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ARTICLE

Carbon sequestration and growth of six common tree and shrub shelterbelts in Saskatchewan, Canada[1]

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Abstract: Shelterbelts sequester and store atmospheric carbon as a direct result of the growth of trees and thus present an opportunity for climate change mitigation. The objectives of this paper were to quantify the growth characteristics and to estimate the carbon stocks of six common shelterbelt species in Saskatchewan: hybrid poplar, Manitoba maple, Scots pine, white spruce, green ash, and caragana. Growth curves (3PG) and carbon dynamics (CBM-CFS3) modelling approaches were used to simulate shelterbelt growth and to estimate the carbon stocks in 50 439 km shelterbelts containing the six species. Shelterbelt width ranged from 6.3 to 14.0 m, age ranged from 5 to 100 yr, and tree density ranged from 356 to 791 trees ha^{-1}. The r^2 of the growth curve equations ranged from 28% to 97%, with <50% root-mean-square error and <30% bias. The total ecosystem carbon stocks of all shelterbelts of the six species in Saskatchewan were 10.8 Tg C (1 Tg C = 1 million Mg C), of which 3.77 Tg C was sequestered in the soil and shelterbelt biomass since 1990. The climate mitigation potential of the six shelterbelt species, ranging from 1.78 to 6.54 Mg C km^{-1} yr^{-1}, emphasized the important role that trees can have on the agricultural landscape to mitigate greenhouse gases (GHGs). Planting shelterbelt trees and shrubs on agricultural landscapes is an important strategy for mitigating GHGs.

Key words: 3PG, agroforestry, carbon, CBM-CFS3, greenhouse gases, shelterbelts.

Résumé : Les brise-vents séquestrent et stockent plus de carbone atmosphérique à cause de la croissance même des arbres. Ils pourraient donc concourir à atténuer le changement climatique. Les auteurs ont quantifié les paramètres de croissance et les réserves de carbone de six espèces de brise-vent courantes en Saskatchewan : le peuplier, l'érable à Giguère, le pin sylvestre, l'épinette blanche, le frêne vert et le caragana arborescent. À cette fin, ils ont modélisé la courbe de croissance (3PG) et la dynamique du carbone (CBM-CFS3) de manière à simuler la croissance des arbres et à estimer les réserves de carbone de 50 439 km de ceintures de brise-vents regroupant les six essences. La largeur des ceintures variait de 6,3 à 14,0 m, l'âge, de cinq à cent ans, et la diversité, de 356 à 791 spécimens par hectare. La valeur quadratique moyenne des équations représentant la courbe de croissance varie de 28 à 97 %, avec un écart-type de moins de 50 % et un biais inférieur à 30 %. En Saskatchewan, l'écosystème constitué des ceintures des six brise-vents renferme au total 10,8 Tg (1 Tg = 1 million Mg) de carbone, dont 3,77 Tg séquestrés dans le sol et dans la biomasse des arbres depuis 1990. Le potentiel d'atténuation annuel des six espèces de brise-vent varie de 1,78 à 6,54 Mg de carbone par km, ce qui souligne le rôle important joué par ces arbres dans le paysage agricole, en réduisant les émissions de gaz à effet de serre (GES). Planter des brise-vent et des arbustes sur des terres cultivées est une stratégie importante pour atténuer les dégagements de GES. [Traduit par la Rédaction]

Mots-clés : 3PG, agroforesterie, carbone, CBM-CFS3, gaz à effet de serre, brise-vent.

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Abbreviations: 3PG, physiological principles in predicting growth model; **CBM-CFS3**, Carbon Budget Model of the Canadian Forest Sector; **CG**, caragana; **DBH**, diameter at breast height; **GA**, green ash; **GHG**, greenhouse gas; **HP**, hybrid poplar; **IPCC**, Intergovernmental Panel on Climate Change; **MM**, Manitoba maple; **OD**, oven dry; **PSP**, Prairie Shelterbelt Program; **RBS**, randomized branch sampling procedure; **RMSE**, root-mean-square error; **SP**, Scots pine; **TEC**, total ecosystem carbon; **WS**, white spruce.

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Introduction

Shelterbelts have been planted in Saskatchewan for more than a century, since 1901, under the provisions of the Government of Canada's Prairie Shelterbelt Program (PSP; Howe 1986). Shelterbelts provide a means to protect farmyard infrastructure and reduce soil erosion through tree planting. Shelterbelts also serve as wildlife habitat, improve biodiversity and water quality (Kulshreshtha et al. 2011), and capture and store atmospheric carbon as a direct result of the growth of shelterbelt trees, and thus present an additional opportunity for climate change mitigation (Amichev et al. 2016).

In 2003, the Intergovernmental Panel on Climate Change (IPCC; Penman et al. 2003) released a document entitled "Good practice guidance for land use, land-use change and forestry" that details the estimating, measuring, monitoring, and reporting of carbon pool changes and greenhouse gases (GHGs) emissions under various categories such as cropland, grasslands, and forestland. Agroforestry systems, such as shelterbelts, represent a combination of these categories. The IPCC stated that shelterbelts planted after 1990 are to be reported under the afforestation or reforestation category, and for any shelterbelts that were planted before 1990, the country can choose to report as cropland, grazing land, or forest management categories. Carbon stocks estimation techniques were also provided by the IPCC and are mainly focused on the estimation of aboveground biomass of trees, using direct measurements of diameter at breast height (DBH) and appropriate allometric equations, developed from destructive sampling of trees (Penman et al. 2003). In contrast, there is a lack of standardized methods for belowground biomass estimation, mainly because they are very costly and time consuming. Hence, the IPCC recommendation was to estimate belowground biomass from aboveground biomass equations, or through simulation models (Penman et al. 2003).

In the past two decades, the carbon storage potential of planted shelterbelts was recognized by Kort and Turnock (1999), but there was a lack of shelterbelt distribution data and tree growth models that are needed for carbon inventory analyses. Recently, Amichev et al. (2015) mapped the distribution, quantified the expected total length of shelterbelts in Saskatchewan, and mapped shelterbelt establishment throughout eight decades and across the five soil zones that span the Province (Brown, Dark Brown, Black, Dark Gray, and Gray) (Agriculture and Agri-Food Canada Soil Landscapes of Canada (SLC) Working Group 2010). These distribution maps were used to identify important historical factors that influenced planting of shelterbelts in Saskatchewan (Amichev et al. 2015). Briefly, until the 1960s, shelterbelt establishment was uniform, situated immediately next to major roadways, and most likely due to Saskatchewan's expansive road infrastructure. In the 1970s and 1980s, shelterbelts were planted at cross road areas to control snow accumulation, and in the 1990s and 2000s, the use of field shelterbelts increased (Amichev et al. 2015). There is a total of 51 653 km of shelterbelts (both farm and field shelterbelts) in Saskatchewan with a varying number of tree rows, determined by digitizing existing shelterbelts from high-resolution areal imagery (J. Piwowar, personal communication, University of Regina, Regina, SK). When the lengths of these multirow shelterbelts are represented as the cumulative lengths of all individual single rows of trees included in the design, the estimated provincial single-row shelterbelt inventory is 60 633 km. The latter estimate included all shelterbelts established between 1925 and 2009 at various planting designs and consisting of various shelterbelt tree and shrub species (Amichev et al. 2015).

In a previous study, we demonstrated the process of quantifying and mapping the carbon storage in all white spruce (WS; *Picea glauca* [Moench] Voss) shelterbelts in Saskatchewan (Amichev et al. 2016). Briefly, shelterbelt field data were collected from a number of sampling sites throughout Saskatchewan and were used to parameterize two models for use in shelterbelt analysis. White spruce tree growth was modeled with the Physiological Principles in Predicting Growth (3PG) model, and carbon flux and stocks in WS shelterbelts were modeled with the Carbon Budget Model of the Canadian Forest Sector (CBM-CFS3). Annual total ecosystem carbon (TEC) stocks and carbon stock additions were estimated for the entire WS shelterbelt inventory in the Province.

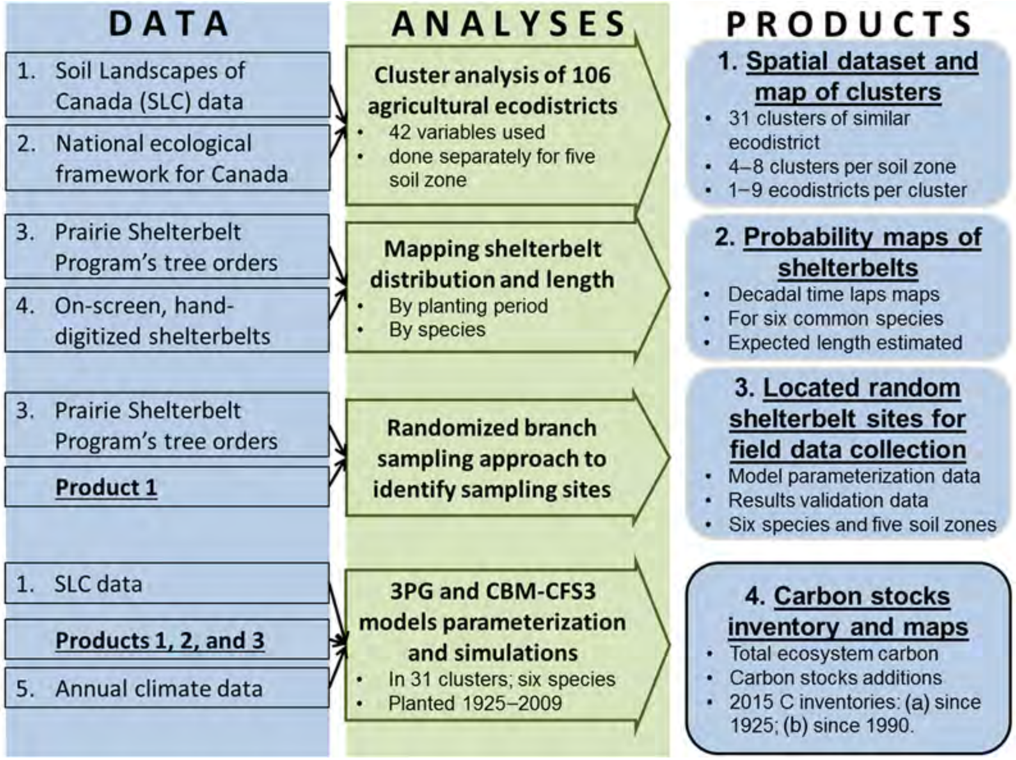
Based on the same methodology described in Amichev et al. (2016), and using the 3PG and CBM-CFS3 models individually adapted for other shelterbelt species, and using a spatially explicit database of shelterbelt trees ordered from the PSP from 1925 to 2009, we quantified and mapped the shelterbelt carbon storage for five additional common shelterbelt species in this current study: caragana (CG; *Caragana arborescens* Lam.), green ash (GA; *Fraxinus pennsylvanica* Marsh), hybrid poplar (HP; *Populus* spp.), Manitoba maple (MM; *Acer negundo* L.), and Scots pine (SP; *Pinus sylvestris* L.). The goals of this paper were to develop shelterbelt tree growth curves for these planted species and to use them to create inventories of the TEC storage for all shelterbelts in Saskatchewan.

Materials and Methods

Data sources and analyses

To estimate the carbon stocks in shelterbelts for the agricultural land of Saskatchewan, a number of sequential data analysis steps were performed, each resulting in a unique shelterbelt product that was used in the subsequent steps (Fig. 1). First, cluster analysis with province-wide soils data (Agriculture and Agri-Food Canada Soil Landscapes of Canada (SLC) Working

Fig. 1. Overview of shelterbelt data analyses and products created for the agricultural land in Saskatchewan.



Group 2010) and data for other ecological factors (Marshall et al. 1999) were used to group and map 106 agricultural ecodistricts in Saskatchewan into 31 clusters based on similar tree growth variables for simulation modeling purposes (Amichev et al. 2015). The direct product of the cluster analysis was a map of the locations of the clusters in which shelterbelt growth and carbon stocks were estimated (Fig. 1).

Second, shelterbelt distribution mapping and length estimation were done using detailed shelterbelt tree orders from the PSP and on-screen digitized shelterbelts data from randomly selected areas in the province (Amichev et al. 2015). As a result, probability distribution maps and their estimated length for the six shelterbelt species planted from 1925 to 2009 were created across the 31 clusters.

Third, an unbiased selection of field sampling sites was conducted by a modified randomized branch sampling (RBS) procedure (Valentine et al. 1984; Amichev et al. 2016) to collect data from shelterbelts at randomly selected township locations, within randomly selected soil polygons, within randomly selected ecodistricts, and within the cluster with the highest number of trees ordered though the PSP (i.e., model parameterization cluster). Field data were collected from shelterbelts containing the six shelterbelt species at a total of 151 separate sites: 21 sites for destructive sampling (with a total of 50 harvested trees and shrubs), 59 sites for model parameterization, and 71 sites for validation of the model simulation results (Table 1). To increase the accuracy of the shelterbelt allometric equations used in the models, we combined the shelterbelt data collected by destructive sampling in this study with additional shelterbelt data for the six species by Kort and Turnock (1999) — a total of 164 additional trees harvested from different locations across the province, which were also collected by destructive sampling methods.

Finally, the collected field data were used to parameterize the 3PG model and perform tree growth simulations for a 60 yr period, from 1954 to the end of 2014, for three shelterbelt spacings (2.0, 3.5, and 5.0 m, all within a linear row of planted trees) and four mortality levels (0%, 15%, 30%, and 50%) within the parameterization cluster (Amichev et al. 2016). The 3PG model growth curves were used in the CBM-CFS3 model for carbon stocks estimation in the 31 clusters in Saskatchewan (Amichev et al. 2016). Maps of the carbon stocks inventories were created for (1) the period 1925–2009 and (2) the period since 1990, regardless of the planting year.

Shelterbelt growth modelling

Tree and shrub growth predictions with the 3PG model were based on species-specific properties and variables. The 3PG model was chosen for the shelterbelt analysis in this study because of its proven success in Canada for a number of species and environments. The 3PG model was previously used to predict hybrid poplar growth in plantations in central

Table 1. Shelterbelt field data sampling in Saskatchewan from 2012 to 2014.

Type of data	Description
Species	Green ash, hybrid poplar, caragana, white spruce, Manitoba maple, and Scots pine
Soil zones	Brown, Dark Brown, Black, Gray, and Dark Gray
Measurement sites	59 for model parameterization and 71 for model validation
Measurements taken at each site	Number of stems, crown width, DBH, height, tree spacing, tree cores (for age determination), shelterbelt tree mortality, and location coordinates
Destructive sampling	50 trees harvested in this study: 10 green ash, 9 hybrid poplar, 12 caragana, 9 Manitoba maple, 3 Scots pine, and 7 white spruce Data for 164 additional trees were used from a previous study[a]
Tree state	Leaf on
Shelterbelt age	5–100 yr
Method used to determine fresh and oven-dry whole tree weight	The randomized-branch sampling (RBS) approach by Valentine et al. (1984) was modified for shelterbelt use. Portions of the cut trees were collected and weighed in the lab, and the data were used to estimate whole tree weight with less than 15% error
Samples collected	Branch samples for whole tree branch biomass estimation (by the RBS approach), tree cookies whole tree stem biomass estimation (by the RBS approach), soil samples (0–5, 5–10, 10–30, 30–50 cm), litter layer samples, fine root samples (0–50 cm), tree cores (for age determination), and foliage samples for whole tree foliage estimation (by the RBS approach) and for leaf area index estimation (for the 3PG model)
Subsamples for carbon content determination	A 50% carbon content of wood was assumed, similar to what is used in the CBM-CFS3 carbon model

[a] Harvested trees from a shelterbelt study by Kort and Turnock (1999).

Saskatchewan (Amichev et al. 2010), shrub willow growth in short-rotation coppice systems (Amichev et al. 2011, 2012), Douglas-fir growth in forests in British Columbia (Coops et al. 2010), and more recently, for WS growth predictions in shelterbelts in Saskatchewan (Amichev et al. 2016).

For each variable in the 3PG model, a parameter value was assigned, which would best represent the growth and development of each of the six shelterbelt tree and shrub species in shelterbelt rows. Four methods of variable parameterization were used: (1) field data from sampled shelterbelts in our study; (2) data from the literature; (3) default 3PG model parameters; and (4) finally, we applied a multiple iteration approach so that a best fit was reached between 3PG model predictions and the field data for tree height and diameter. By systematically changing the values of the fitted parameters (Amichev et al. 2016), the lowest root-mean-square error and bias and the highest r^2 of observed versus predicted data were achieved.

Shelterbelt allometric equations were required to parameterize the 3PG model for the six species. We combined the shelterbelt data collected in this study with the shelterbelt data by Kort and Turnock (1999) which represented a wide variety of shelterbelts across Saskatchewan ranging in tree age, tree biomass, tree spacing, tree mortality, height, and diameter data. The 3PG model was parameterized separately for each species and was used to generate growth curves for the six shelterbelt species in the 31 clusters encompassing the entire agricultural land base in Saskatchewan. A 2 m spacing was used to generate the growth curves in this study because stand biomass projections were nearly equal for spacings ranging from 2 to 5 m (Amichev et al. 2016). A more detailed description of the complete shelterbelt growth modelling methodology and growth curve comparisons by different levels of mortality (0%–50%) and spacing (2–5 m) is available in Amichev et al. (2016).

Carbon stocks estimation

The yield tables quantifying shelterbelt volume increment that were generated by the 3PG model were used as input data in the CBM-CFS3 model. Carbon stocks for the six shelterbelt species were generated in the CBM-CFS3 model for 31 clusters in the province and validated with independent field data. The estimated TEC stocks included the carbon in the soil, litter layer, belowground biomass, and aboveground biomass. The carbon stock additions were estimated as the sum of carbon stocks of all ecosystem components minus the preplanting mineral soil carbon stocks. A detailed description of the complete shelterbelt carbon stocks modelling methodology is available in Amichev et al. (2016).

Statistical analysis

Root-mean-square error (RMSE, %), bias (%), and the r^2 of observed versus predicted estimates were used to evaluate the accuracy of the carbon stocks predictions reported in this study that was the cumulative accuracy from both the 3PG and CBM-CFS3 models. Observed data were aboveground biomass carbon sequestration rates (kg C tree^{-1} yr^{-1}) derived directly from field data, and predicted data were aboveground biomass carbon sequestration rate predictions made by the CBM-CFS3 model using 3PG growth curves as input data. Negative bias indicated overestimation, and positive bias indicated underestimation.

Result validation was performed by estimating the aboveground biomass carbon sequestration rates (kg C tree^{-1} yr^{-1}) to account for the large variation of the sampled shelterbelts that were used for model validation purposes. To account for the different levels of tree mortality in our data set, the carbon sequestration rates were estimated on the basis of the number of live trees in all sampled shelterbelts. Similarly, to account for the different tree spacing in shelterbelt establishment that are based on the farmer's choice of number of planted trees per kilometer, the carbon sequestration rates were averaged on an individual tree basis in each shelterbelt. Finally, to account for the different ages of the sampled shelterbelts, the carbon sequestration rates were averaged per year of tree growth. Therefore, the aboveground biomass carbon sequestration rates (kg C tree^{-1} yr^{-1}) provided an unbiased validation method of the carbon sequestration results through the use of independent shelterbelt field data from a broad range of growing conditions and locations across the province.

Results

Shelterbelt growth in Saskatchewan

The shelterbelt tree orders from the PSP indicated that millions of trees had been planted across Saskatchewan. During the course of eight decades, the following shelterbelt trees and shrubs were planted: >1.54 million WS, >5.68 million HP, >3.23 million MM, >9.91 million GA, >1.96 million SP trees, and >64.5 million CG shrubs. The total length (in kilometre) of the shelterbelts of these six species was 991 (WS), 4144 (HP), 2646 (MM), 5841 (GA), 1573 (SP), and 35 245 (CG). About 35% (WS; 347 km), 23% (HP; 942 km), 14% (MM; 375 km), 42% (GA; 2482 km), 30% (SP; 479 km), and 20% (CG; 7053 km) of these shelterbelts were planted in the last 25 yr.

The collected shelterbelt field data illustrated a wide range of existing shelterbelt ages, planting designs, and arrangements. Field sampling indicated that WS shelterbelts varied in age (6–76 yr), designs (1–10 rows with 1–5 m spacing between trees within a row), and planting arrangement, combined with up to four other species on the same farm. Hybrid poplar shelterbelts ranged from 13 to 55 yr of age, were planted in 1–7 rows designs with 1.0–9.5 m spacing between trees within a row, and were combined with up to six other species. Manitoba maple shelterbelts also varied in age (5–100 yr), designs (1–9 rows with 1.0–4.5 m spacing between trees within a row), and planting arrangement, combined with up to seven other species on the same farm. Planted green ash shelterbelts ranged 5–80 yr of age and were planted in 1–11 rows designs with 1.5–4.5 m spacing between trees within a row), and were combined with up to five other species. Field data showed that planted Scots pine shelterbelts varied in age (8–60 yr), and designs (1–14 rows with 1–6 m spacing between trees within a row) and were planted with up to four other species. Planted caragana shelterbelts also varied in age (6–80 yr), designs (1–11 rows with 0.5–1.8 m spacing between plants within a row), and planting arrangement, combined with up to five other species on the same farm.

Growth curves generated with the 3PG model necessitated allometric equations that were developed specifically for the six shelterbelt species in this study. These allometric equations were based on a wide range of shelterbelt field data, including tree age (5–100 yr), oven-dry (OD) tree biomass (0.6–1520.2 kg tree^{-1}), tree spacing (0.4–10.0 m), tree mortality (0%–68%), height (1.9–23.5 m), and diameter (1.3–63.0 cm) (Table 2). Tree mortality was evaluated by the number of dead trees as the percent of all trees within the shelterbelt. The r^2 of the allometric equations was >65% in WS > HP > SP > GA > MM (in descending order) tree shelterbelts and was the lowest in the caragana shrub shelterbelts (28%). The RMSE was <50%, and bias was <30% for all shelterbelt species. The highest r^2 of the allometric equations was for the WS (97%) and HP (84%) shelterbelt species (Fig. 2). The low r^2 of the caragana shrub allometric equation is largely due to the wide variation of the field data that were used for equation development (Fig. 2).

The 3PG model was parameterized separately for each species and was used to generate separate growth curves for ages 1–60 yr for the six shelterbelt species (Fig. 3). The growth curves presented in Fig. 3 were for 2 m spacing because stand biomass and height were almost unchanged for spacings ranging from 2 to 5 m; DBH was shown to increase at the wider spacings (Amichev et al. 2016). In general, biomass growth (stem, branches, and bark) in shelterbelts, age 60 yr, ranged from 139 to 593 OD Mg km^{-1} in HP > WS > SP > MM > CG > GA shelterbelts (in descending order). Tree DBH, or diameter at 30 cm height (for caragana), ranged from 30 to 61 cm, and height ranged from 9 to 17 m. The fastest growing trees, in terms of tree height (at age 10 yr), were HP (10 m) and SP (6 m), and the slowest growing trees were GA and WS, both at 4 m height (Fig. 3).

At age 60 yr, hybrid poplar growth in shelterbelts across the 31 clusters in the province ranged from 397 to 634 OD Mg km^{-1} for mean aboveground biomass, DBH was 52–63 cm, and height was 15–17 m. In white spruce shelterbelts, mean aboveground biomass ranged from 152 to 253 OD Mg km^{-1} at age 60 yr, DBH was 29–34 cm, and height was 14–17 m. Scots pine growth in shelterbelts ranged from 119 to 201 OD Mg km^{-1} for mean aboveground biomass at age 60 yr, DBH was 28–37 cm, and height was 11–13 m. Manitoba maple growth in shelterbelts ranged from 118 to 193 OD Mg km^{-1} for mean aboveground biomass, at age 60 yr,

Table 2. Oven-dry (OD) biomass equations for six common shelterbelt species in Saskatchewan.

	Allometric equations and evaluation					Ranges of input data: tree and shelterbelt properties						
	Biomass (kg) = $a \times (\text{diameter, cm})^b$											
Species	a	b	r^2 (%)	RMSE (%)	Bias (%)	N	Diameter (cm)	Height (m)	Biomass (kg tree^{-1})	Age (yr)	Spacing (m)	Mortality (%)
Hybrid poplar	0.09142	2.3011	84	39	−16	32	13.6–59.0	8.8–23.5	20.5–1520.2	13–60	0.5–10.0	0–25
White spruce	0.00660	3.1832	97	22	27	19	1.3–38.0	1.9–21.5	0.6–1128.1	6–76	0.5–4.0	0–66
Scots pine	0.43264	1.8870	74	19	1	15	17.5–63.0	6.9–16.7	93.0–326.9	15–74	1.0–3.2	0–50
Manitoba maple	0.29428	1.8980	66	32	−9	32	3.2–43.6	2.9–15.2	2.8–380.1	5–100	1.0–5.0	0–47
Green ash	0.20637	2.1217	71	48	−0.3	36	10.9–37.0	4.1–14.2	28.2–580.5	12–79	1.0–5.0	0–68
Caragana	0.02840	2.5760	28	40	−7	80	5.3–24.2	2.5–13.6	2.5–78.8	7–43	0.4–2.4	0–29

Note: Accuracy of the equations was evaluated by r^2 (%) of observed versus predicted values, root-mean-square error (RMSE, %), and bias (%); negative percent bias indicates overestimation.

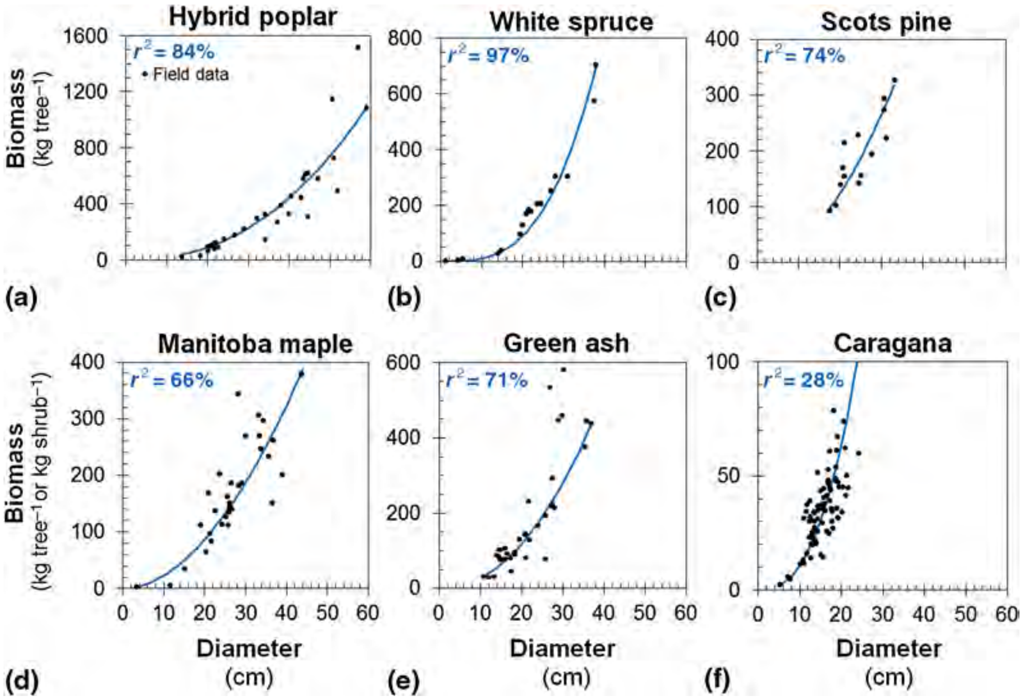
DBH was 34–44 cm, and height was 9–11 m. In caragana shelterbelts, mean aboveground biomass ranged from 93 to 147 OD Mg km^{-1} at age 60 yr, diameter at 30 cm height was 30–36 cm, and height was 8–9 m. Finally, green ash growth in shelterbelts ranged from 93 to 148 OD Mg km^{-1} for mean aboveground biomass at age 60 yr, DBH was 25–31 cm, and height was 10–12 m (Fig. 3). Because of the multistem properties of most shelterbelt trees and shrubs, the estimated diameters represent the diameter of a circle with area equal to the cumulative basal area at breast height of all stems of a multistem tree (i.e., DBH), or at 30 cm height for a caragana multistem shrub. Similarly, the height estimates represent the height of the tallest stem of a multistem tree or shrub.

Carbon stocks in shelterbelts

The carbon sequestration potential per unit area (1 ha) of the six shelterbelt species in Saskatchewan was 1.3–5.3 Mg C ha^{-1} yr^{-1} (Fig. 4). Across five soil zones in Saskatchewan, the total carbon additions of these six species were estimated at 3.3–5.2 (HP), 1.3–2.7 (CG), 1.4–3.3 (SP), 2.2–4.1 (WS), 2.0–3.9 (GA), and 2.8–5.3 (MM) Mg C ha^{-1} yr^{-1} (Fig. 4). Because shelterbelts are linear agroforestry systems in their design, their estimated carbon sequestration potential on an area basis, per hectare, implies the area directly underneath the crowns of all live trees in the shelterbelt. Depending on the growth properties of the different shelterbelt species, crown widths could range from 6.3 m (MM) to 14.0 m (HP). Therefore, fewer numbers of trees with larger crowns would have the same crown footprint area as a greater number of trees with smaller crowns, all planted at the same 2 m spacing within a shelterbelt row. For the six species studied here, 1 ha of tree or shrub crown footprint area is comprised of 356 HP trees, 527 CG shrubs, 610 SP trees, 636 WS trees, 751 GA trees, and 791 MM trees (Fig. 4). The estimated average C sequestration rate on a length basis, per km, for WS shelterbelts was 2.43–2.75 Mg C km^{-1} yr^{-1}. Similarly, the estimated average C sequestration rate for MM, GA, SP, CG, and HP shelterbelts was 2.39–2.60, 1.78–1.98, 1.90–2.17, 1.73–2.03, and 6.03–6.54 Mg C km^{-1} yr^{-1}, respectively.

Cumulative TEC stocks and C stocks additions produced by shelterbelt planting for the six species during the course of eight decades were 10.8 and 4.85 Tg C (1 Tg, teragram = 1 million Mg), respectively. About 78% of these C stocks additions (3.77 Tg C) occurred since 1990 (Table 3). About 69% of the C stocks additions occurring since 1990 were in caragana shelterbelts, mainly because of the very large number of planted caragana shelterbelts, followed by hybrid poplar (15%) and green ash (9%) (Table 3). The total value of 3.77 Tg C stocks additions would be \$208 million, estimated at a price of \$15 per Mg CO_2-eq; the same carbon price scenario was used for all other examples in the text.

Fig. 2. Biomass (oven dry) as a function of diameter for six common shelterbelt species in Saskatchewan; diameter is the measure of a circle with area equal to the cumulative basal area of all stems of a multistem tree at breast height, and at 30 cm height for caragana. Field data (black dots) represent randomly selected, individual, destructively sampled trees and shrubs. Note: the *y*-axis scales vary by shelterbelt species as follows: 1600 for hybrid poplar, 800 for white spruce, 600 for green ash, 400 for Scots pine and Manitoba maple, and 100 for caragana.



Total ecosystem carbon stocks per species ranged widely from 7.86 to 0.13 Tg C in the descending order CG > HP > GA > MM > SP > WS (Table 3). Total ecosystem carbon stocks and C stocks additions in WS shelterbelts were 0.13 and 0.05 Tg, respectively, and nearly 90% of these C stocks additions (0.045 Tg) occurred since 1990, regardless of the tree planting period, with an estimated value of $2.50 million. Similarly, TEC stocks in MM, GA, SP, CG, and HP shelterbelts were 0.36, 0.96, 0.18, 7.9, and 1.3 Tg C, respectively, and C stocks additions in MM, GA, SP, CG, and HP shelterbelts were 0.21, 0.43, 0.064, 3.4, and 0.68 Tg C, respectively. Approximately 67%, 80%, 87%, 77%, and 83% of the C stocks additions in MM, GA, SP, CG, and HP shelterbelts, respectively, occurred since 1990, regardless of tree planting period, and have an estimated value of $7.8 million, $19 million, $3.1 million, $144 million, and $31.2 million, respectively.

The cumulative total length of the six shelterbelt species planted in Saskatchewan during any planting period was estimated at 50 439 km, and ranged from 991 (WS) to 35 245 km (CG) (Table 3). For these six shelterbelt species in Saskatchewan, the total length of WS shelterbelts is 2.0%, with their TEC stocks being 1.2%, of the cumulative length and TEC stocks, respectively. In comparison, the total length of MM, GA, SP, CG, and HP shelterbelts is 5.2%, 12%, 3.1%, 70%, and 8.2% of the cumulative length, respectively, and the TEC stocks stored in MM, GA, SP, CG, and HP shelterbelts is 3.4%, 8.9%, 1.7%, 73%, and 12% of the cumulative TEC stocks, respectively (Table 3).

A distribution analysis of the six shelterbelt species from south to north illustrated that caragana was dominant in the Brown, Dark Brown, and half of the Black soil zone clusters, followed by green ash and hybrid poplar trees (Fig. 5). Conifer shelterbelt species were preferred mainly in the Gray and Dark Gray soil zone clusters (latitude >52°), while caragana was relatively minimal. The highest number of WS shelterbelts was in the Dark Brown soil zone, but these shelterbelts were also relatively more common, compared with other species, in the Dark Gray and Gray soil zones, where they represent up to 38% of the cumulative TEC stocks in some clusters (Fig. 5). Similarly, about 86%, 83%, 86%, 76%, and 85% of MM, GA, SP, CG, and HP shelterbelts, respectively, are located in the Dark Brown soil zone. Caragana shelterbelts represent about 20%–70% of the cumulative TEC stocks in the Black soil zone and in the Brown soil zone, they represent consistently >75% of the cumulative TEC stocks across all clusters (Fig. 5). Green ash and hybrid poplar shelterbelts are also common in the Dark Gray and Gray soil zones, where they represent up to 36% and 30%, respectively, of the cumulative TEC stocks.

The estimated rate of C sequestration (Fig. 4) from 3PG and CBM-CFS3 model simulations and the relative

Fig. 3. Growth curves of six common shelterbelt species in Saskatchewan developed with the 3PG model at 2 m spacing for (*a*) shelterbelt biomass (oven dry) accumulation, (*b*) diameter, and (*c*) height increase for a 60 yr simulation period.

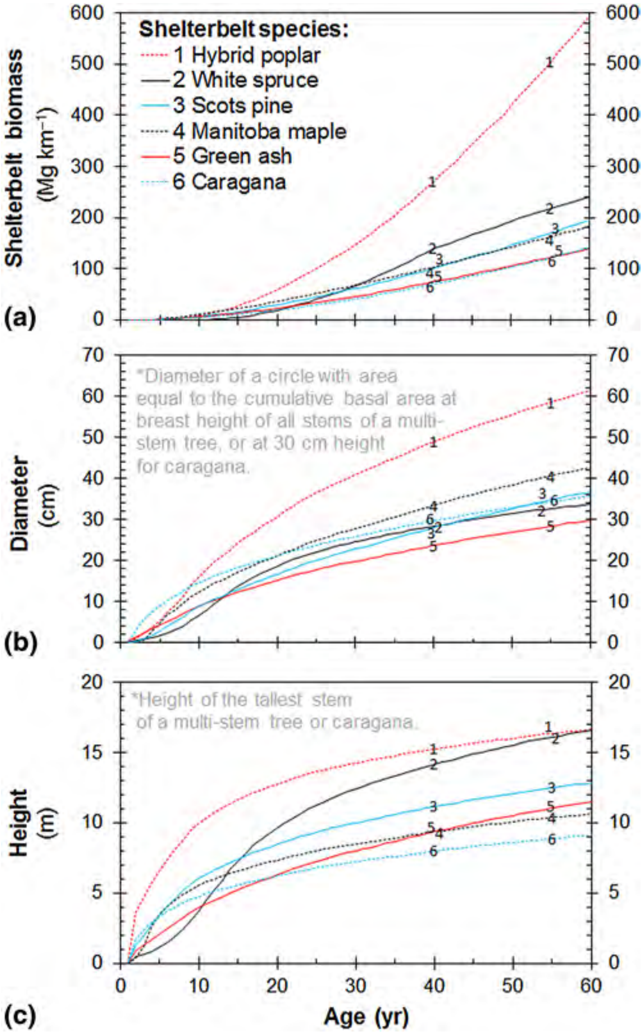
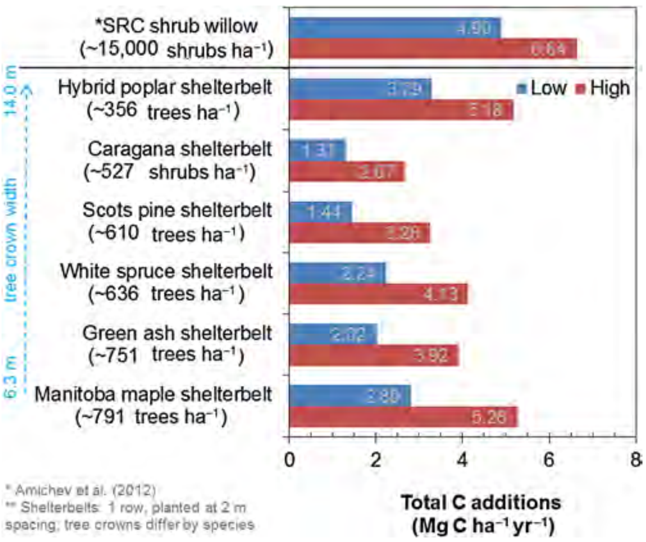


Fig. 4. Annual C stocks additions in oven-dry biomass, litter, and the soil in planted shelterbelts in Saskatchewan for six common shelterbelt tree and shrub species and compared with shrub willow short-rotation coppice (SRC) stands that were also planted on agricultural land (Amichev et al. 2012). The low and high estimates represent the range of values for all clusters across the Province.



* Amichev et al. (2012)
** Shelterbelts: 1 row, planted at 2 m spacing; tree crowns differ by species

spatial occurrence from the species distribution data (Fig. 5), were used together to identify the best locations for future planting of these six shelterbelt species. The shelterbelt species with the best predicted future GHG mitigation potential for the Brown soil zone are HP and CG; the species for the Dark Brown soil zone is HP; the species for the Black soil zone are WS, MM, GA, and SP; the species for the Dark Gray soil zone is WS; and the species for the Gray soil zone are WS, HP, MM, GA, SP, and CG.

Carbon stocks validation

Although the validation of the carbon stocks results done with the aboveground biomass carbon sequestration rate, estimated as kilogram C per tree per year, accounted for the broad range of shelterbelt tree mortality, tree spacing, and age, this approach could not account for any tree growth changes resulting from specific shelterbelt management practices, such as weed control, irrigation, fertilization, tree pruning, and animal grazing. Therefore, prior to the validation analysis, the shelterbelt field data used for validation purposes were carefully studied to identify any potential outliers on the basis of specific shelterbelt management practices used, either reported by the farmers or observed by our field crews, which could alter shelterbelt tree growth. Thirty-one (of 71 total) validation sites were identified as outliers, nine sites were in the Black soil zone, and four, five, seven, and three sites were in the Brown, Dark Brown, Dark Gray, and Gray soil zones, respectively (Table 4).

The shelterbelt sites identified as outliers were for all six species and all ages. A full description of the reported specific shelterbelt management practices, or the shelterbelt's specific local conditions, for the nine sites in the Black soil zone are presented in Table 4. For example, in the two caragana shelterbelts in the Black soil zone, the model predictions were one order of magnitude greater than the observed values, largely due to the harsh local growing conditions of these shelterbelts, such as a ridge top planting or next to a ditch with standing water location, both resulting in dead spaces within these shelterbelts (Table 4). Additionally, some caragana shelterbelts' ability to regrow after biomass harvesting that could be used by farmers to manage these shelterbelts, could also alter the caragana growth patterns over time. For the outlier validation

Table 3. Year 2015 carbon stocks inventories (total ecosystem carbon stocks and carbon stocks additions) of six common shelterbelts species planted in Saskatchewan from 1925 to 2009, for two accounting periods: (1) since 1925 and (2) since 1990.

		Total ecosystem C[a]		C stocks additions[b]		
No.	Species	Since 1925[d] (Mg C)	Since 1990[e] (Mg C)	Since 1925 (Mg C)	Since 1990 (Mg C)	Length[c] (km)
1	Caragana	7 864 038	3 712 920	3 403 911	2 617 188	35 245
2	Green ash	964 207	576 098	432 497	346 605	5841
3	Hybrid poplar	1 303 391	734 540	684 186	568 097	4144
4	Manitoba maple	364 000	170 453	212 503	141 542	2646
5	Scots pine	184 214	96 290	64 392	55 936	1573
6	White spruce	131 750	78 359	50 440	45 348	991
	Total (Mg C)	10 811 599	5 368 660	4 847 929	3 774 715	50 439
	Tg C	10.81	5.37	4.85	3.77	

Note: 1 Tg C = 1 million Mg C.

[a] Total ecosystem carbon stocks include the C stocks in above- and belowground biomass, litter layer, initial soil C pool, and new C added to the soil.

[b] C stocks additions, carbon stocks added as a result of planting shelterbelts; equal to TEC stocks minus the initial soil C pool.

[c] Length, expected cumulative shelterbelt length; because most shelterbelts are multispecies, with separate rows per species, each 1 km of a two-species shelterbelt was accounted as 1 km of species one, and a separate 1 km of species two. Therefore, the C stocks for the individual species in a multispecies shelterbelt can be added together for a farm level C inventory analysis.

[d] C stocks since 1925, carbon stocks estimated for the period 1925–2015. A 60 yr C value was assigned for shelterbelts aged >60 yr because our growth curves were limited to 60 yr.

[e] C stocks since 1990, carbon stocks estimated for the period 1990–2015. These stocks were estimated by subtracting from the "Since 1925" C stocks the "up-to-1990" C stocks; they represent only the C sequestered in the period 1990–2015, regardless of when shelterbelts were planted, i.e., planted since 1925. Note that "Since 1990" TEC stocks also include the initial soil C pool only for the shelterbelts planted on or after 1990 but not for any shelterbelts planted prior to 1990.

Fig. 5. Prevalence of six common shelterbelt species planted from 1925 to 2009 in Saskatchewan (*a*), estimated as percent of the provincial total ecosystem carbon (TEC) stocks of each species and graphed (*b*) and mapped (*c*) by soil zone and cluster. Note: the map of soil zones and 31 clusters was created by a cluster analysis (Amichev et al. 2015) using data from the Soil Landscapes of Canada dataset, v. 3.2 (Agriculture and Agri-Food Canada Soil Landscapes of Canada (SLC) Working Group 2010), and data from the National Ecological Framework for Canada dataset (Marshall et al. 1999).

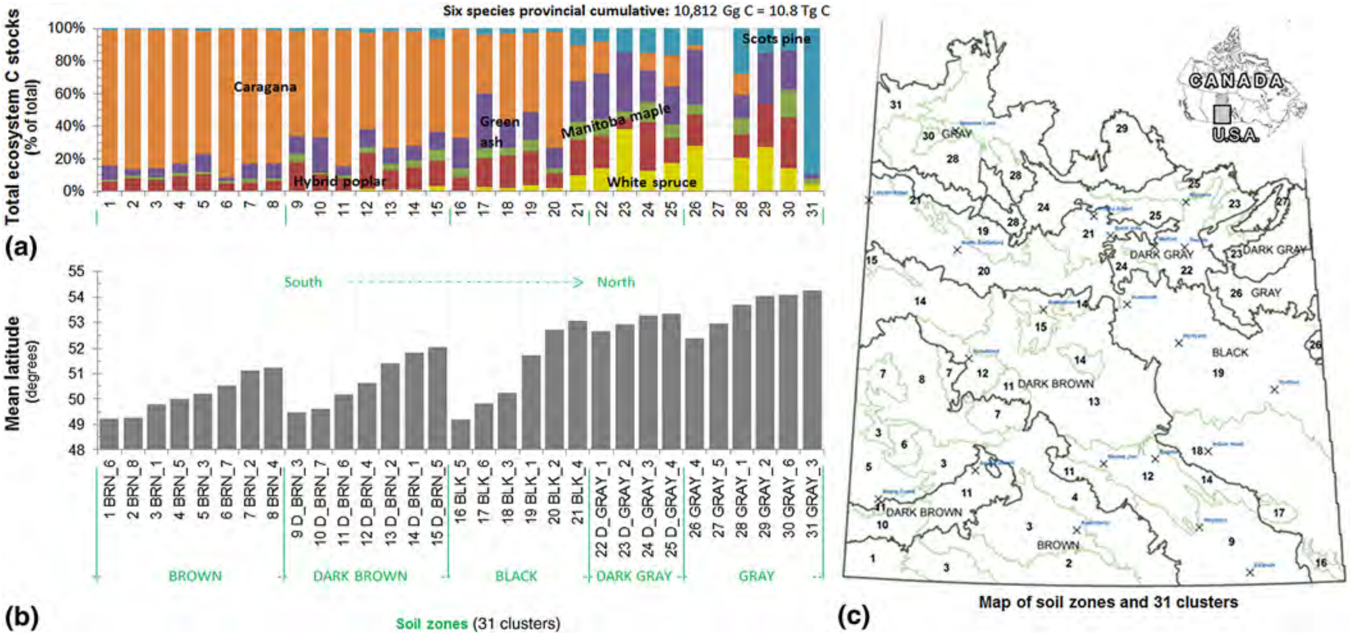


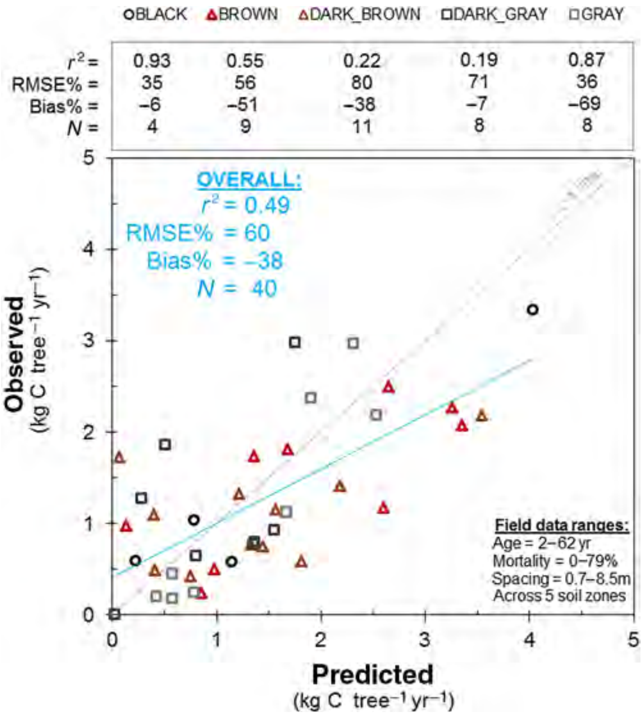
Table 4. Field data outliers identified and removed from the validation analysis for six shelterbelt species planted across five soil zones in Saskatchewan. The six species are caragana (CG), green ash (GA), hybrid poplar (HP), Manitoba maple (MM), Scots pine (SP), and white spruce (WS).

			Aboveground biomass C		
Soil zone	Examples of the reasons for validation data outlier removal	Species, age[a]	Observed (kg C tree^{-1} yr^{-1})	Predicted (kg C tree^{-1} yr^{-1})	Difference[b] (%)
Black: 14 sites	9 outliers removed as follows:				
	1 Dead spaces are present within the shelterbelt. Its location is on the top of a ridge, exposing it to the elements	CG, 23 yr	0.082	0.943	1048
	2 An old shelterbelt that has been repeatedly coppiced at ground level. It is planted next to a ditch full of standing water	CG, 23 yr	0.033	1.191	3494
	3 A small shelterbelt on the inside row surrounding the farmyard. Herbicide was sprayed within couple meters of the trees	GA, 20 yr	1.918	0.992	−48
	4 HP trees were interplanted with older MM trees that have died back. There was no ground cover or leaf litter around the base of the shelterbelt trees due to regular goat browsing. It is planted near a dugout within a goat pasture. The DBH (107 cm) of the HP trees was beyond the range of our biomass equations	HP, 46 yr	23.492	6.905	−71
	5 The trees represented the remains of a very old shelterbelt in the middle of the farm yard. The age of the shelterbelt was beyond the range of our model simulations	MM, 93 yr	0.889	1.904	114
	6 There was sapsucker damage to the trees of this very old shelterbelt. There was tall grass, shrub, and herbaceous undergrowth within the shelterbelt row. The age was beyond the range of our model simulations	MM, 73 yr	1.069	2.500	134
	7 There was significant porcupine damage to this shelterbelt. There was a dugout with shrub willow next to the shelterbelt. The trees were subjected to winds off the lake, along with abundant soil water	SP, 11 yr	2.339	0.581	−75
	8 The shelterbelt trees were dug out from a nearby ditch, and were 8–10 yr old when replanted at this location. The trees were pruned up to 3 m height. The undergrowth grass was mowed entirely next to the trees	WS, 45 yr	8.805	3.112	−65
	9 There was bare ground under the shelterbelt trees indicating that herbicide was used for weed control	WS, 33 yr	5.462	1.215	−78
Brown: 14 sites	4 outliers removed	1 CG, 2 GA, 1 SP			
Dark Brown: 16 sites	5 outliers removed	1 CG, 1 GA, 1 HP, 1 SP, 1 WS			
Dark Gray: 16 sites	7 outliers removed	1 CG, 1 GA, 1 HP, 1 MM, 1 SP, 2 WS			
Gray: 11 sites	3 outliers removed	1 GA, 1 MM, 1 SP			

[a] Caragana shrubs have the capability to resprout and regrow new stems following any event that would damage the aboveground biomass (i.e., wildlife browsing, flooding, and harvesting), which could interfere with the ageing procedures used in these shelterbelts, usually done with cut stem cross sections or stem core samples.

[b] Percent difference between predicted and observed values was estimated as 100 × (predicted − observed)/observed; predicted, CBM-CFS3 model prediction of aboveground biomass C sequestration rate for any specific validation site using 3PG model growth curves as input data; observed, aboveground biomass C sequestration rate estimated from direct field measurements.

Fig. 6. Aboveground biomass annual C sequestration rates predicted by the CBM-CFS3 model (using 3PG model growth curves as input data) and validated by direct shelterbelt observations for six shelterbelt species planted by various designs across five soil zones in Saskatchewan. The accuracy of the predictions was evaluated by r^2 (%) of observed versus predicted rates, root-mean-square error (RMSE, %), and bias (%); negative percent bias indicates overestimation.



sites planted with tree species, the model predictions ranged from an underestimation of −78% to an overestimation of 134% (Table 4). The model predictions underestimated the observed values for the majority of these outliers due to weed control practices used by the farmers — by herbicide application, goat grazing, or grass mowing underneath the trees, which resulted in enhanced tree growth. The model predictions overestimated the observed values in older shelterbelts and those with observed tree damage from wildlife (Table 4).

The validation analysis was done with data from the remaining forty validation sites, ranging in age (2–62 yr), tree mortality (0%–79%), and tree spacing (0.7–8.5 m), sampled from across the five soil zones in the province (Fig. 6). In general, for all species and soil zones, the r^2 of predicted versus observed aboveground biomass carbon sequestration rates (kg C tree^{-1} yr^{-1}) was 0.49, with RMSE of 60% and bias of −38% (indicating an overestimation). Because of the outlier identification and removal process, a different number of validation sites remained for use for the individual validation analyses done per soil zone, ranging from 4 (Black) to 11 (Dark Brown) sites (Fig. 6). The highest r^2 of predicted versus observed values were for the Black (0.93) and Gray (0.87) soil zones, followed by the Brown soil zone at 0.55. There was a low correlation between predicted and observed values for the Dark Brown (r^2 = 0.22) and Dark Gray (r^2 = 0.19) soil zones (Fig. 6). Across the individual soil zones, RMSE ranged from 35% to 80%, and bias ranged from −69% to −6% (Fig. 6).

Discussion

Carbon sequestration in shelterbelts

On average, the carbon sequestration potential of planted shelterbelts in Saskatchewan was 1.3–5.3 Mg C ha^{-1} yr^{-1} (Fig. 4), which was similar to other regions in the world. Globally, shelterbelts sequester 0.7–2.0 and 1.5–2.0 Mg C ha^{-1} yr^{-1} in aboveground biomass, and 0.4–1.0 and 0.8–1.5 Mg C ha^{-1} yr^{-1} in the soils, in Asia (Nair 2012) and Europe (Chendev et al. 2013), respectively. Much lower C sequestration rates have been reported elsewhere in North America at 0.37–0.73 Mg C ha^{-1} yr^{-1} (Udawatta and Jose 2012). When compared with other types of agroforestry systems in Saskatchewan, planted shelterbelts sequester carbon at rates that are comparable with intensively managed shrub willow plantations (planted at 15 000 shrubs ha^{-1}) in the province at 4.9–6.6 Mg C ha^{-1} yr^{-1} (Amichev et al. 2012) and to higher density hybrid poplar plantations (planted at 1600 trees ha^{-1}) in western Canada at 1.7–6.1 Mg C ha^{-1} yr^{-1} (Arevalo et al. 2009).

The field data that were used to parameterize the 3PG model were collected from shelterbelts of various designs and ages across Saskatchewan. Any attempts to identify more effective planting designs and strategies for GHG mitigation of planted shelterbelts would require shelterbelt species distribution data (i.e., maps) and species growth models. Species-specific maps and growth models are required because shelterbelt designs that are suitable for one area of Saskatchewan and for one shelterbelt species, may not be transferrable with other areas or other shelterbelt species, due to differences in climatic and edaphic properties and species growth characteristics. Furthermore, to evaluate different shelterbelt designs, a new knowledge is needed as to how these shelterbelt species distribution data and growth models correlate with various shelterbelt planting designs used by farmers, and that have withstood the test of time many decades after planting. Although the latter knowledge is still lacking, the shelterbelt species data and growth models necessary for such analysis have been gathered and developed in this study. The results presented here (Figs. 3–5) and those that were recently published (Amichev et al. 2015, 2016) could be used in future shelterbelt studies and carbon inventories in Saskatchewan to identify the most effective shelterbelt designs, for each region in the province, along with a proper species selection for enhanced GHG mitigation.

In addition to the importance of selection of appropriate shelterbelt species to plant, our earlier work

(Amichev et al. 2016) identified other important factors driven by the land owner's choice on the carbon sequestration potential of shelterbelts. These include the choice of shelterbelt management that controls tree mortality and, in particular, the choice of shelterbelt design in terms of the distance between planted trees within a row. Growth simulations for different spacing and mortality levels by Amichev et al. (2016) provided a generalized, but valuable, insight into the differences of certain shelterbelt designs. For example, on average, TEC stocks stored in white spruce shelterbelts after a 60 yr period were 258, 236, 214, and 186 Mg C km^{-1} (including the initial soil carbon pools) in shelterbelts with tree mortality of 0%, 15%, 30%, and 50%, respectively (Amichev et al. 2016). By more than doubling the tree spacing from 2.0 to 5.0 m, equivalent in reducing the number of planted trees by >50%, the TEC stocks only slightly decreased from 258 to 247 Mg C km^{-1}, because the evenly spaced larger gaps between planted trees at the wider spacing levels were utilized for the growth of larger trees (Amichev et al. 2016). In contrast, 50% tree mortality often occurs unevenly within the shelterbelt, mostly along continuous longer stretches of the shelterbelt, which formed larger gaps that were not utilized for tree growth. Therefore, the simulations done by Amichev et al. (2016) emphasized the relatively higher effects of tree mortality, compared with the farmer's choice of suitable tree spacing planting designs, on the potential carbon sequestration of shelterbelts in Saskatchewan. As such, future shelterbelt studies should also focus on inventorying, better understanding the ecosystem processes involved, and accurately modelling the effects of different shelterbelt management practices (e.g., weed control, fertilization, tree pruning, and irrigation) on the effectiveness of shelterbelts for GHG mitigation.

Validation of results

The validation analysis of predicted carbon sequestration rates for the six shelterbelt species in this study showed an overestimation (i.e., negative bias) of 38% and prediction error of 60% (Fig. 6) for a broad range of sampled shelterbelts. The accuracy of model predictions for future carbon stocks inventories in shelterbelts could be improved by increasing the overall sample size of the validation data set, which could be very resource and time intensive, or by performing validation analyses only on selected age classes or specific shelterbelt species. About 44% of the validation data that were collected in this study were identified as outliers and had to be removed from the analyses (Table 4). In future validation analyses, decreasing the broad range of inventoried shelterbelts to the most common age classes and species would allow a more focused resource allocation for validation purposes and lead to an accuracy increase of the shelterbelt carbon rates and stocks predictions.

The validation results in this study could serve as guidelines for future shelterbelt carbon stocks inventories across the province and could be used to emphasize the differences between the individual soil zones. For example, the lowest RMSE error in the Black and Gray soil zones indicated that a smaller validation data sample size could be used. In contrast, the sample size should be larger for the other three soil zones (Fig. 6). Additionally, the validation shelterbelt sites should be selected to be representative of all shelterbelts in their respective soil zone, region, or local growing conditions. Any field crew observations or farmer's records of specific shelterbelt management practices used at the validation sites, that could alter shelterbelt growth patterns, should be taken into account in all carbon stocks inventory validation analyses, and these validation sites should be removed as outliers. The results in the current study did not account for specific shelterbelt management practices, such as weed control, irrigation, fertilization, and tree management, which were beyond the scope of this study. Future shelterbelt studies should include separate carbon stocks inventories and validation analyses for those shelterbelts that are being maintained with specific shelterbelt management practices.

Shelterbelt growth

Allometric equations for shelterbelt species are lacking in the literature, and our study provided new equations for six species in Saskatchewan. The caragana shrub shelterbelts exhibited the widest growth range of the six species. Caragana shrubs have the capability to resprout and regrow new stems if the aboveground biomass was damaged, such as from wildlife browsing, which could change the growth rates of the regrown caragana shelterbelt.

The shelterbelt biomass equations (Table 2) and curves (Fig. 2) developed in this study can be used by land owners and producer to estimate shelterbelt biomass from diameter data and to evaluate the relative growth and growing conditions of their shelterbelts. For example, our analysis showed that it takes from 20 (HP) to 60 (GA) yr of growth for shelterbelt trees to reach 30 cm DBH (Fig. 3). Shelterbelt trees with a 30 cm DBH would have biomass ranging from 199 to 332 OD kg $tree^{-1}$ for WS > GA > SP = HP > MM trees (in descending order) (Fig. 2).

In the course of this study, there were no any two shelterbelt designs that were the same across all the sites that were visited for field sampling. Although this observation exceeded our expectations for the shelterbelts design diversity in Saskatchewan, shelterbelts are planted by farmers and producers to meet their specific interests and goals. Although understanding the farmer's intentions for the planted shelterbelts was beyond the scope of this study, our data indicated that planting a fast-growing hybrid poplar shelterbelt, which could grow up to a 10 m height by age 10 yr, would create a wind barrier in the shortest time. Also, by planting, a white spruce shelterbelt, because of its characteristic dense tree crown, would create a denser wind barrier in the long term despite it being one of the slowest growing of the six species (Fig. 3).

Because tree crowns in shelterbelts are open on two sides due to the linear feature of these systems, there is a reduced competition for light, soil water, and nutrients between the trees due to uninhibited root growth on two sides regardless of within-row proximity of shelterbelt trees. These growing conditions for shelterbelt trees are dramatically different from trees in a forest, where there is an increased competition between neighboring trees from all directions. In shelterbelt agroforestry systems, Amichev et al. (2016) concluded that shelterbelt trees accumulated biomass primarily by increasing their stem diameters, rather than growing taller stems. Their findings along with the allometric equations and growth curves presented in the current study represent a significant increase in the understanding and knowledge of shelterbelt tree and shrub growth in Saskatchewan.

Conclusions

The cumulative total length of the six shelterbelt species in this study (50 439 km) represented 83% of the total shelterbelt inventory in Saskatchewan (60 633 km). The length of planted shelterbelts in the Province is >3 round trips from Saskatoon, Saskatchewan to Paris, France. The century-long shelterbelt legacy of the PSP is deeply rooted in the lives of the farmers, thus directly benefiting Saskatchewan's agricultural land, as well as indirectly benefiting the local and global climate. Planting shelterbelt trees and shrubs on agricultural landscapes is an important strategy for mitigating GHGs, with 10.8 Tg C that are already sequestered in the soil and tree biomass of shelterbelts. The climate mitigation potential of the six shelterbelt species, ranging from 1.78 to 6.54 Mg C km^{-1} yr^{-1}, emphasized the important role that trees can have on the agricultural landscape to mitigate GHGs.

The tree growth (3PG) and carbon dynamics (CBM-CFS3) modelling approaches were used to determine the total ecosystem C stocks and C stocks additions in shelterbelts of different ages, six species, and planting locations in five soil zones across the Province of Saskatchewan. The analyses in this study indicated that the 3PG model is a valuable modelling research tool for shelterbelt biomass estimation, shelterbelt performance evaluation, and decision support systems for future tree planting on agricultural landscapes. The shelterbelt biomass equations and curves developed in this study can be used by land owners to estimate biomass from diameter data and to determine relative tree growth at the farm scale. In addition, when the 3PG derived shelterbelt yield data we used for carbon dynamics simulations, our analyses indicated that the CBM-CFS3 model is another valuable research and carbon inventory tool for shelterbelt agroforestry systems.

The accuracy of the tree growth and C dynamics model simulations could be improved with more field sampling, suggesting that these types of modelling endeavors would be very resource intensive at large scales. If shelterbelts are to play a role in mitigating future GHG emissions, further research is warranted in the Canadian Prairies. A future project should aim to address the climate change effects on shelterbelt growth, to map, quantify, and understand shelterbelt removal (by some farmers), and to outline shelterbelt designs and specific management practices that could serve as a template for future shelterbelt expansion and support Canada's goal of enhanced GHG mitigation in the agricultural and food production sector.

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