emissions will be required (IPCC 2018).

Recommendations for afforestation initiatives

Tree planting initiatives, such as the Two Billion Tree Commitment in Canada or other forest carbon programs can consider the following recommendations in their design:

1. Spatially-explicit tracking of afforestation activities is required to confirm seedling presence, enhance transparency and estimate the carbon outcomes of the afforestation project.
2. The compilation of activity data should include tools that contain standardized domains by having drop-down lists for the tree-planting contractors to complete throughout the afforestation process. This is important for subsequent database queries and to enhance the organization of large datasets. Standardization will make the validation process and carbon modeling more efficient. For carbon modeling purposes, standardized options (checkboxes) for the following variables are required from planting surveys: year planted, area of the site (ha), tree species, stock type, number of each species planted per site, previous/original use (with subcategories for agricultural-related uses), site-preparation activities, planting density, and biomass information. Information on the pre and post-planting above-ground biomass conditions is needed to allow the estimation of carbon implications (Kurz *et al.* 2009). This includes having consistent options to select from for the cover type (i.e., woody plants, herbs, grasses, invasive species, etc.), percent cover, and average height. Sample photos of the site before, immediately after planting as part of the planting quality assessments and during survival assessments will also provide insight into the biomass conditions. A comment section can be utilized if the tree planters feel more details are needed. Databases should also be organized to efficiently include updated numbers from refill plantings (i.e., planting year, total trees and species planted) and survival assessments. In addition to the above variables that are collected at the time of planting, fields for soil order, soil organic carbon, soil depth and ecozone are required in the final dataset and can be supplemented from open source data (i.e., Agriculture and Agri-Food Canada) and the species composition and hardwood/softwood composition should be calculated from the original planting information.
3. Land management support, stewardship initiatives, and simple program designs are needed to inform and encourage private landowner/community involvement and long-term commitment to afforestation projects (Schirmer and Bull 2014; Torabi *et al.* 2016). Straightforward administration processes and forms that do not require a large time or monetary commitment increase the willingness of landowners to join afforestation programs (Torabi *et al.* 2016). Furthermore, education and skill training promote active landowner participation and improve the likelihood of successful management of afforested sites (Schirmer and Bull 2014). For example, FO hosts tree planting and forest management workshops for landowners. Additionally, incentive programs such as the Managed Forest Tax Incentive Program (MFTIP) administered by the Ontario Ministry of Natural Resources and Forestry (MNRF), encourages landowners to maintain and manage existing woodlots as well as plant more trees in order to qualify for a property tax reduction.
4. In addition to initial financial support to implement tree planting activities, long-term funding is crucial for ongoing monitoring, landowner engagement, stand management/improvement (i.e., tending, vegetation management, invasive species removal, thinning, etc.), refill plantings, and data validation. After planting, trees should be monitored and managed to ensure successful establishment, especially during the first 5 years of development. A planting quality assessment should be conducted either

during or soon after the planting has been completed to assess if seedlings have been properly planted (i.e., spacing/density, root exposure, planting depth, etc.). Newly planted trees are most vulnerable during the first couple of years of establishment and should be assessed to determine survival, growth, and if refill or tending is required (Grossnickle 2012). Site assessments also provide insight on site conditions such as weed competition, browse, pest or rodent damage as well as tending recommendations. For example, mowing or herbicide application to control competition, herbivory management, refill plantings to maintain stand density, and subsequent stand management (thinning), are activities that can improve an afforested site's ability to reach free-growing status and can alter the carbon dynamics of the site (Mayer *et al.* 2020). Therefore, such management activities should ideally be included in the quantification of mitigation outcomes.

5. Although the above information is useful, there are fewer data for forecasting growth and yield curves for young trees because the merchantable wood volume (above the merchantable size limit) has not yet accumulated, therefore species-specific data (i.e., age, survival rate, average height, average DBH) from after a stand reaches the free-growing stage is more valuable for carbon estimation (Lacerte *et al.* 2006; Metsaranta 2019). It is recommended that free-growing surveys be completed 15 years post-planting, in addition to the year 1, 2, and 5 survival assessments.
6. We recommend the incorporation of land eligibility criteria which adhere to the definitions and guidelines used for Canada's national GHG reporting into afforestation program designs. For example, "land is eligible for afforestation if, prior to planting, it is at least 0.050 to 1.0 ha in size and has less than 10 to 30% tree crown cover, with trees that have the potential to reach a height of 2m to 5m at maturity at that location" (White and Kurz 2005; IPCC 2006). The addition of these criteria will allow for more efficient tracking of afforestation specifically for national GHG reporting purposes, while continuing to track other reforestation and tree planting events that do not meet the formal definitions.
7. In this case study, 35 sites (81 ha) are identified as afforested but later converted back to agriculture or another land use (i.e., residential). It would be useful to create a form with the purpose of following-up on the reasons and motivations behind conversions. Standardized follow-up in this way will provide insights into the reasons why the land was converted back to agriculture or another use (i.e., economic factors, landowner change, etc.) or why the plantation failed (i.e., drought, flooding, etc.) and may contribute to program design aimed at reducing such losses of afforested lands.

Future research

Understanding afforested lands ecosystem C dynamics is a necessary but not sufficient analysis of GHG impacts. Although not included in the scope of this project, the GCBM has the capacity to include disturbances such as wildfire, forest harvest, and insect outbreaks (Kurz *et al.* 2009). More extensive modeling is needed to include estimates of emissions from potential disturbance events on afforested sites (Voicu *et al.* 2017). Further research on the effects of management activities (i.e., thinning and fertilization) on the carbon dynamics of afforested sites, will help inform and prioritize stand management decisions and secure long-term funding (Metsaranta 2019). If thinning or harvesting occurs on afforested sites, analyses will also need to assess the fate of the C contained in wood transferred to the harvested wood products (HWP) sector, as well as the impacts of HWP uses on emission reductions through product substitution, including wood for concrete, steel in the product sector, and bioenergy for fossil fuels (Kurz *et al.* 2016). Lastly, the collection of field data from older, well-established afforested sites can be used to validate against the yield curves used in carbon modeling.

Afforestation as a climate change mitigation strategy

In the face of global climate change, the ability of forests to enhance the sequestration of atmospheric carbon and increase above and below-ground carbon stocks are important processes that can be utilized to reduce GHG emissions (McKenney *et al.* 2000; Kurz *et al.* 2009). As a result of this, the practice of afforestation or planting trees where previously there were none has become globally recognized as a potential nature-based climate change mitigation strategy (White and Kurz 2005; IPCC 2018). This article focuses on afforestation through the lens of carbon implications; monocultures are often seen as the easiest and most productive choice to increase carbon stores, but without proper forest management they may not succeed in promoting forest resilience and maintaining biodiversity values (McKenney *et al.* 2000; Bashir *et al.* 2019; Seddon *et al.* 2019). Therefore, many variables need to be taken into account when selecting the appropriate sites and trees to plant; this includes factors such as growth-rates, site productivity and history, soil type, expected succession patterns, natural disturbance regimes, genetic diversity, future climatic conditions, and species-specific cold and drought tolerance levels (Mansuy *et al.* 2013; Bashir *et al.* 2019; Isabel *et al.* 2019).

In addition to tree species selection, it is also crucial to carefully choose sites that are appropriate for forest conversion (Hodgman and Munger 2009). For example, replacing land that was originally native forest with exotic and or single-species plantations may cause more harm than good through the loss of biodiversity and forest resilience (Seddon *et al.* 2019; Mayer *et al.* 2020). Other ecosystems, such as peatlands and natural grasslands provide many ecosystem services including innately storing carbon, and therefore are not ideal areas for afforestation (Seddon *et al.* 2019). As mentioned above, localized natural disturbances must be considered when planting trees (Mansuy *et al.* 2013). Climate change is increasing the occurrence and severity of forest disturbances and adding more forest biomass onto the landscape through afforestation has the potential to further intensify the risk of wildfires and insect outbreaks (Mansuy *et al.* 2013). Management decisions surrounding site and species selection, planting density and spacing, thinning, and prescribed fire treatments are important. Such decisions may reduce the carbon storage on the site, but they create more fire-resilient forests and lower the risk of catastrophic wildfires (Hodgman and Munger 2009; Mansuy *et al.* 2013). Ultimately, it is clear afforestation is an interdisciplinary strategy that requires long-term management and must consider a magnitude of values, ranging from carbon and biodiversity to economic feasibility and risk-management (Mansuy *et al.* 2013; Seddon *et al.* 2019).

Conclusion

Through using remote sensing resources to analyze over 12 000 ha of land planted in Ontario between 2007 and 2016, we concluded that 83% of the afforested area is confirmed as treed, 10% could not be verified and 6% is not treed. The majority of afforestation occurred on either active or historical agricultural land, whether that be abandoned, marginal, fallow, pasture or cropland. The high success rate observed in this study confirms the positive potential of user-supervised validation as a tool to assess afforestation presence. Over a 54-year period, the GCBM projected 2.4 million tonnes of cumulative CO_2e sequestered from the seedlings planted in 2007 to 2016 through FO's 50 MTP. This project confirms that afforestation in the study area will create a small carbon sink by 2060. However, only by quantifying ecosystem net GHG balance, emissions from HWP, and emission reductions through product substitution, can comprehensive mitigation scenarios be developed.

FO's tree planting database is a reliable baseline for afforestation tracking when considered with the addition of pre- and post-planting above-ground biomass data, more standardized options for recording site information, and additional land-eligibility requirements. Data derived from the database can be used in the GCBM for estimating changes in carbon stocks for Canada's national GHG inventory reports and hence UNFCCC annual reporting (UNFCCC 2002; Kurz *et al.* 2009). In addition to supplementary data, we highlight the importance of financial incentives, long-term funding, and landowner outreach to support the establishment, management, and success of afforestation planting projects. Afforestation in Canada (slow growing trees) is always a long-term strategy, the benefits of which will increase substantially over time. Therefore, if Canada wants afforested areas to contribute to net zero emission targets by 2050, additional tree planting initiatives have to start as soon as possible.

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References

Agriculture and Agri-Food Canada. 2013. Terrestrial Ecozones of Canada [online]. Available from: https://open.canada.ca/data/en/dataset/7ad7ea01-eb23-4824-bccc-66adb7c5bdf8 [accessed 8 February 2021].

Alberta Sustainable Resource Development. 2005. Resource Information Management Branch. Alberta Vegetation Inventory Interpretation Standards. Available from: https://www1.agric.gov.ab.ca/$department/deptdocs.nsf/all/formain15910/$file/AVI-ABVegetation3-InventoryStan-Mar05.pdf?OpenElement [accessed 8 February 2021].

Bashir, A., D.A. MacLean and C.R. Hennigar. 2019. Growth-mortality attributes and species composition determine carbon sequestration and dynamics of old stand types in the Acadian Forest of New Brunswick, Canada. Ann. For. Sci. 76(35): 1–12. doi:10.1007/s13595-019-0821-3.

B.C. Ministry of Forests. 1999. Forest Practices Branch. Guidelines for developing stand density management regimes. Ministry of Forests, Forest Practices Branch, Victoria, British Columbia, Canada. Available from: www.for.gov.bc.ca/hfp/publications/00083/sdm.pdf [accessed 8 February 2021].

Borczon, E.L. 1982. Evergreen challenge: The agreement forest story. Queen's Printer for Ontario, Toronto, ON.

Canada's National Forest Inventory. 2014. Canada's National Forest Inventory Tree Species List Version 4.5. Available from: https://nfi.nfis.org/resources/general/3-TreeSpeciesList-Version4.5.pdf [accessed 8 February 2021].

Dominy, S.W.J., R. Gilsenan, D.W. McKenney, D.J. Allen, T. Hatton, A. Koven, J. Cary, D. Yemshanov and D. Sidders. 2010. A retrospective and lessons learned from Natural Resources Canada's Forest 2020 afforestation initiative. For. Chron. 86(3): 339–347. doi:10.5558/tfc86339-3.

Dyk, A., D. Leckie, S. Tinis and S. Ortlepp. 2015. Canada's National Deforestation Monitoring System: System Description. Natural Resources Canada, Canadian Forest Service, Pacific Forestry Centre, Victoria, B.C. Report BC-X-439. Available from: https://cfs.nrcan.gc.ca/publications?id=36042 [accessed 8 February 2021].

ECCC. 2020a. Environment and Climate Change Canada. Canadian environmental sustainability indicators: Progress towards Canada's greenhouse gas emissions reduction target. Available from: www.canada.ca/en/environment-climate-change/services/environmental-indicators/progress-towards-canada-greenhouse-gas-emissions-reduction-target.html [accessed 8 February 2021].

ECCC. 2020b. Environment and Climate Change Canada. National Inventory Report 1990–2018: Greenhouse gas sources and sinks in Canada: Executive summary. Available from: https://www.canada.ca/en/environment-climate-change/services/climate-change/greenhouse-gas-emissions.html [accessed 8 February 2021].

Forests Ontario. 2019a. The economic value of tree planting in southern Ontario. Available from: https://www.forestsontario.ca/en/resource/the-economic-value-of-tree-planting-in-southern-ontario [accessed 8 February 2021].

Forests Ontario. 2019b. Forests Ontario's 50 Million Tree Program: Fact Sheet. Available from: https://forestsontario.ca/en/program/50-million-tree-program [accessed 8 February 2021].

Government of Canada. 2007. Canada's initial report under the Kyoto Protocol. Available from: https://unfccc.int/files/national_reports/initial_reports_under_the_kyoto_protocol/application/pdf/initial_report_of_canada.pdf [accessed 8 February 2021].

Government of Canada. 2020. Two Billion Trees Commitment. Available from: https://www.canada.ca/en/campaign/2-billion-trees.html [accessed 8 February 2021].

Grossnickle, S.C. 2012. Why seedlings survive: influence of plant attributes. New Forests 43: 711–738. doi:10.1007/s11056-012-9336-6.

Hodgman, T. and J. Munger. 2009. Managing afforestation and reforestation projects for carbon sequestration: key considerations for land managers and policymakers. *In*: M.L Tyrrell, M.S. Ashton, D. Spalding, and B. Gentry (Eds). Forests and carbon: a synthesis of science, management, and policy for carbon sequestration in forests. pp. 313–346. Bull. - Yale Univ., Sch. For. Environ. Stud. 42. Available from: https://elischolar.library.yale.edu/fes-pubs/42 [accessed 8 February 2021].

IPCC. 1997. Intergovernmental Panel on Climate Change. Revised 1996 IPCC guidelines for national greenhouse gas inventories: Reference manual (Volume 3). Houghton, J.T., L.G. Mera Filho, B. Lim, K. Treanton, I. Mamaty, Y. Bonduki, D.J. Griggs, B.A. Callender. (Eds). IPCC/OECD/IEA, Bracknell, UK. Available from: https://www.ipcc-nggip.iges.or.jp/public/gl/invs6.html [accessed 8 February 2021].

IPCC. 2006. Intergovernmental Panel on Climate Change. 2006 IPCC guidelines for national greenhouse gas inventories. Eggleston, H.S., L. Buendia, K. Miwa, T. Ngara, K. Tanabe. (Eds.). Intergovernmental Panel on Climate Change National Greenhouse Gas Inventories Programme, Institute for Global Environmental Strategies, Hayama, Japan. Available from: http://www.ipcc-nggip.iges.or.jp/public/2006gl [accessed 8 February 2021].

IPCC. 2018. Intergovernmental Panel on Climate Change. Summary for Policymakers. *In*: Global warming of 1.5 °C. An IPCC Special Report on the impacts of global warming of 1.5 °C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty. Masson-Delmotte, V. *et al.* (Eds.). World Meteorological Organization, Geneva, Switzerland. Available from: https://www.ipcc.ch/sr15/chapter/spm/ [accessed 8 February 2021].

Isabel, N., J.A. Holliday and S.N. Aitken. 2019. Forest genomics: Advancing climate adaptation, forest health, productivity, and conservation. Evol. Appl. 13: 3–10. doi:10.1111/eva.12902.

Kull, S.J., G.J. Rampley, S. Morken, J. Metsaranta, E.T. Neilson and W.A. Kurz. 2016. Operational-scale Carbon Budget Model of the Canadian Forest Sector (CBM-CFS3) Version 1.2: User's Guide. Nat. Resour. Can., Can. For. Serv., North. For. Cent., Edmonton, AB. Available from: https://cfs.nrcan.gc.ca/publications?id=36556 [accessed 8 February 2021].

Kurz, W.A. and M.J. Apps. 2006. Developing Canada's National Forest Carbon Monitoring, Accounting and Reporting System to meet the reporting requirements of The Kyoto Protocol. Mitigation and Adaptation Strategies for Global Change 11(1): 33–43. doi:10.1007/s11027-006-1006-6.

Kurz, W.A., C. Smyth and T.C. Lempriere. 2016. Climate change mitigation through forest sector activities: Principles, potential and priorities. Unasylva 246 (67): 61–67. Available from: www.fao.org/3/a-i6419e.pdf [accessed 8 February 2021].

Kurz, W.A., C.H. Shaw, C. Boisvenue, G. Stinson, J. Metsaranta, D. Leckie, A. Dyke and E.T. Neilson. 2013. Carbon in Canada's boreal forest- A synthesis. Environ. Rev. 21(4): 260–292. doi:10.1139/er-2013-0041.

Kurz, W.A., C.C. Dymond, T.M. White, G. Stinson, C.H. Shaw, G.J. Rampley, C. Smyth, B.N. Simpson, E.T. Neilson *et al.* 2009. CBM-CFS3: A model of carbon-dynamics in forestry and land-use change implementing IPCC standards. Ecol. Modell. 220(4): 480–504. doi:10.1016/j.ecolmodel.2008.10.018.

Lacerte V., G.R. Larocque, M. Woods, W.J. Paton and M. Penner. 2006. Calibration of the forest vegetation simulator (FVS) model for the main forest species of Ontario, Canada. Ecol. Model. 199(3): 336–349. doi:10.1016/j.ecolmodel.2006.05.028.

Laganière, J., D. Angers and D. Paré. 2010. Carbon accumulation in agricultural soils after afforestation: A meta-analysis. Global Change Biology 16(1): 439–453. doi:10.1111/j.1365-2486.2009.01930.x.

Mansuy, N., S. Gauthier and Y. Bergeron. 2013. Afforestation opportunities when stand productivity is driven by a high risk of natural disturbance: A review of the open lichen woodland in the eastern boreal forest of Canada. Mitig. Adapt. Strat. GL 18: 245–264. doi:10.1007/s11027-012-9362-x.

Mayer, M., C.E. Prescott, W.E.A. Abaker, L. Augusto, L. Cécillon, G.W.D. Ferreira, J. James, R. Jandl, K. Katzensteiner *et al.* 2020. Tamm review: Influence of forest management activities on soil organic carbon stocks: A knowledge synthesis. For. Ecol. Manage. 466:1–25. doi:10.1016/j.foreco.2020.118127.

McKenney, D., M. Stephens and K.L. Campbell. 2000. Afforestation potential in Canada: a spatial analysis of economic land suitability with carbon sequestration benefits. *In*: C.H. Shaw and M.J. Apps. Proceedings of IBFRA 2000 Conference: The Role of Boreal Forests in Forestry in the Global Carbon Budget. pp. 1–15. Canadian Forest Service, Natural Resources Canada, Edmonton, Alberta, Canada. Available from: https://www.researchgate.net/publication/280491542_Afforestation_potential_in_Canada_a_spatial_analysis_of_economic_land_suitability_with_carbon_sequestration_benefits [accessed 8 February 2021].

Metsaranta, J.M. 2019. Long-term tree-ring derived carbon dynamics of an experimental plantation in relation to species and density in Northwestern Ontario, Canada. For. Ecol. Manage. 441: 229–241. doi:10.1016/j.foreco.2019.03.038.

Ministry of Environment, Conservation and Parks. 2018. Preserving and Protecting our Environment for Future Generations: A Made-in-Ontario Environment Plan. Queen's Printer for Ontario, Toronto, Ontario. Available from: https://prod-environmental-registry.s3.amazonaws.com/2018-11/EnvironmentPlan.pdf [accessed 8 February 2021].

Parker, W.C., G. Nielsen, J. Gleeson and R. Keen. 2009. Forecasting carbon storage and carbon offsets for southern Ontario afforestation projects: The 50 Million Tree planting program. Ontario Ministry of Natural Resources, Applied Research and Development Branch, Ontario, Canada. Available from: http://www.climateontario.ca/MNR_Publications/276933.pdf [accessed 8 February 2021].

Schirmer, J. and L. Bull. 2014. Assessing the likelihood of widespread landholder adoption of afforestation and reforestation projects. Global Environmental Change. 24: 306–320. doi:10.1016/j.gloenvcha.2013.11.009.

Seddon, N., B. Turner, P. Berry, A. Chausson and C.A.K. Girardin. 2019. Grounding nature-based climate solutions in sound biodiversity science. Nat. Clim. Change 9: 82–87. doi:10.1038/s41558-019-0405-0.

Soil Classification Working Group. 1998. The Canadian System of Soil Classification, 3rd ed. Agriculture and Agri-Food Canada Publication 1646: 187–187. Available from: http://sis.agr.gc.ca/cansis/publications/manuals/1998-cssc-ed3/cssc3_manual.pdf [accessed 8 February 2021].

Soil Landscapes of Canada Working Group. 2010. Soil Landscapes of Canada version 3.2. [online]. Agriculture and Agri-Food Canada. Available from: https://sis.agr.gc.ca/cansis/nsdb/slc/v3.2/index.html [accessed 8 February 2021].

Teitelbaum, S. and R. Bullock. 2012. Are community forestry principles at work in Ontario's County, Municipal, and Conservation Authority forests? For. Chron. 88: 697–707. Available from: https://pubs.cif-ifc.org/doi/pdf/10.5558/tfc2012-136 [accessed 8 February 2021].

Torabi, N., L. Mata, A. Gordon, G. Garrard, W. Wescott, P. Dettmann and S.A. Bekessy. 2016. The money or the trees: What drives landholders' participation in biodiverse carbon plantings? Global Ecol. Conser. 7: 1–11. doi:10.1016/j.gecco.2016.03.008.

Trees Ontario. 2012. A discussion paper for alternative approaches to afforestation in Ontario. Toronto, Ontario. Available from: https://www.forestsontario.ca/en/resource/alternative-approaches-to-afforestation [accessed 8 February 2021].

UNFCCC. 2002. United Nations Framework Convention on Climate Change. Conference of the Parties–Report of the Conference of the Parties on its seventh session, held at Marrakesh from 29 October to 10 November 2001. Part two: Action taken by the conference of the Parties. United Nations Office, Geneva, Switzerland. Available from: https://unfccc.int/resource/docs/cop7/13a01.pdf [accessed 8 February 2021].

Voicu, M.F., C. Shaw, W.A. Kurz, T. Huffman, J. Liu and M. Fellows. 2017. Carbon dynamics on agricultural land reverting to woody land in Ontario, Canada. J. Environ. Manage. 193: 318–325. doi:10.1016/j.jenvman.2017.02.019.

Wang, J., H. Wang, X. Fu, M. Xu and Y. Wang. 2016. Effects of site preparation treatments before afforestation on soil carbon release. For. Ecol. Manage. 361: 277–285. doi:10.1016/j.foreco.2015.11.022.

White, T.M., and W.A. Kurz. 2005. Afforestation on private land in Canada from 1990 to 2002 estimated from historical records. For. Chron. 81(4): 491–497. doi:10.5558/tfc81491-4.