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Carbon sequestration by white spruce shelterbelts in Saskatchewan, Canada: 3PG and CBM-CFS3 model simulations

Beyhan Y. Amichev[a,*], Murray J. Bentham[a], Werner A. Kurz[b], Colin P. Laroque[a], Suren Kulshreshtha[c], Joseph M. Piwowar[d], Ken C.J. Van Rees[a]

[a] University of Saskatchewan, Department of Soil Science, Saskatoon, SK, Canada
[b] Natural Resources Canada, Canadian Forest Service, Victoria, BC, Canada
[c] University of Saskatchewan, Department of Bioresource Policy, Business and Economics, Saskatoon, SK, Canada
[d] University of Regina, Department of Geography, Regina, SK, Canada

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ABSTRACT

For more than a century, planted shelterbelts in Saskatchewan, Canada have protected farmyards from the elements, decreased soil erosion, sequestered atmospheric carbon, as well as provided many other ecological functions. It is estimated that there are >60,000 km of planted shelterbelts throughout the province, and considerably more in all of the Canadian Prairies. This paper details the overall process of quantifying and mapping the carbon stocks in white spruce (*Picea glauca*) shelterbelts planted in Saskatchewan. Shelterbelt data collected from field sampling sites, which were identified by a unique site selection approach, were used to parameterize two models for use in shelterbelt systems; an independent data set was used to validate model predictions. Shelterbelt tree growth was modeled with the Physiological Principles in Predicting Growth (3PG) model, and carbon flux and stocks in shelterbelts were modeled with the Carbon Budget Model of the Canadian Forest Sector (CBM-CFS3). Annual total ecosystem carbon (TEC) flux in white spruce shelterbelts increased one order of magnitude, from −0.33 to 4.4 Mg C km^{-1} yr^{-1}, for age 1–25 years, and reached a peak of 5.5 Mg C km^{-1} yr^{-1} (age 39 years). An initial soil carbon loss from the shelterbelt, caused by the land-use change, was offset in full by tree growth by age 17, 18, and 21 years for trees planted at 2.0, 3.5, and 5.0 m spacing within a row, respectively. Increase in carbon stocks, after 60 years of growth, was predicted in the litter layer (21.8 Mg C km^{-1}), belowground biomass (26.1 Mg C km^{-1}), and aboveground biomass (117.6 Mg C km^{-1}). Across all the different provincial soils, carbon additions were 106–195 Mg C km^{-1} in 60-yr-old white spruce shelterbelts. Cumulatively, accounting for eight decades of white spruce shelterbelt planting and tree growth, carbon additions totaled 50,440 Mg C province-wide in 991 km of white spruce shelterbelts. The C additions represented 38% of the province-wide TEC stocks, which totaled 131,750 Mg C. The cumulative carbon storage in all components of planted white spruce shelterbelts far exceeded the initial carbon levels present at the time of shelterbelt planting.

1. Introduction

Shelterbelts have been planted in Saskatchewan, Canada for more than a century, from 1901 to 2013, under the provisions of the Prairie Farm Rehabilitation Act (Howe, 1986). Throughout the decades, shelterbelt trees have provided protection of farmyards, infrastructure and crops from the elements, soil protection from erosion, and a myriad of other ecological functions such as wildlife habitats, improved biodiversity and water quality (Kulshreshtha et al., 2011). In the past two decades a new shelterbelt characteristic was recognized by Kort and Turnock (1999) who emphasized the carbon storage capacity of planted shelterbelts.

Until recently, there was a lack of shelterbelt distribution data for the agricultural land in Saskatchewan. 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). There are about 991 km of planted white spruce (*Picea glauca*) shelterbelts throughout the province which were established between 1925 and 2009 at various planting designs (Amichev et al., 2015). A spatially explicit-database for the white spruce shelterbelts in

* Corresponding author. Tel.: +1 979 704 0345.
E-mail address: beyhan.amichev@vt.edu (B.Y. Amichev).

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Saskatchewan (Amichev et al., 2015) was used in this current study to quantify and map shelterbelt carbon storage for this species.

The aim of this paper was to demonstrate the process of quantifying and mapping the carbon storage in all white spruce shelterbelts in Saskatchewan. The specific objectives of this paper were to: (1) adapt existing tree growth and carbon dynamics models for analyzing these shelterbelts; and (2) quantify the carbon stocks and produce carbon stocks inventory maps of white spruce shelterbelts in Saskatchewan.

2. Materials and methods

2.1. Spatial scales of analysis and mapping

There are 106 agricultural ecodistricts in Saskatchewan that span across five soil zones (Amichev et al., 2015). Each ecodistrict is a polygon containing continuous, homogeneous land with regard to climatic, geologic, topographic and edaphic characteristics that affect tree growth in shelterbelts. The number of ecodistricts was reduced from 106 to 31 clusters (of similar ecodistricts) by grouping all non-continuous, homogeneous ecodistricts into clusters based on similar tree-growth variables for simulation modeling purposes (Amichev et al., 2015). White spruce tree growth in shelterbelt systems was modeled by the Physiological Principles in Predicting Growth (3PG) model, and carbon stocks and stock changes were estimated by the Carbon Budget Model of the Canadian Forest Sector (CBM-CFS3).White spruce shelterbelt carbon stocks were summarized and mapped at the scale of clusters, soil zones and the province. Additionally, cluster scale carbon stock maps were overlaid with the shelterbelt probability map produced by Amichev et al. (2015) to create a new, higher resolution, carbon stock map at the farm scale (1 × 1 km grid cell size).

2.2. Data sources

2.2.1. Climate data

Climatological input data required for the 3PG model include monthly maximum, minimum, and average air temperature (°C), vapor pressure deficit (mBar), precipitation (mm), solar radiation (MJ m^{-2} day^{-1}), and the average number of days per month with rain and frost events from 1954 to 2014. The CBM-CFS3 model only requires mean annual temperature. With the exception of vapor pressure deficit and solar radiation, all other variables were obtained from the national climate data and information archive (EC-NCD, 2008) of 19 climate stations across Saskatchewan (Fig. S1). Vapor pressure deficit and solar radiation variables were derived from available temperature and precipitation data using the same procedures as described in Amichev et al. (2010).

2.2.2. Soils data

The soil landscapes of Canada (Version 3.2) (SLC, 2010) data set was used to extract mean minimum, maximum, and average available soil water holding capacity, soil texture, and soil organic carbon (0–100 cm depth) data for each cluster. These variables were used as input in the 3PG and CBM-CFS3 model simulations. Tree growth modeling in 3PG required one additional input parameter, site fertility, which was adopted from Amichev et al. (2011, 2010).

2.2.3. Site selection and shelterbelt field data collection

Field data collection in a given cluster necessitated determination of where white spruce trees were planted, and their approximate age. This information was obtained from the shelterbelt tree orders and distribution database from the Prairie Shelterbelt Program (PSP), which was described in detail in Amichev et al. (2015). In short, the PSP shelterbelt tree orders from 1925 to 2009 were analyzed, and the intended tree planting locations of all white spruce tree orders were mapped. Each record in the PSP database contained the year and quantity of white spruce ordered, and a legal land description, which was converted to latitude and longitude coordinates and overlaid on the cluster map. The total number of white spruce trees ordered was summarized for each cluster. The cluster with the highest cumulative number of white spruce trees was used to randomly locate sites for field sampling of shelterbelts for 3PG model parameterization purposes. One parameterization site was located within each of ten equal-size age classes, which included the entire age range of all PSP orders, to assure equal and complete sampling coverage of all planted white spruce shelterbelts. The validation sites were sampled in all clusters where white spruce trees were ordered from the PSP, and these sites targeted the oldest expected age classes of all planted shelterbelts. Field sampling for parameterization and validation purposes was completed in the summer and fall of 2013.

A unique study-site selection approach, to sample white spruce shelterbelts in the field, was developed by modifying the randomized branch sampling (RBS) procedure by Valentine et al. (1984). The RBS procedure was originally designed to quantify largely scattered tree components, such as fruits or leaves (of a single, randomly selected tree), by only sampling a small number of branches that were also randomly selected from within the tree (Valentine et al., 1984). The RBS procedure was modified to identify white spruce shelterbelt sites across the province (from a larger data set) at randomly selected township locations within randomly selected soil polygons within randomly selected ecodistricts within the parameterization cluster. By applying this modified RBS procedure for site selection, bias in the collected data was minimized. The RBS procedure was also used to identify one random white spruce tree in the shelterbelt (at the farm scale) that was measured for height, diameter at breast height (DBH), average crown width, and age (via increment cores). Exact location coordinates (for mapping purposes), total shelterbelt length, total number of shelterbelt trees, tree mortality (%), shelterbelt design (i.e., number of rows, spacing between planted trees) were also recorded. These data, and the algorithms of the RBS procedure, allowed the estimation of carbon stocks within shelterbelts at each site. At the parameterization sites (but not at the validation sites) three soil cores were collected with an auger at three depths (0–10, 10–30, 30–50 cm) for soil organic carbon analysis and for fine root biomass estimation, for a total of 90 samples from all sites. Data collected at the parameterization sites were used to parameterize and adapt the 3PG and CBM-CFS3 models for analyzing shelterbelt systems. Aboveground data were collected from the validation sites to evaluate the CBM-CFS3 carbon stocks results in this paper.

2.3. White spruce growth in shelterbelts—A 3PG model simulation

2.3.1. 3PG parameterization

The 3PG model is based on species-specific properties and parameters grouped into five main categories (Table S1): (i) biomass partitioning and turnover; (ii) growth modifiers; (iii) stem mortality and self-thinning; (iv) canopy structure and processes; and (v) wood and stand properties. Although the 3PG model was originally intended for tree growth modeling in forests, in this current paper we applied the model to shelterbelts, using key input parameters that were derived from measurements obtained from trees grown in shelterbelts. For each variable in the above categories, a parameter value was assigned that would best represent the growth and development of white spruce trees growing in shelterbelt rows. Four methods of 3PG variable parameterization were used: (1) empirical observations from white spruce shelterbelts in our study sites; (2) data from the literature; (3) the default 3PG parameters (i.e., default for *Pinus radiata D. Don* species); and (4) the remaining parameters were set so that best fit was reached between the 3PG model output results for tree height and DBH and our shelterbelts' observations (Table S1).

Fifteen of the 3PG variables in Table S1 were parameterized based on shelterbelt field data. All data needed to develop allometric relationships were collected from shelterbelts in this study (Table S1). Estimates for white spruce biomass partitioning to roots were used from the literature (Strong and La Roi, 1983), while the parameters for root turnover rate were fitted. A conservative approach was adopted to simulate tree mortality in the 3PG model since long-term, annual mortality data in shelterbelts were not available in the literature. We assumed that all tree mortality would occur in the first growing season after planting. Although tree mortality at the parameterization sites ranged from 0 to 73%, there were no available records regarding the approximate tree age when any (or all) of the dead or missing trees died (ranging from 9 to 54 years). Finally, 14 other 3PG variables in Table S1 were parameterized by fitting model simulation results to white spruce height and DBH observations from the parameterization shelterbelt sites. Default 3PG values were left unchanged for the remaining 30 variables (Table S1) similar to the approach previously used for hybrid poplar (Amichev et al., 2010) and shrub willow (Amichev et al., 2011) growth simulations in 3PG.

Allometric equations for white spruce planted in shelterbelts were based on tree biomass, tree spacing, height, and DBH data. Detailed tree data were obtained in this study from a previously compiled data set (Kort and Turnock, 1999), and by destructively sampling nineteen random white spruce trees in shelterbelts across Saskatchewan, which were collected at different locations separate from the parameterization and validation data. Similar to the approach from other modeling studies (Amichev et al., 2010, 2011; Anderson and Luckert, 2007), the solver procedure in Microsoft Excel was used to fit our white spruce data to the allometric equations needed in the 3PG model (Sands, 2004b), which was accomplished via multiple iterations so that the sum of the absolute difference between estimated and observed data was minimized.

2.3.2. 3PG model simulation scenarios

White spruce tree growth simulations were conducted for a 60-yr period, from 1954 to 2014. Separate 3PG simulations were conducted for three 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%) for white spruce shelterbelts within the parameterization cluster. These simulations were used to determine the relative effects of tree spacing and mortality on white spruce growth. Finally, 3PG simulations were also conducted for the remaining 30 clusters encompassing the entire agricultural land base in Saskatchewan, using the same four mortality levels at 2-m tree spacing. Yield tables quantifying volume increment of a white spruce shelterbelt were generated by 3PG and used as input data for the CBM-CFS3 model because traditional yield tables for shelterbelts were not available in the literature.

2.4. Carbon dynamics—A CBM-CFS3 model simulation

2.4.1. CBM-CFS3 parameterization

One of the features of the CBM-CFS3 model is its capability to simulate C dynamics at the stand-level. Here we applied the model to individual shelterbelts. For each stand, the model estimates carbon stocks and fluxes in biomass, dead organic matter (DOM) and soil pools, and the impact of disturbance events (e.g., planting) on these pools (Kull et al., 2011; Kurz et al., 2009). Previous CBM-CFS3 simulation analyses involving afforestation on agricultural land were conducted by Amichev et al. (2012).

In this study, the stand-level project creator (SLPC) in CBM-CFS3 (Version 1.2.5212.235) was used to create an afforestation project for each cluster, spacing and mortality level. An afforestation disturbance was used to simulate planting of white spruce shelterbelts at time step 1 (year 1954), followed by 60 years of shelterbelt tree growth, ending with harvesting of the trees, and followed by slash burning, which was simulated at time step 60 (year 2014). Harvesting was chosen as the likely scenario of what might happen if the land owner decided to remove the shelterbelts for an alternate land use.

Site-specific initial soil carbon stocks, mean annual temperature, and white spruce growth curves in shelterbelts (i.e., annual-tree volumes), which were estimated in 3PG, were used as inputs in the CBM-CFS3 model. We assumed that all tree mortality in the CBM-CFS3 simulations occurred in the first growing season after planting, and therefore the stem annual turnover rates and snag fall rates within CBM-CFS3 algorithms were both set to 0. This was a conservative assumption regarding shelterbelt carbon storage because if white spruce trees lived beyond the first growing season, additional carbon stocks could be sequestered, although these stocks would not be accounted for in this study. Due to lack of shelterbelt data for coarse and fine woody debris needed in the CBM-CFS3 model, default turnover rates for white spruce trees (derived from white spruce forest stands) were left unchanged. Because shelterbelts are purposely planted systems with no sapling and non-merchantable components, the volume to biomass expansion factors for both stand components were set to eliminate these components from all estimations.

Due to the linear feature of planted white spruce shelterbelts, all CBM-CFS3 simulations were performed in per-km units as opposed to the default per-ha units, and all carbon stocks predictions were reported in per-km units. To accomplish this, all input data such as the annual tree volume data (from 3PG) were first converted from per-ha to per-km units using a crown width to age relationship, which we developed from the parameterization data; crown width $(m) = 0.1964 \times \text{Age (yr)}$, for ages 0–40 years ($r^2 = 0.80$), and assigned a 40-yr crown width to older shelterbelts. This crown width to age relationship was used because the length of a shelterbelt required to cover one ha area decreases as the trees grow and crowns get wider. One ha was the area underneath the tree crowns of 2.546 km of 20-yr-old shelterbelt trees with 3.93 m crowns, and underneath 1.273 km of 60-yr old shelterbelt trees with 7.86 m crowns. In this study, age specific conversion factors were used to convert tree volume data from 3PG from per-ha to per-km units for all simulation scenarios. The 1.273, 1.498, 1.818, 2.546 km ha^{-1} conversion factors were used for simulation scenarios of 0, 15, 30, and 50% shelterbelt tree mortality, respectively. For example, the observed mean crown diameter of a 40-yr (or older) white spruce shelterbelt was 7.86 m indicating that a shelterbelt of approximately 1273 m length would cover 1 ha ($=1273 \times 7.86 = 10{,}000\ m^2 = 1$ ha) of area located directly underneath the shelterbelt trees' crowns. For shelterbelts with higher mortality, where shelterbelt gaps exist in the space of the dead trees, a longer stretch of the shelterbelt is required to approximate 1 ha of area underneath the live trees' crowns.

2.4.2. CBM-CFS3 model simulation scenarios

All CBM-CFS3 simulations were conducted for a 60-yr period, from 1954 to 2014. Separate simulations were performed for three spacings (2.0, 3.5, and 5.0 m) and four mortality levels (0, 15, 30, and 50%) in white spruce shelterbelts within the parameterization cluster. Additional simulations were carried out for the remaining 30 clusters using the same four mortality levels at 2-m tree spacing. Data from all CBM-CFS3 simulations were used to generate C stock look-up tables for shelterbelts of different ages, spacings, and mortality and located in different soil zones in Saskatchewan.

Finally, to account for the different ages of white spruce shelterbelts planted in different decades, additional CBM-CFS3 simulations were conducted for six decadal planting sub-periods for a total of 60 years, to generate C stock look-up tables for shelterbelts of different planting time which therefore grew under different climatic and environmental conditions.

2.4.3. Carbon stocks mapping

Total ecosystem carbon stocks (TEC) (Mg C km^{-1}) and carbon stock additions (Mg C km^{-1}), as a result of white spruce shelterbelt planting, were estimated for each cluster and eight decades (1925–2009) of tree planting. TEC stocks included the carbon in the soil, litter layer, belowground, and aboveground biomass components, while the carbon stocks additions represented the sum of carbon stocks of all ecosystem components minus the initial (pre-planting) levels of mineral soil carbon stocks. All other biomass and dead organic matter carbon stocks were assumed to be zero at the time of planting. Average carbon stock estimates per cluster and decade were used to map the carbon stocks (Mg C km^{-1}) of white spruce shelterbelts across Saskatchewan, assuming a single row of planted shelterbelt trees. These maps were overlaid with map layers representing approximate shelterbelt age (Amichev et al., 2015), approximate tree mortality levels, approximate number of rows of planted shelterbelt trees (Amichev et al., 2015), and a shelterbelt distribution probability map (Amichev et al., 2015). Digitizing individual rows of planted trees from aerial imagery was not reasonable because of the large extent of the project. Therefore, an approximate number of shelterbelt rows were estimated from the number of trees in the PSP data set and shelterbelt length data (Amichev et al., 2015). Spatial analyses of all overlaid mapping layers were completed at the raster grid cell resolution of 1 × 1 km in ArcGIS^{TM} software (ESRI, Inc., Redlands, CA, USA; Version 10.0).

Carbon stocks inventory maps were created for each grid cell where white spruce shelterbelts were planted between 1925 and 2009 across Saskatchewan. A 60-yr carbon stock estimate was used for shelterbelts planted 1925–1955 due to our growth curves being limited to age 60 years; this was a conservative carbon value of these >60-yr-old shelterbelts. The length of currently existing shelterbelts was determined by manually digitizing individual shelterbelts from current high-resolution aerial photos as described in Amichev et al. (2015). Therefore, the C inventory estimates and maps in this current study account for all currently existing white spruce shelterbelts planted in the last eight decades. All planted shelterbelts that were subsequently removed by the land owners were excluded from this analysis due to lack of data. Finally, carbon stocks for all currently existing shelterbelts planted in all decades were summarized by cluster, soil zone, and the entire province.

2.4.4. Carbon stocks results validation

Data from 22 validation sites were sampled across all five soil zones in Saskatchewan to estimate aboveground biomass carbon stocks (Mg C km^{-1}) for the purposes of validating carbon predictions by the CBM-CFS3 model. The collected field data (DBH, height, age, spacing, mortality, shelterbelt length, selection probability of the sampled tree within the entire shelterbelt) and an allometric equation for aboveground biomass estimation, (aboveground biomass, kg tree^{-1} = 0.0066 × (DBH, cm)$^{3.18}$ developed for use in the 3PG model), were all used to estimate aboveground biomass C stocks (Mg C km^{-1}) at each validation site.

Additional CBM-CFS3 simulations were performed for each of the 22 validation sites to produce aboveground C stock predictions (Mg C km^{-1}), which were explicit for each validation site's specific conditions, such as tree mortality, age, and tree spacing. CBM-CFS3 carbon stock predictions were then compared against the field data.

2.5. 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 predictions made by the 3PG and CBM-CFS3 models. The 3PG model was parameterized mainly by fitting model predictions to observed field data (at parameterization sites). To determine when the best fit was achieved, multiple iterations of the 3PG model were performed, by systematically changing the values of the fitted parameters (Table S1) until the lowest RMSE and bias, and highest r^2 of observed versus predicted DBH and height, were achieved. Observed data were the field data measurements, DBH and height for 3PG model fitting, or field data-derived C stocks for CBM-CFS3 model evaluation. Predicted data were mean DBH and height (for 3PG model fitting) or aboveground biomass carbon stocks (Mg C km^{-1}) (for CBM-CFS3 model evaluation); negative bias indicated overestimation and positive bias indicated underestimation. Additionally, *t*-tests (at 0.05 alpha level) were used to determine significant differences of mean CBM-CFS3 predicted aboveground biomass C stocks (Mg C km^{-1}) compared to field data in each of five soil zones in Saskatchewan.

2.6. 3PG model sensitivity analysis

A sensitivity analysis was carried out to demonstrate the suitability of the 3PG model for use in shelterbelt agroforestry systems, which could be described as rows (single or multiple) of planted trees, since the 3PG model was originally intended for modeling tree growth in forest stands (Sands, 2004b; Sands and Landsberg, 2002). This sensitivity analysis investigated the magnitude of effects of all 'light interception, production and respiration' variables (independent variables) used in 3PG on the amount of total radiation intercepted by the shelterbelt canopy (*radtn intcptn*) and the light utilization efficiency of shelterbelt trees (*epsilon*) (dependent variables) (Sands, 2004a). Specifically, the relative changes (%) in *radtn intcptn* and *epsilon* were evaluated by changing the independent variables by −40% to +40% from the default value. The independent variables were *k* (extinction coefficient for photosynthetically active radiation absorption by canopy), *fullCanAge* (age at full canopy cover within the tree row), *alpha* (maximum canopy quantum efficiency), and *Y* (ratio NPP/GPP). Additionally, the changes in *radtn intcptn* and *epsilon* were evaluated by changing the parameters (by −40% to +40% from the default values) of three selected soil variables (*FR* = fertility rating; *MinASW* = minimum available soil water; and *MaxASW* = maximum available soil water) (independent variables), which were part of the 3PG model's stand initialization and site factors input data. Finally, a similar 3PG model sensitivity analysis was carried out to determine the effects of changing the values of the same seven independent variables (*k, fullCanAge, alpha, Y*, FR, *MinASW, and MaxASW*) on mean DBH and mean stem biomass per shelterbelt tree (dependent variables).

All sensitivity analyses were carried out separately for each independent variable keeping all other independent variables unchanged. The evaluation of all dependent variables was done at the final time step of the 3PG model simulations (age 60 years) to account for any cumulative effects over time.

3. Results

3.1. White spruce growth in shelterbelts

3PG model parameterization by the fitting method was achieved for mean DBH with RMSE = 21%, bias = −11%, and r^2 = 0.82, and for height with RMSE = 22%, bias = −31% and r^2 = 0.86 (Fig. 1). These results were achieved for a wide range of study site conditions:

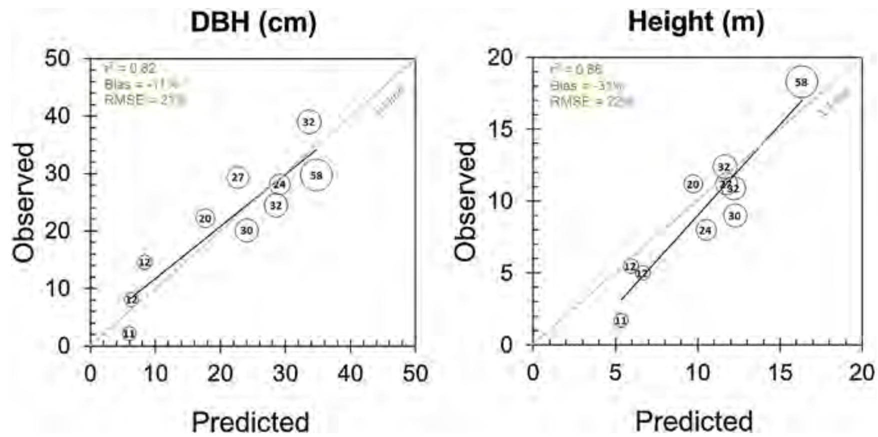

Fig. 1. 3PG model parameterization by fitting model predictions for mean DBH and height to observed field data; values within each data circle (and circle size) indicate the age of the white spruce shelterbelt at each parameterization site.

2.2 to 39.0 cm range of DBH, 1.7 to 18.3 m range of height, from 0 to 73% tree mortality, from 1 to 5 m tree spacing (resulting in 200 to 1000 trees km^{-1} tree density), and 11 to 58 year range in shelterbelt age.

Tree mortality effects on mean tree height and on DBH differed for shelterbelts (Fig. 2b and d). While tree height was nearly the same for shelterbelts with varying tree mortality (0–50%), mean DBH increased in shelterbelts with higher tree mortality (≈42.0 cm at age 60 years and 50% mortality), where live trees used the gaps from dead trees for additional growth, compared to shelterbelts with no tree mortality (DBH = 33.7 cm at age 60 years) (Fig. 2d). Both mean tree height and DBH increased asymptotically from planting to age 60 years with no indication of a plateau being reached at the end of the simulation period. Stand and root biomass decreased proportionately as shelterbelt tree mortality increased (Fig. 2a and c). Due to the limited extent of our field data, no predictions were possible for white spruce growth in shelterbelts older than age 60 years.

The effects of tree spacing on stand biomass, root biomass, mean tree height, and DBH were lower compared to the effects of tree mortality (Fig. 3a–d). Stand biomass predictions were 241.3, 238.6, and 227.3 Mg km^{-1} at age 60 years for tree spacings of 2.0, 3.5, and 5.0 m, respectively (Fig. 3a). Because of the additional tree growing space created in the gaps from dead trees, predicted mean DBH was larger in shelterbelts planted at wider tree spacing (≈44.1 and 33.7 cm, at age 60 years, planted at 5.0 and 2.0 m spacing, respectively) (Fig. 3d). Although individual trees planted at wider spacing had larger DBH, there were fewer larger trees per km (e.g., 200 trees km^{-1} at 5.0 m spacing), which resulted in lower total stand and root biomass, compared to narrower spacing shelterbelts (e.g., 500 trees km^{-1} at 2.0 m spacing) (Fig. 3a and c). Tree height was lower at wider tree spacing levels (≈15.8 m and 16.6 m, at age 60 years, planted at 5.0, and 2.0 m spacing, respectively) (Fig. 3b).

3.2. Annual carbon flux and stocks in shelterbelts

The annual changes in TEC stocks indicated an initial soil carbon release (−0.16 to −0.33 Mg C km^{-1} yr^{-1}) following shelterbelt planting (Fig. 4a), which after approximately 17 years was offset in full by carbon sequestration in biomass, litter, and soil, as a result of white spruce growth (Fig. 4c). Annual TEC flux in white spruce shelterbelts increased one order of magnitude, from −0.33 to 4.4 Mg C km^{-1} yr^{-1}, between age 1 and 25 years, and reached a peak of 5.5 Mg C km^{-1} yr^{-1} at age 39 years, followed by periods of fluctuation due to climatic differences throughout the simulation period (Fig. 4a). TEC flux predictions were lower for higher mortality scenarios. On average, annual TEC flux was 3.9, 3.4, 2.9, and 2.2 Mg C km^{-1} yr^{-1} in the years following the initial peak, reached at approximately age 25, 27, 29, and 32 years in white spruce shelterbelts with 0, 15, 30, 50% tree mortality, respectively (Fig. 4a). Annual climatic conditions affected carbon sequestration in shelterbelts. Observed local carbon emission peaks were associated with higher mean annual temperatures, which increased decomposition rates in the CBM-CFS3 model.

The effects of tree spacing were similar to those observed with the 3PG model for white spruce growth. Annual TEC flux reached a peak at approximately the same age (25 years) for the three spacing scenarios and all flux values converged at approximately age 40 years when the tree canopy was closed (within a shelterbelt row) even at the widest tree spacing (Fig. 4b). The initial carbon loss from the soil (Fig. 4b) was offset in full by white spruce tree growth by age 17, 18, and 21 years in shelterbelts planted at 2.0, 3.5, and 5.0 m tree spacing, respectively (Fig. 4d). On average, TEC stocks in white spruce shelterbelts after 60 years of tree growth 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 (Fig. 4c). In comparison, by more than doubling the tree spacing from 2.0 to 5.0 m, the TEC stocks decreased from 258 to 247 Mg C km^{-1} (Fig. 4d).

Throughout the 60-yr simulation period, the soil carbon levels decreased below the initial levels observed at planting with annual soil carbon flux ranging from −0.33 to −0.04 Mg C km^{-1} yr^{-1}. Soil carbon stocks decreased from initial values by approximately 11% (from 100.3 to 89.5 Mg C km^{-1}) during the 60-yr simulation period. However, this carbon loss from the soil was offset by carbon sequestration in the other components: the litter layer C increased from 0 to 21.8 Mg C km^{-1}, belowground biomass C increased from 0 to 26.1 Mg C km^{-1}, and aboveground biomass C increased from 0 to 117.6 Mg C km^{-1}. Therefore, total carbon stocks after 60 years far exceeded the carbon stocks at the time of planting.

TEC stocks in shelterbelts planted in different decades in the period from 1954 to 2004 (Fig. S2a) were compared with TEC stocks of shelterbelts planted in 1954 and simulated at different levels of tree mortality (Fig. S2b). The results showed that when 30% of shelterbelt trees were dead or missing, the underutilized carbon sequestration potential was approximately equal to 10 years of tree growth. And when shelterbelt tree mortality was 50%, the underutilized potential was doubled to 20 years (Fig. S2b). These results are noteworthy and reflect a wide range of conditions of currently existing shelterbelts; our observed mean mortality was 16% (ranging from 0 to 55%) in shelterbelts aged 8–54 years.

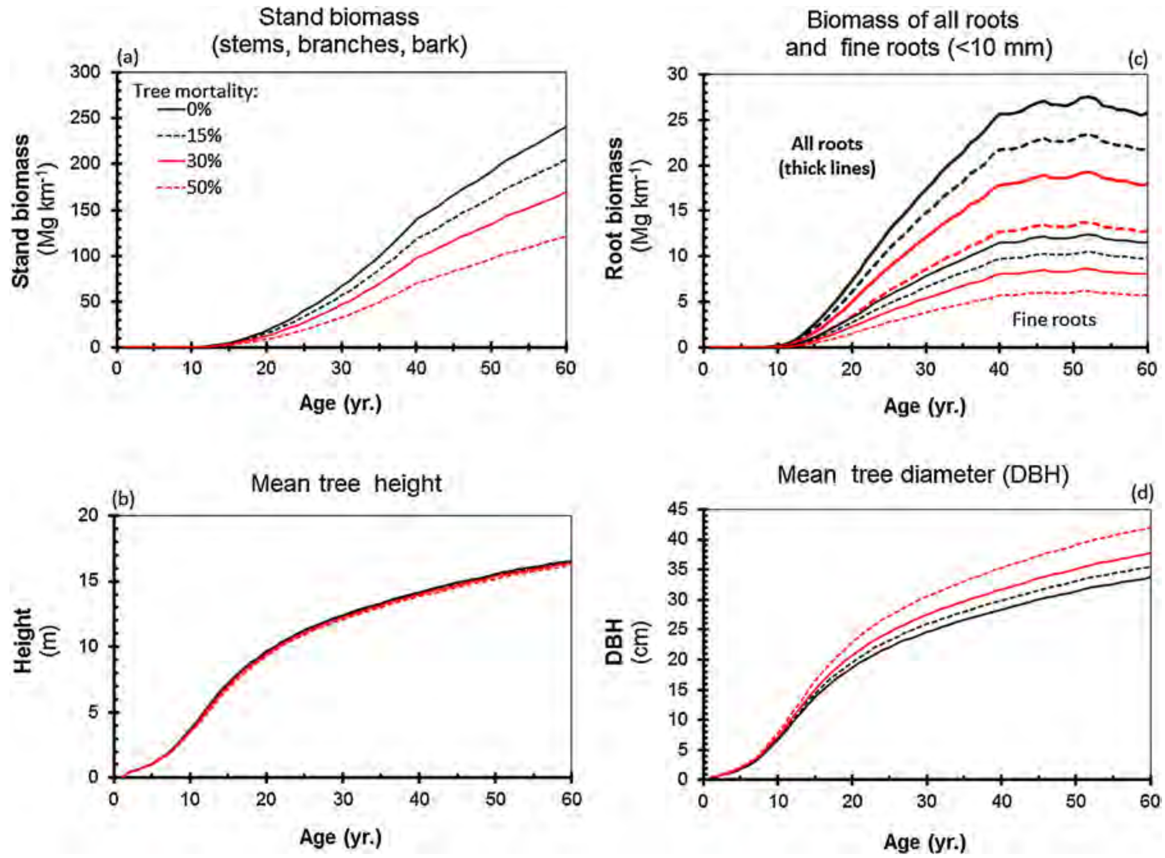

Fig. 2. 3PG model predictions for white spruce growth in shelterbelts at four mortality levels (0, 15, 30, 50%) and 2-m tree spacing. Tree mortality (%) = 100 – number live white spruce trees (%).

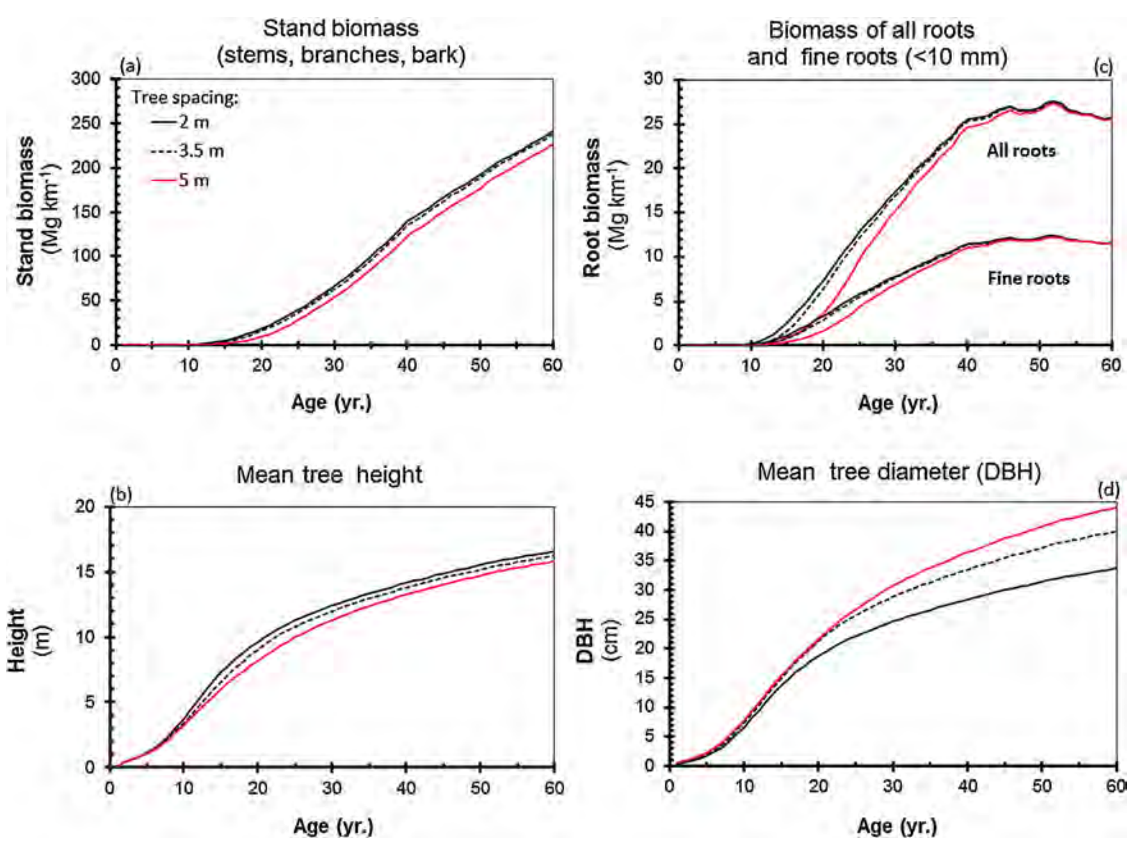

Fig. 3. 3PG model predictions for white spruce growth in shelterbelts at three tree spacing levels (2.0, 3.5, 5.0 m) and 0% tree mortality.

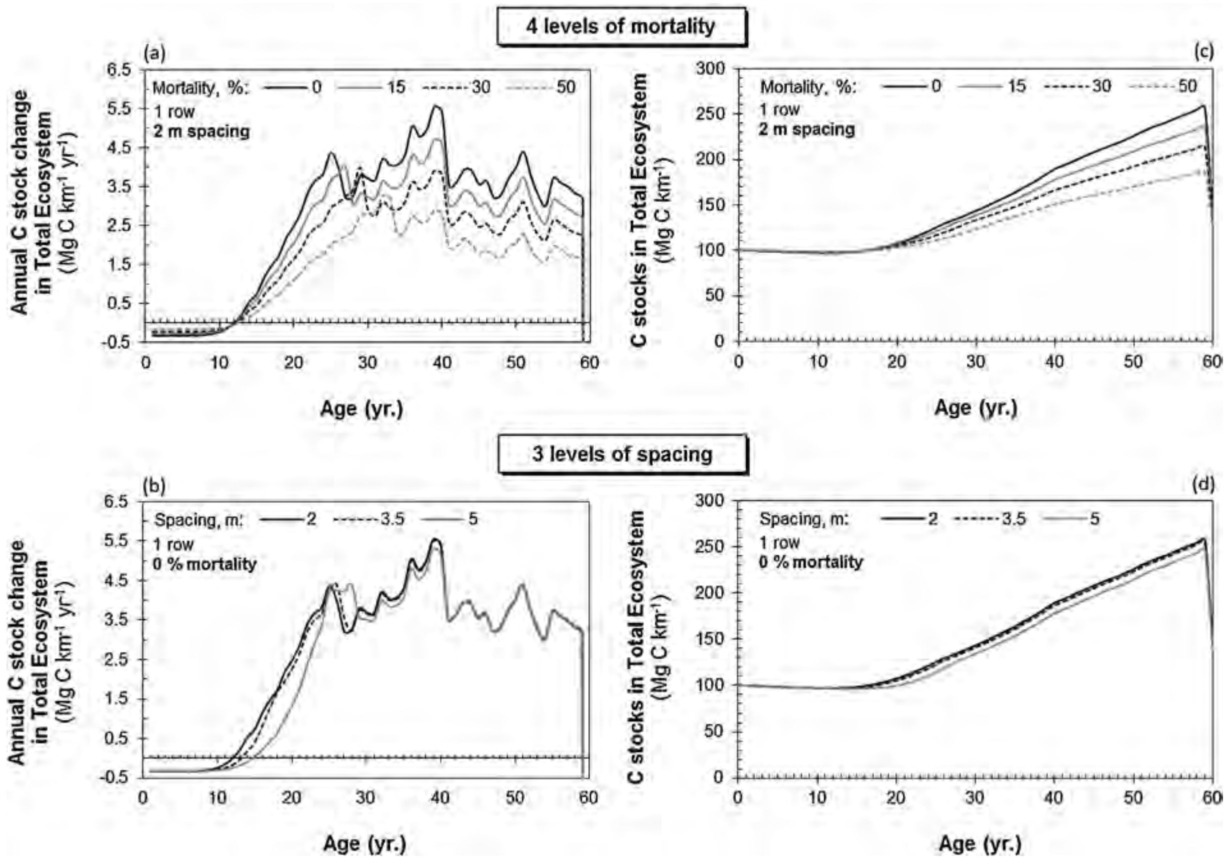

Fig. 4. Annual carbon stock change (a and b) and cumulative total ecosystem carbon stocks (c and d) in white spruce shelterbelts in Saskatchewan planted at 2.0 m spacing with 0, 15, 30, and 50% tree mortality (a and c), and planted at 2.0, 3.5, and 5.0 m tree spacing with 0% tree mortality (b and d).

3.3. Maps of carbon stocks in shelterbelts

Province-wide maps show the current distribution of TEC stocks in white spruce shelterbelts (Fig. 5), and carbon stocks additions from shelterbelt planting (Fig. 6). Both types of maps were used to identify potential areas for planting future shelterbelts within the province where the highest amount of atmospheric CO_2 would be sequestered.

Across the 31 clusters of agricultural land in Saskatchewan, TEC stocks were 162–267 Mg C km^{-1} (0% mortality) in 60-yr-old white spruce shelterbelts, and were 144–244, 136–221, 118–191 Mg C km^{-1} in shelterbelts with 15, 30, and 50% tree mortality, respectively (Fig. 5). The areas in the province where white spruce shelterbelts were predicted to have the highest carbon stocks were located in clusters in the eastern half of the agricultural area in the province. Several clusters within the Black, Dark Brown, and Dark Gray soil zones had the highest carbon stocks (>250 Mg C km^{-1}, age 60 years) (Fig. 5). Estimates of soil carbon stocks at time of planting in the Gray, Dark Gray, Black, Brown, and Dark Brown soil zones, were 49, 100, 95, 64, 82 Mg C km^{-1}, respectively, representing approximately 27, 39, 38, 30, 35% of the TEC stocks in white spruce shelterbelts (age 60 years).

The predictions for carbon stock additions (in the soil, total tree biomass and litter layer) were highest for clusters in the south-eastern part of Saskatchewan (parts of the Brown, Dark Brown, and Black soil zones) (Fig. 6). Carbon stocks declined during the first 10 and 20 years of tree growth in approximately 58 and 19% of all clusters, respectively (Fig. 6). Carbon stocks increased for all clusters in older (>20 years) white spruce shelterbelts. Across all five soil zones, carbon stock additions (0% mortality) were 106–195 Mg C km^{-1} in 60-yr-old white spruce shelterbelts (Fig. 6).

3.4. Inventory maps of carbon additions and storage

Carbon stock additions summarized for each raster grid cell (1 × 1 km) over the planting period from 1925 to 2009 ranged from −4.6 to 32.2 Mg C (grid cell)$^{-1}$ across the five soil zones in Saskatchewan (Fig. S3). Summarized at the cluster level, carbon stock additions ranged from 8 to 8612 Mg C (cluster)$^{-1}$. Eleven clusters (of 31 total) located mainly in the eastern parts of agricultural Saskatchewan had >2000 Mg C additions. Individual clusters in the Black, Dark Brown, and Dark Gray soil zones had >3000 Mg C additions. Carbon stock additions at the soil zone level ranged from 23,353 to 1286 Mg C (soil zone)$^{-1}$ in descending order in the Dark Brown > Dark Gray > Black > Brown > Gray soil zones. At the provincial level, carbon stock additions since 1925 totaled 50,440 Mg C (province)$^{-1}$, which represented 38% of current TEC carbon stocks, equal to 131,750 Mg C (province)$^{-1}$ in 991 km of white spruce shelterbelts (Fig. S3).

3.5. Validation of carbon stocks predictions

Field data from the validation sites had wide ranges in shelterbelt age (17–79 years), tree spacing (1.9–8.5 m), and mortality (0–79%), reflecting the variation in shelterbelt designs used by individual land owners. Because the CBM-CFS3 model used as input 3PG-derived biomass curves, the validation analysis evaluated the combined performance of both the 3PG and CBM-CFS3 models.

Generally, most of the bias of our C predictions (from CBM-CFS3) was caused by the input biomass data from the 3PG model, which was parameterized with field data from shelterbelts that

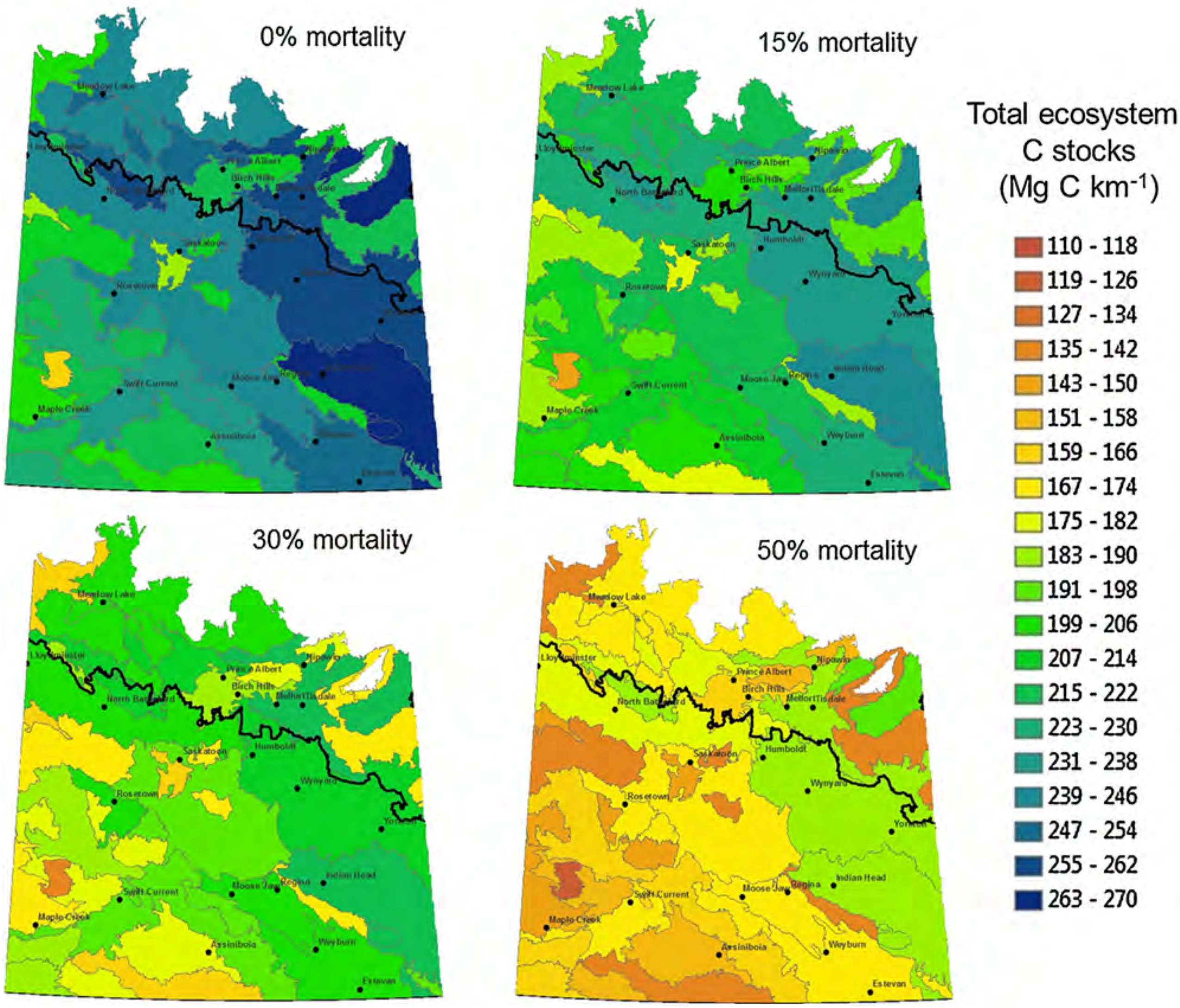

Fig. 5. Total ecosystem carbon stocks in white spruce shelterbelts with 0, 15, 30, and 50% tree mortality (age 60 yr.) across thirty-one clusters in Saskatchewan; Mg C km^{-1} estimates are for 1 row of trees planted at 2 m spacing. Bolded line on maps indicates the boundary between the Boreal Plains (north) and Prairies (south) ecozones in the province.

varied in design, age, and management. The 3PG model aboveground biomass bias ranged from −34 to 57% across the five soil zones, which was carried forward into the CBM-CFS3 model. Carbon estimates derived from the CBM-CFS3 model added only minimal bias ranging from −11 to 1%. This result emphasized the importance of accurate yield predictions for estimation of shelterbelt carbon dynamics.

Overall, based on all validation data in Saskatchewan, aboveground biomass carbon stocks were underestimated (bias = 13%) with RMSE = 94%, and r^2 = 0.60 between observed and predicted values (Fig. 7). RMSE of C stocks predictions were 32–93% in ascending order in the Gray < Brown < Dark Brown < Dark Gray < Black soil zones (Fig. 7). With the exception of the Dark Gray soil zone, correlations between observed and predicted C stocks were with $r^2 > 0.50$. In general, our results underestimated the aboveground biomass carbon stocks with bias ranging from −45 to 58% in ascending order in the Dark Brown < Gray < Brown < Black < Dark Gray soil zones. A *t*-test (at the 0.05 level) indicated that carbon stock predictions in aboveground biomass and observed data were not significantly different for all soil zones: Brown (p = 0.5995), Dark Brown (p = 0.7009), Black (p = 0.4259), Dark Gray (p = 0.0797), and Gray (0.7781).

3.6. 3PG model sensitivity analysis

There were no effects due to light interception, production and respiration variables (*k, fullCanAge, alpha, Y*) on the amount of total radiation intercepted by the shelterbelt canopy, *Radtn intcptn* (Table 1). There were exact proportional effects of the maximum canopy quantum efficiency, *alpha*, on the light utilization efficiency of shelterbelt trees, *epsilon*. For example, ±40%, ±20%, and ±5% changes in the parameter value of *alpha* resulted in exactly proportional changes in the value of *epsilon*. The effects on *epsilon* of soil fertility and available soil water were from −11 to 11% and from −22 to 1%, respectively (Table 1). Although not exactly proportional to the percent increase or decrease in soil fertility, the resulting change of *epsilon* was of similar magnitude. In contrast, the effects of decreased available soil water on *epsilon* were much higher than the changes caused by a proportional increase of available soil water (Table 1). These results showed that the 3PG model was designed to simulate the light utilization efficiency of trees (i.e., *epsilon*), which was done by parameterizing the *alpha* input variable, rather than simulating both *Radtn intcptn* and *epsilon*. The amount of total radiation intercepted by a 60-yr-old white spruce shelterbelt canopy was approximated by a parameter value, which

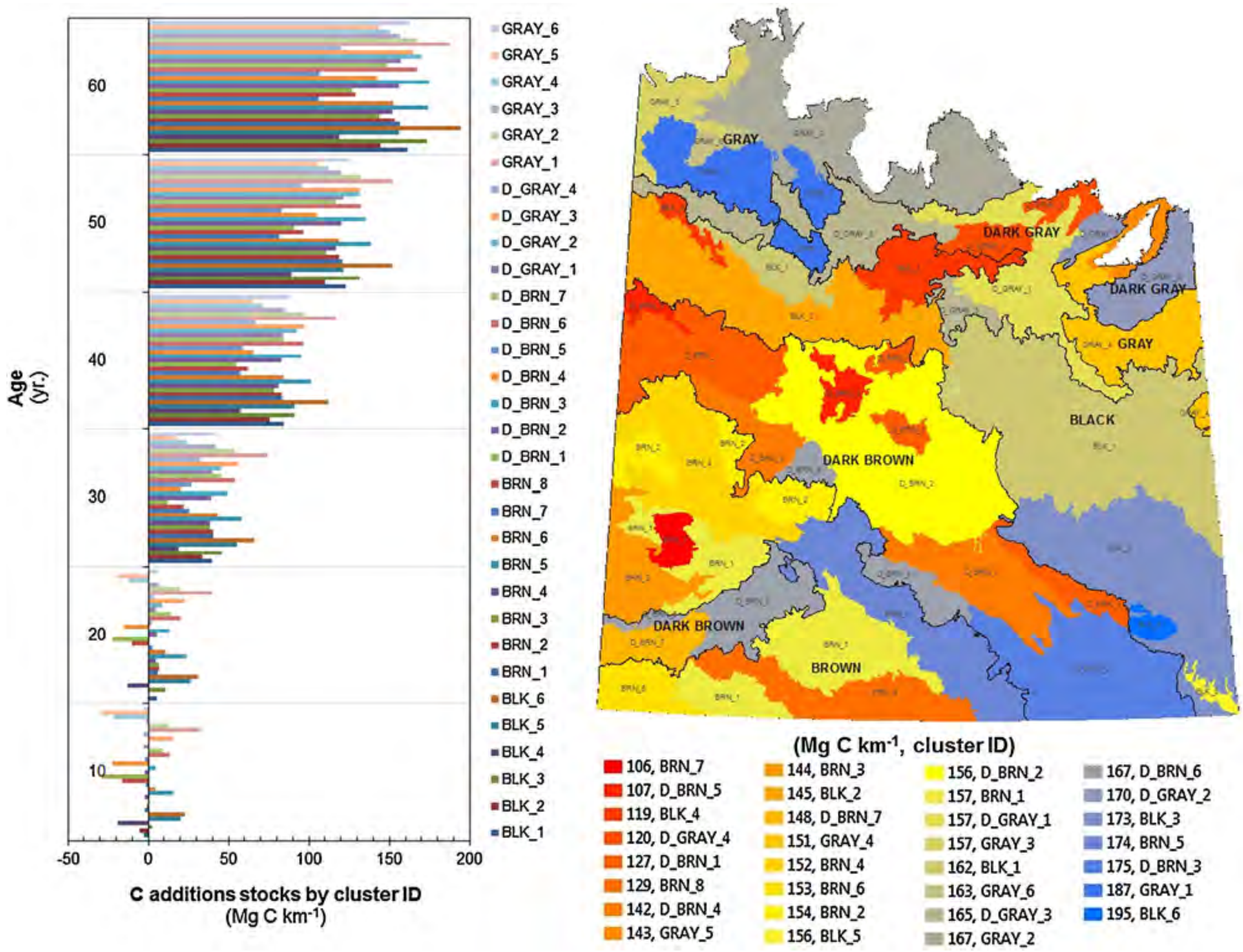

Fig. 6. Carbon additions (by cluster) in 10, 20, 30, 40, 50, and 60-yr-old planted white spruce shelterbelts (left) and a cluster distribution map in increasing order of the 60-yr carbon additions stocks in Saskatchewan (right). Carbon additions estimates were for 1 row of trees planted at 2 m spacing with 0% mortality, and were estimated by subtracting the initial soil carbon stocks from the total ecosystem carbon stocks (including C in the soil, whole tree biomass, and the litter layer) at any shelterbelt age. A 60-yr carbon additions estimate was used for 1925–1955 planted shelterbelts because growth curves are limited to age 60 yr.

stayed constant (7534 MJ m^{-2} $month^{-1}$) regardless of the values of the independent variables tested, and which is a function of input climate and latitude data needed in the 3PG model. In contrast, changes in the values of the same independent variables resulted in differences in the growth of shelterbelt trees, as indicated by the changes in mean DBH and mean stem mass.

The effects of *k*, *fullCanAge*, *alpha*, and *Y* variables and soil fertility and available soil water on tree growth were evaluated by changes in the values of mean DBH and mean stem mass (Table 1). Any changes of any of the light interception, production, and respiration variables, or the three soil variables, resulted in different tree growth of shelterbelt trees (Table 1). For example, percent change of mean DBH from −6 to 2%, from −0.3 to −0.1%, from −19.3 to 13.5%, and from −19.3 to 13.5% was observed due to changes in the parameter values of *k*, *fullCanAge*, *alpha*, and *Y* variables, respectively. Changes in mean stem biomass were higher than the changes in mean DBH and were from −17.8 to 6.6%, from −0.8 to 0.1%, from −49.5 to 49.5%, and from −49.5 to 49.5% due to changes in the parameter values of *k*, *fullCanAge*, *alpha*, and *Y* variables, respectively (Table 1). A similar pattern was observed in the effects of soil fertility and available soil water, for which the effects on mean stem mass were higher than mean DBH. Although not exactly proportional to the percent increase or decrease in soil fertility, the resulting change of mean DBH was of similar magnitude as an increase or decrease, respectively, ranging from −4.4 to 4.0% (Table 1). Lastly, percent decrease in available soil water resulted in greater changes of mean DBH compared to a similar percent increase of available soil water (Table 1).

4. Discussion

4.1. White spruce growth in shelterbelts

Similar to other planted, tree-based ecosystems where competition for resources had not yet started (Amichev et al., 2010), white spruce tree crowns were open on two sides due to the linear nature of shelterbelts. This attribute of the shelterbelts leads to a reduced competition for soil water and nutrients between the trees due to uninhibited root growth on two sides regardless of within-row proximity of shelterbelt trees. The combined reduced competition for resources could explain our observations of similar tree height, but associated with different DBH, in shelterbelts planted at different spacing, or growing at different mortality levels (where gaps were formed from missing or dead trees). Shelterbelt trees accumulated biomass primarily by increasing their stem diameters, rather than growing taller stems.

Larger tree DBH observations and 3PG model predictions for shelterbelt trees planted at wider tree spacing, or growing at higher tree mortality levels, were in accord with other planted tree-based ecosystems (Amichev et al., 2010). Amichev et al. (2010) reported

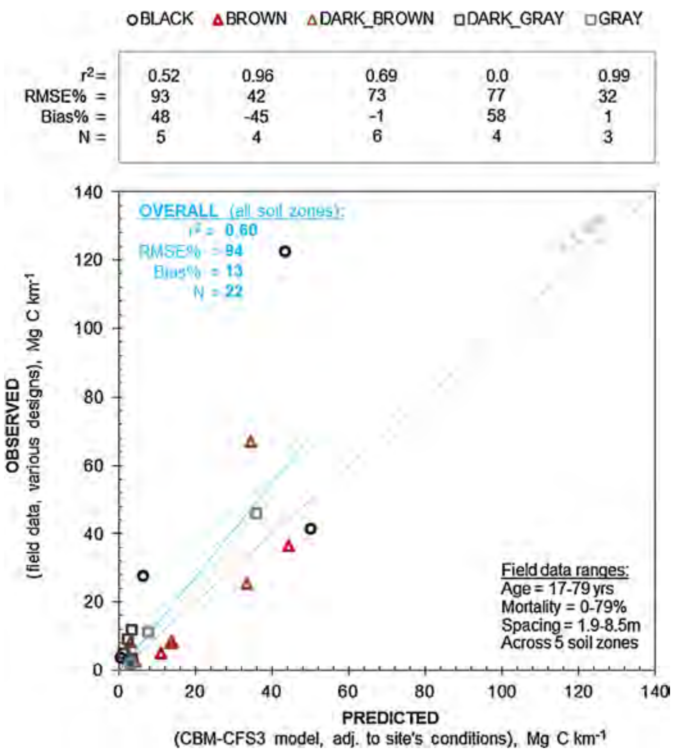

Fig. 7. Validation of CBM-CFS3 carbon stock predictions in aboveground biomass with field data across five soil zones by estimating RMSE, bias, and r^2 of observed versus predicted carbon stocks (left), and by performing a *t*-test at 0.05 alpha level (right).

significantly larger DBH of hybrid poplar trees planted at wider tree spacing levels for stand age >6 years. White spruce DBH differences were observed much later (>12 years age) in shelterbelts caused by a much slower growth compared to hybrid poplar.

4.2. Carbon sequestration by shelterbelts

When trees are planted on agricultural land to establish shelterbelt systems, mostly annual, shallow-rooted crops are replaced with longer-lived, lignin-rich, deeper rooted trees with slower turnover C dynamics (i.e., longer soil C residence time). Afforestation on agricultural land entirely transforms the soil carbon dynamics (over time) to that of the tree-based ecosystem, with different soil C sequestration rates and stock changes. This transformation is caused by differences between shelterbelt trees and agricultural crops, which include growth rate and form, chemical composition of plant components, decomposition rate of dead organic matter, accumulation of litter layer, maximum rooting depth, changes in soil temperature and moisture from shading, and management frequency. The CBM-CFS3 model's afforestation module simulates the land-use change to a tree-based ecosystem by projecting an initial soil C loss caused by the reduction of crop residue C inputs into the soil. The initial soil C stocks in CBM-CFS3, at the time of tree planting, were assigned equal to the adjacent crop land.

The projected initial soil carbon loss in white spruce shelterbelts was in agreement with other studies of afforested agricultural land (Amichev et al., 2012; Davis and Condron, 2002; Paul et al., 2002). Generally, afforestation events resulted in approximately 3.5% annual C loss from the soil C pool (0–10 cm layer) in the first 5 years, relative to the initial soil C levels (Paul et al., 2002). The C levels in the surface soil layers recovered to pre-planting levels in older plantations (>30 years), and a net increase of 0.50–0.86% was measured in subsurface layers (Paul et al., 2002). Similarly, in a paired sites study of grassland afforestation in New Zealand, the effects of afforestation were observed mainly in the surface 0–10 cm soil layer where 9.5% soil C loss was estimated compared to pre-planting levels. However, after 20 years, there were no significant differences in the soil C levels between the afforested land and adjoining grassland sites (Davis and Condron, 2002). For Canadian conditions, Amichev et al. (2012) reported soil carbon loss during the first 6 years of short rotation coppice willow establishment on agricultural land was caused by the land-use change. In this current study, CBM-CFS3 simulations indicated that the shelterbelt ecosystem recovered from the initial soil carbon losses by approximately age 17 years. Carbon additions in shelterbelts were predicted in the litter layer, belowground and aboveground biomass, while soil carbon levels were projected to continue to decrease throughout the simulation period. Due to lack of data from older shelterbelts (>60 years), it was not possible to determine the number of years it would take to achieve the pre-planting soil carbon levels.

There is a lack of carbon sequestration studies in planted shelterbelts in Saskatchewan that could be used for comparison analyses. Although most hybrid poplar plantations were originally established for bioenergy feedstock production (Arevalo et al., 2009), there is a similarity with the white spruce shelterbelts in that both systems were established on agricultural land by an afforestation event (i.e., tree planting). Annual carbon stock additions in white spruce shelterbelts (2.2–4.1 Mg C ha^{-1} yr^{-1}) were within the carbon stocks range of 2–9-year-old hybrid poplar plantations in western Canada, 1.7–6.1 Mg C ha^{-1} yr^{-1} (Arevalo et al., 2009). The higher carbon values in these hybrid poplar plantations were likely due to the faster growth rate of younger hybrid poplar trees and a denser planting design (1600 trees ha^{-1}), when compared to the white spruce shelterbelts in the current study. The C simulations for white spruce in Saskatchewan reported in this paper were for shelterbelts planted at a much lower tree density (636 trees ha^{-1}) and based on assumed harvest age of 60 years. Per-ha shelterbelt *C* values in this current study were derived from CBM-CFS3 predictions (reported in per-km units) using the conversion factors in Section 2.4.1, and represented the C stocks for the area underneath the crowns of all live shelterbelt trees.

In shelterbelt studies elsewhere, one order of magnitude lower annual C stocks additions of 0.38 Mg C ha^{-1} yr^{-1} were reported for agroforestry systems (AFS) practices in the US (including alleycropping, and windbreaks) (derived from Nair et al., 2009). Similarly, lower C sequestration rates were estimated in hybrid poplar and white spruce windbreaks planted in North America, 0.73 and 0.37 Mg C ha^{-1} yr^{-1}, respectively (Udawatta and Jose, 2012). Udawatta and Jose (2012) estimated these rates based on published data for the US and Canada at assumed harvest age of 20 years and tree density of 40 trees ha^{-1}.

Udawatta and Jose (2012) reviewed recent work on CO_2 mitigation strategies based on planting AFS in temperate North America. They identified a lack of sufficient C studies for shelterbelt systems compared to much more abundant literature for alley cropping, riparian buffers, and silvopasture AFS. Udawatta and Jose (2012) and Nair et al. (2009) expressed concerns over the limitations of published AFS carbon data with regard to data accuracy and data standardizing. Nair et al. (2009) summarized some of the major methodological issues in regard to C sequestration estimation in AFS, the main difficulties being the area under agroforestry, stand age, tree biomass and belowground biomass estimation.

4.3. The 3PG and CBM-CFS3 models use in shelterbelt systems

A comparison between 3PG-modeled growth of white spruce trees planted in shelterbelt systems and those grown in forests, was beyond the scope of this work. However, in support of this analysis, we tested whether the 3PG model was suitably applied

Table 1
Sensitivity analysis results for white spruce shelterbelt tree growth simulations using the 3PG model. Changes (%) in the parameter values of total solar radiation intercepted by the tree canopy (*Radtn intcptn*) and light utilisation efficiency (*Epsilon*) were evaluated by changing (from −40% to +40%) each of the four light interception, production and respiration variables utilized by the 3PG model (*k, fullCanAge, alpha, Y*) and by changing three selected soil variables (*FR, MinASW, MaxASW*). Additionally, the same model sensitivity analysis was carried out for mean DBH and mean stem mass predictions. Bolded values indicate absolute change of parameter/prediction values > 5%.

[a]3PG variable	White spruce shelterbelt parameter		[b]Parameter/prediction value change					
	Value	Units	−40%	−20%	−5%	+5%	+20%	+40%
Decrease or increase (%) of Radtn intcptn; Epsilon parameters at age 60 yr								
k	0.500	–	0; 0	0; 0	0; 0	0; 0	0; 0	0; 0
fullCanAge	11.000	yr	0; 0	0; 0	0; 0	0; 0	0; 0	0; 0
alpha	0.030	–	0; **−40**	0; **−20**	0; **−5**	0; **5**	0; **20**	0; **40**
Y	0.470	–	0; 0	0; 0	0; 0	0; 0	0; 0	0; 0
FR	0.5419	–	0; **-10.6**	0; **−5.3**	0; −1.3	0; 1.3	0; **5.3**	0; **10.6**
MinASW	130	mm	0; **-22.4**	0; **−7.4**	0; −1.3	0; 0.6	0; 1.3	0; 1.3
MaxASW	180	mm	0; **-6**	0; 0	0; 0	0; 0	0; 0	0; 0
Decrease or increase (%) of mean DBH; Mean stem mass predictions at age 60 yr								
k	0.500	–	**−6**; −17.8	−2.1; **-6.4**	−0.4; −1.3	0.4; 1.1	1.3; 4	2; **6.6**
fullCanAge	11.000	yr	0; 0.1	0; 0.1	0; 0	0; 0	−0.1; −0.3	−0.3; −0.8
alpha	0.030	–	**−19.3; −49.5**	**−8.5; −24.7**	−2; **−6.2**	1.9; **6.1**	**7.2; 24.8**	**13.5; 49.5**
Y	0.470	–	**−19.3; −49.5**	**−8.5; −24.7**	−2; **−6.2**	1.9; **6.1**	**7.2; 24.8**	**13.5; 49.5**
FR	0.5419	–	−4.4; **−13.4**	−2.2; **−6.7**	−0.5; −1.7	0.5; 1.6	2; **6.6**	4; **13.4**
MinASW	130	mm	**−7.4; −21.6**	−2.5; **−7.8**	−0.5; −1.6	0.4; 1.3	1.1; 3.5	1.2; 4
MaxASW	180	mm	−2; **−6.3**	0; 0	0; 0	0; 0	0; 0	0; 0

[a] k = extinction coefficient for PAR absorption by canopy; fullCanAge = age at full canopy cover (along a tree row); alpha = maximum canopy quantum efficiency; Y = ratio NPP/GPP; FR = fertility rating; MinASW = minimum available soil water; MaxASW = maximum available soil water.
[b] Radtn intcptn = total solar radiation intercepted by canopy (7534 MJ m^{-2} $month^{-1}$); Epsilon = Light utilisation efficiency based on total biomass (0.3439 gDM MJ^{-1}); Mean DBH = stand-based mean DBH (33.7 cm); Mean stem mass = mean stem biomass per tree (483 kgDM $tree^{-1}$).

in shelterbelt systems, by using field data, collected from planted shelterbelt systems and used them to parameterize the 3PG model.

The *alpha* variable is a key variable in the 3PG model to estimate biomass production from intercepted radiation (Medlyn et al., 2003), and was parameterized in the current paper by using biomass and tree allometric data from harvested trees, which were collected from planted white spruce shelterbelt systems, and not from forest stands. This was purposely done because white spruce trees planted in shelterbelts have different growth patterns (i.e., different allometric relationships and *alpha*) than white spruce trees in a fully-stocked forest. Shelterbelt trees are defined as growing on agricultural soils and having a closed canopy only within the planted row, while trees in a forest have a closed canopy on all sides and grow on forest soils. Similar to the parametrization of the *alpha* variable, input soil variables were also parameterized using spatial data sets that were specific to the location of planted white spruce shelterbelts, and not from white spruce forest stands. Simulated light utilization efficiency of trees is also affected by input, site-specific soil fertility and available soil water data, which were incorporated in the algorithms of the 3PG model thereby reflecting a widely studied and well-known interaction between soil properties and tree growth.

The suitability of the CBM-CFS3 model for use in shelterbelt systems was assured by using appropriate shelterbelt-specific tree growth data (annul tree growth curves), which we derived with the 3PG model. Specific parameters within the CBM-CFS3 model, such as the sapling and non-merchantable components, were eliminated from the shelterbelt C estimates. However, the dead organic matter estimates in CBM-CFS3 could be biased depending on how individual land owners dealt with dead trees within their own shelterbelt systems. For example, if dead wood or branches were removed by the land owner, then dead organic matter pool estimates from the model could be larger than observed. Simulation of land owner' choices of dead wood removal was beyond the scope of this work. However, our field observations and expert knowledge of the shelterbelt systems support the argument that removing trees is costly to the land owner and any dead shelterbelt trees were often just pushed back (out of the way of cropping machinery) into the shelterbelt system where they decomposed.

5. Conclusions

The 3PG and CBM-CFS3 models were applied successfully to estimate tree growth and carbon sequestration in shelterbelt systems. This represents the first modelling of these types of agroforestry systems in Canada. Accuracy of the simulations for the models could be improved with more field sampling suggesting that these types of modelling endeavors would be very resource intensive at large scales. The 991 km of white spruce shelterbelts in Saskatchewan, Canada accounted for carbon additions of 106–195 Mg C km^{-1} with total cumulative carbon additions were estimated at 50,440 Mg C during an eight decade period of shelterbelt simulations. Although white spruce represents a small portion of all shelterbelt species planted across Saskatchewan, these results suggest that planted shelterbelts as a whole could contribute to mitigating greenhouse gas emissions by sequestering C in the biomass, dead organic matter and soil. If shelterbelts are to play a role in mitigating future greenhouse gasses emissions then further research is warranted to estimate biomass growth and C sequestration potential in a changing climate to determine which species to plant to maximize carbon sequestration into the future. The maps generated in this study provide an indication of the regions in Saskatchewan that are best suited for shelterbelt expansion.

Conflict of interest statement

All co-authors of this manuscript confirm that there are no conflicts of interest.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.ecolmodel.2016.01.003.

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