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Mapping and quantification of planted tree and shrub shelterbelts in Saskatchewan, Canada

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Abstract The Government of Canada's farm assistance programs have affected >80 % of Canada's agricultural land base. One important program in the Prairie Provinces was the prairie shelterbelt program (PSP). A significant aspect of the PSP was shelterbelt tree planting to protect farmyard infrastructure and reduce soil erosion. The main goal of this paper was to map historical shelterbelt establishment, total expected shelterbelt length, and total expected number of six common planted shelterbelt species: caragana (*Caragana arborescens*), green ash (*Fraxinus pennsylvanica*), Manitoba maple (*Acer negundo*), Scots pine (*Pinus sylvestris*), white spruce (*Picea glauca* Monch), and hybrid poplar (*Populus* spp.). A clustering approach was designed to group all agricultural ecodistricts (106 total) into clusters (31 total) based on their similarity in 42 variables within five soil zones of Saskatchewan. Correlations between trees ordered through the PSP and observed shelterbelt length (across 2.1 Mha cumulative study area) were used for shelterbelt probability mapping. Mapping accuracy of planted shelterbelts was 48–86 %. Total shelterbelt length (of any species) ranged from 322 to 45,231 km for (in descending order) dark brown > brown > black > dark gray > gray soil zones. Novel decadal time-lapse maps and species-specific shelterbelt maps were produced to capture the progression of shelterbelt establishment for the first time at a province-wide scale which gave a new perspective, in map format, of the expansive impact of the living legacy of the PSP. Shelterbelt data gaps and high priority clusters of agricultural land in Saskatchewan were identified for future shelterbelt research.

Keywords Prairie farm rehabilitation administration (PFRA) · Shelterbelt distribution · Ecodistricts · Decadal shelterbelt maps · Soil zones · Species-specific shelterbelt length

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Introduction

Federal programming supported the planting of prairie shelterbelts since 1901, including provision of seedlings through the federal tree nursery at Indian Head, Saskatchewan and, beginning in 1935, special support for establishing field shelterbelts for erosion control under the Prairie Farm Rehabilitation Act. Throughout the period of 1901 to 2013, seedlings have been provided for protecting farmyards, fields and for other environmental plantings. Shelterbelts also limit animal waste odours from farms, lower the risk of crop damage due to pesticide spray-drift, as well as minimize the risk of potential flooding on farms and fields (Wiseman et al. 2009). Shelterbelts also serve as wildlife habitat, improve biodiversity and water quality, and capture and store atmospheric carbon as a direct result of the growth of shelterbelt trees (Kulshreshtha et al. 2011).

For nearly two decades Canada was interested in the potential of shelterbelts to capture and store atmospheric carbon (Kort and Turnock 1999). Although species-specific shelterbelt characteristics were studied and reported by Kort and Turnock (1999), there is still a lack of shelterbelt distribution maps and overall shelterbelt length data encompassing all of the agricultural land in Saskatchewan. Such maps and data are needed for province-wide carbon capture and storage studies. Therefore, a new approach was designed and applied in this paper to produce a probability map of shelterbelt establishment across Saskatchewan. The specific objectives of this paper were to: (i) identify a manageable number of homogeneous land units across agricultural Saskatchewan for shelterbelt data analysis; (ii) create a probability map of all shelterbelts planted in Saskatchewan from 1925 to 2009 with emphasis on six common shelterbelt species: caragana (CG; *Caragana arborescens* Lam.), green ash (GA; *Fraxinus pennsylvanica* Marsh), Manitoba maple (MM; *Acer negundo* L.), Scots pine (SP; *Pinus sylvestris* L.), white spruce (WS; *Picea glauca* Monch Voss.), and hybrid poplar (HP; *Populus* spp.); (iii) quantify shelterbelt distribution and length for the homogeneous land units within the five soil zones of the province; and (iv) identify and map high priority agricultural areas in the province for future shelterbelt research.

Materials and methods

Data sources

Ecodistricts of agricultural Saskatchewan

Thirty-two climatic, site, and soil variables (Table 1) summarized at the ecodistrict level were obtained

Table 1 Forty-two variables used in clustering of homogeneous ecodistricts into groups across agricultural Saskatchewan, Canada

No.	Variable	Units	Source
1	Mean elevation	m	Nat. Ecol. Fram. of Canada
2	Growing season start	Julian day	Nat. Ecol. Fram. of Canada
3	Growing season length	day	Nat. Ecol. Fram. of Canada
4	Growing degree-days >0 °C	degree-day	Nat. Ecol. Fram. of Canada
5	Growing degree-days >5 °C	degree-day	Nat. Ecol. Fram. of Canada
6	Mean annual potential evapotranspiration	mm	Nat. Ecol. Fram. of Canada
7	Mean annual precipitation deficit	mm	Nat. Ecol. Fram. of Canada
8	Total annual precipitation	mm	Nat. Ecol. Fram. of Canada
9	Mean daily solar radiation	MJ/m^2/day	Nat. Ecol. Fram. of Canada
10	Mean bright sunshine	h	Nat. Ecol. Fram. of Canada
11	Mean air temperature	°C	Nat. Ecol. Fram. of Canada
12	Minimum Air Temperature	°C	Nat. Ecol. Fram. of Canada
13	Maximum air temperature	°C	Nat. Ecol. Fram. of Canada
14	Mean dew-point temperature	°C	Nat. Ecol. Fram. of Canada
15	Mean vapour pressure	kPa	Nat. Ecol. Fram. of Canada
16	Mean hourly wind speed	km/h	Nat. Ecol. Fram. of Canada
17	LANDCOVER: Forest	% of ecodistrict area	Nat. Ecol. Fram. of Canada
18	LANDCOVER: Cropland	% of ecodistrict area	Nat. Ecol. Fram. of Canada
19	LANDCOVER: Rangeland	% of ecodistrict area	Nat. Ecol. Fram. of Canada
20	LANDFORM: Hilland	% of ecodistrict area	Nat. Ecol. Fram. of Canada
21	LANDFORM: Plain	% of ecodistrict area	Nat. Ecol. Fram. of Canada
22	LANDFORM: Plateau	% of ecodistrict area	Nat. Ecol. Fram. of Canada
23	MATERIAL: Mineral soil	% of ecodistrict area	Nat. Ecol. Fram. of Canada
24	MATERIAL: Organic soil	% of ecodistrict area	Nat. Ecol. Fram. of Canada

Table 1 continued

No.	Variable	Units	Source
25	SURFICIAL GEOLOGY: Till blanket	% of ecodistrict area	Nat. Ecol. Fram. of Canada
26	SURFICIAL GEOLOGY: Till veneer	% of ecodistrict area	Nat. Ecol. Fram. of Canada
27	SURFACE: Dissected	% of ecodistrict area	Nat. Ecol. Fram. of Canada
28	SURFACE: Hummocky	% of ecodistrict area	Nat. Ecol. Fram. of Canada
29	SURFACE: Undulating	% of ecodistrict area	Nat. Ecol. Fram. of Canada
30	PM TEXTURE: Clay	% of ecodistrict area	Nat. Ecol. Fram. of Canada
31	PM TEXTURE: Loam	% of ecodistrict area	Nat. Ecol. Fram. of Canada
32	PM TEXTURE: Sand	% of ecodistrict area	Nat. Ecol. Fram. of Canada
33	Available water holding capacity	mm	SLC 3.2
34	Depth to root-restricting soil layer	cm	SLC 3.2
35	Slope	%	SLC 3.2
36	Coarse fragments content, 0–50 cm depth	%	SLC 3.2
37	Coarse fragments content, 50–100 cm depth	%	SLC 3.2
38	Soils characteristic to black zone	% of ecodistrict area	SLC 3.2
39	Soils characteristic to dark_brown zone	% of ecodistrict area	SLC 3.2
40	soils characteristic to brown zone	% of ecodistrict area	SLC 3.2
41	Soils characteristic to dark_gray zone	% of ecodistrict area	SLC 3.2
42	soils characteristic to gray zone	% of ecodistrict area	SLC 3.2

[a] Variables 17–32 are categorical classes from six categorical variable groups from the National Ecological Framework of Canada dataset. The 16 categorical variables selected for all analyses, and shown in this table, represent the dominant categories across the ecodistricts of Saskatchewan and do not sum to 100 % of the ecodistrict area. For example, in the LANDCOVER categorical group, cropland and rangeland variables represent 100 % of the area, but in the SURFACE categorical group, only 89 % of the area by the selected variables

from the national ecological framework for Canada dataset (Marshall et al. 1999) and were used for grouping of homogeneous ecodistricts into clusters. The values used in our analyses were either the mean, minimum, maximum, total or majority values.

Ten additional variables were obtained from the most recent edition (version 3.2) of the soil landscapes of Canada dataset (SLC) (SLC 2010) (Table 1). Each ecodistrict was assigned the designation of one of five soil zones in agricultural Saskatchewan (black, brown, dark brown, dark gray, or gray) based on majority area representation of all soil types found in each ecodistrict. The spatial extent of the provincial soil zones defined the boundaries of five land domains (i.e., lands falling within each of the five soil zones) within which we performed the clustering analysis by identifying homogeneous ecodistricts and grouping them together into clusters by their similarity in all variables listed in Table 1.

PSP tree orders database and spatial data processing

All shelterbelt tree orders shipped through the prairies shelterbelt program (PSP) from 1925 to 2009 were analyzed using shelterbelt species, the year and quantity shipped as well as the legal land description where orders were sent (Fig. 1). Although the PSP database contained shelterbelt tree orders made post-2009, the analysis in this paper was limited to orders up to and including 2009. This was done because the majority, if not all, shelterbelts planted after 2009 may not appear on the FlySask aerial imagery (SGIC 2013) which we used for on-screen digitizing of established shelterbelts.

To avoid inclusion of mistaken (or unrealistic) large- or low-quantity tree orders in our analyses, several assumptions were made. First, only tree orders with <1,00,000 trees per order were used, as verification of any high-quantity orders was not possible. Second, species names for each order were carefully analyzed to accurately group quantities of the same species, listed under different names. For example, hybrid poplar orders included the sum of orders of all poplar hybrids distributed through the PSP, such as 'Walker Poplar', 'Assiniboine Poplar', 'Brooks Poplar', etc., for a total of thirty-one different poplar hybrids. Lastly, for all shelterbelt tree orders a minimum limit of 50 trees per order was set (i.e., the equivalent of a 100 m single-row shelterbelt at 2 m spacing) in order to avoid inclusion of mistaken (or unrealistic) low-quantity tree orders.

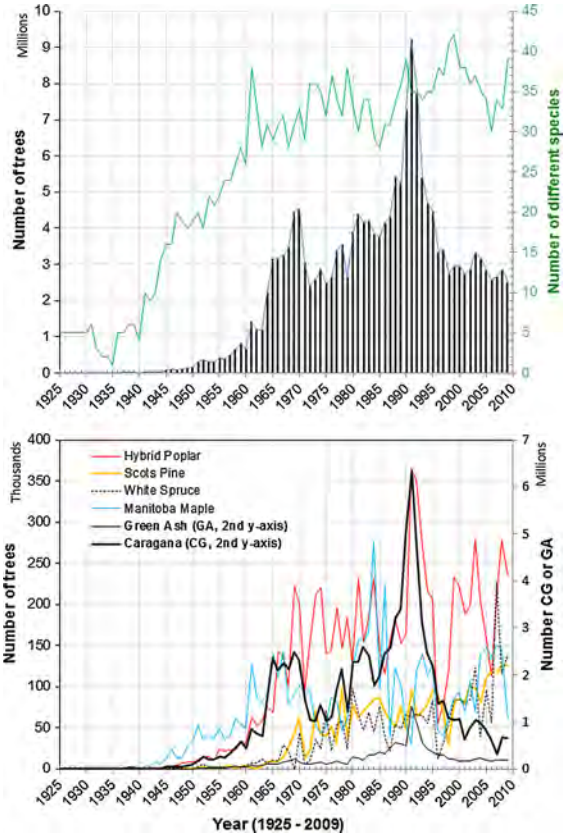


Fig. 1 Historic records for the 1925–2009 period of the total annual number of shelterbelt trees and species ordered (*top*), and annual number of six common shelterbelt species ordered (*bottom*) through the PSP in Indian Head, Saskatchewan

Grouping of homogeneous ecodistricts into clusters

Clustering analysis was performed on similar ecodistricts using the PROC CLUSTER procedure in SAS software (SAS Institute 2013) using the 42 variables in Table 1. All analyses were performed separately within each soil zone and all variables were standardized to mean of zero and standard deviation of one. In order to evaluate the performance of the clustering process, we completed an outlier identification analysis using the PROC UNIVARIATE procedure in SAS software, for each cluster and each variable that were used in the clustering process. The intended use of the outlier identification analysis was to quantify the degree of similarity between ecodistricts grouped together in a cluster, as well as to identify the possible ecodistrict outliers (i.e., values that are farther away from the mean) and probable ecodistrict outliers (i.e., values that are farthest away from the mean) within each cluster.

Probability mapping of planted shelterbelts in Saskatchewan

On-screen digitizing of planted shelterbelts

Planted shelterbelts on farmyards and agricultural fields were manually digitized across the five soil zones of Saskatchewan in randomly selected 10-km radius circle areas using ArcMap software (ESRI 2010) and FlySask aerial photos (SGIC 2013) at 0.62 m resolution pixel size as background imagery. For areas where FlySask data were not currently available, panchromatic SPOT-5 satellite data (SGIC 2013) at 2.5 m pixel size was used as background imagery.

Sixty-eight 10-km-radius circle areas (2.13 million ha) were completed for the correlation modeling analysis and 67 circles (2.10 million ha) were completed for the results validation analysis. In the remainder of this paper, these 68 and 67 ten-km radius circle areas datasets are referred to as the correlation modeling set and validation set, respectively.

Creating shelterbelt probability maps

Although all tree orders in the PSP database were documented in regard to quarter-section land location, date, species, and quantity of trees, there was no information as to where exactly the trees were actually planted. To account for the fact that some ordered shelterbelt trees may be translocated to nearby farmsteads, we assumed that the overall estimated shelterbelt tree density of a given cluster would also apply to the individual quarter-section land locations within this same cluster. To estimate the overall tree density, all trees sent to all quarter-section lands within a given cluster were summed and this quantity was divided by the number of hectares comprising the entire cluster. Shelterbelt probability was estimated using Eq. 1.

$$\begin{aligned} &\textit{Shelterbelt probability}_i(\%) \\ &\quad = \frac{(\textit{Number cells with digitized shelterbelts}_i)}{(\textit{Total number cells in digitized area}_i)} * 100 \end{aligned} \quad (1)$$

where $\textit{Shelterbelt probability}_i$ = percent probability that shelterbelts were planted on the area of a given raster cell (1 × 1 km cell size = 100 ha land) to where a range i of expected number of ordered shelterbelt trees (i.e., SumNtrees) was set, $i = 0$–100, 100–200,…, etc., 6,900–7,000 (multiples of 100); $Number\ cells\ with\ digitized\ shelterbelts_i$ = total number of 1 × 1 km raster cells with a range of i SumNtrees that contained one or more digitized shelterbelts; $Total\ number\ cells\ in\ digitized\ area_i$ = total number of 1 × 1 km raster cells with a range of i SumNtrees within digitized area.

Making decadal, time-lapse series of shelterbelt maps (1925–2009)

The temporal attribute of the shelterbelt probability map was utilized to map the land areas across the province where shelterbelts may have been planted during a specific time. Decadal time periods (i.e., 1925–1930, 1930–1940 to 2000–2009) were chosen to make decadal time-lapse series of maps representing cumulative change in shelterbelt establishment using any shelterbelt species sent through the PSP Center.

Species-specific shelterbelt maps: number of trees, location and accuracy assessment

Species-specific shelterbelt maps were created using the same procedure for making shelterbelt probability and decadal maps. In order to evaluate the accuracy of the species-specific shelterbelt distribution maps, a total of 99 independent shelterbelts were sampled by field crews across the five soil zones of Saskatchewan. The data recorded in the field included shelterbelt age, design (such as number of rows) and a list of the different species planted in each shelterbelt.

The accuracy assessment analysis of the species-specific maps included estimation of the percent of accurately mapped field data, as well as omission and commission errors of the map predictions (Short 2008). The accuracy assessment completed in this paper was adapted for multi-species shelterbelts.

Province-wide expected shelterbelt length: estimation and evaluation

Prediction equations were developed for the estimation of both farmyard and total (i.e., farmyard + agricultural field) shelterbelt lengths, which were done separately for each soil zones, using the correlation modeling dataset of digitized shelterbelts and the total number of trees ordered by landowners from 1925 to 2009. Expected shelterbelt length for all quarter-section land locations was then estimated with these prediction equations using the tree orders in the PSP database. Finally, expected shelterbelt length was summarized by cluster and by soil zone.

The prediction equations were of the type $L = a * T^b$, where L = shelterbelt length, T = number of trees ordered, a and b were equation coefficients. The prediction equations were evaluated using the validation dataset of digitized shelterbelts.

Statistical analysis

The validation dataset of digitized shelterbelts was used to evaluate the shelterbelt length predictions by estimating an overall percent root mean square error (RMSE, %) in Eq 2, and estimating bias (%) in Eq 3, of all shelterbelt length predictions by soil zone.

$$RMSE\ (\%)\ of\ shelterbelt\ length = \frac{\sqrt{\frac{\sum_{i=1}^{N}(Observed_i - Estimated_i)^2}{N}}}{(Mean\ Observed)} * 100 \quad (2)$$

$$Bias\ (\%)\ of\ shelterbelt\ length = \frac{\sum_{i=1}^{N}\frac{(Observed_i - Estimated_i)}{(Observed_i)}}{N} * 100 \quad (3)$$

where $Observed_i$ is the digitized and $Estimated_i$ is the predicted total length (km) of all shelterbelts present in the ith 10-km-radius circle area; N is the number of 10-km-radius circle areas in the validation data set; *Mean Observed* is an estimate of the total length of all shelterbelts per 10-km-radius circle area, averaged across all 67 areas in the validation set; negative bias indicated overestimation and positive bias indicated underestimation of shelterbelt length.

Results

Map of clusters of homogeneous ecodistricts

The clustering approach grouped similar ecodistricts within the five soil zones of agricultural Saskatchewan into clusters for modeling purposes. A total of 31 clusters (comprising 106 ecodistricts) were identified and mapped by the similarity of each ecodistrict to all other ecodistricts within a given soil zone (Fig. 2).

Depending on the variability among same-soil-zone ecodistricts, there were 1 to 9 ecodistricts in a given cluster and 4 to 8 clusters in a given soil zone (Fig. 2).

An outlier identification analysis evaluated the performance of the clustering process, by quantifying the degree of similarity between ecodistricts grouped in a given cluster. On average, 98.9 % of ecodistricts in a given cluster were non-outliers (i.e., were similar to each other) and 94.5 % of all 31 clusters were without any outlier ecodistricts. This high similarity between ecodistricts in any cluster was achieved because no ecodistricts were removed in the clustering process and, instead, they were grouped together with other ecodistricts by similarity, or they were put into a cluster of their own (Fig. 2). Therefore, seven clusters (of 31 total) comprised single ecodistricts, and 12 (of 31 clusters) included <= 2 ecodistricts (Fig. 2).

Probability maps and time-lapse series maps of shelterbelt establishment

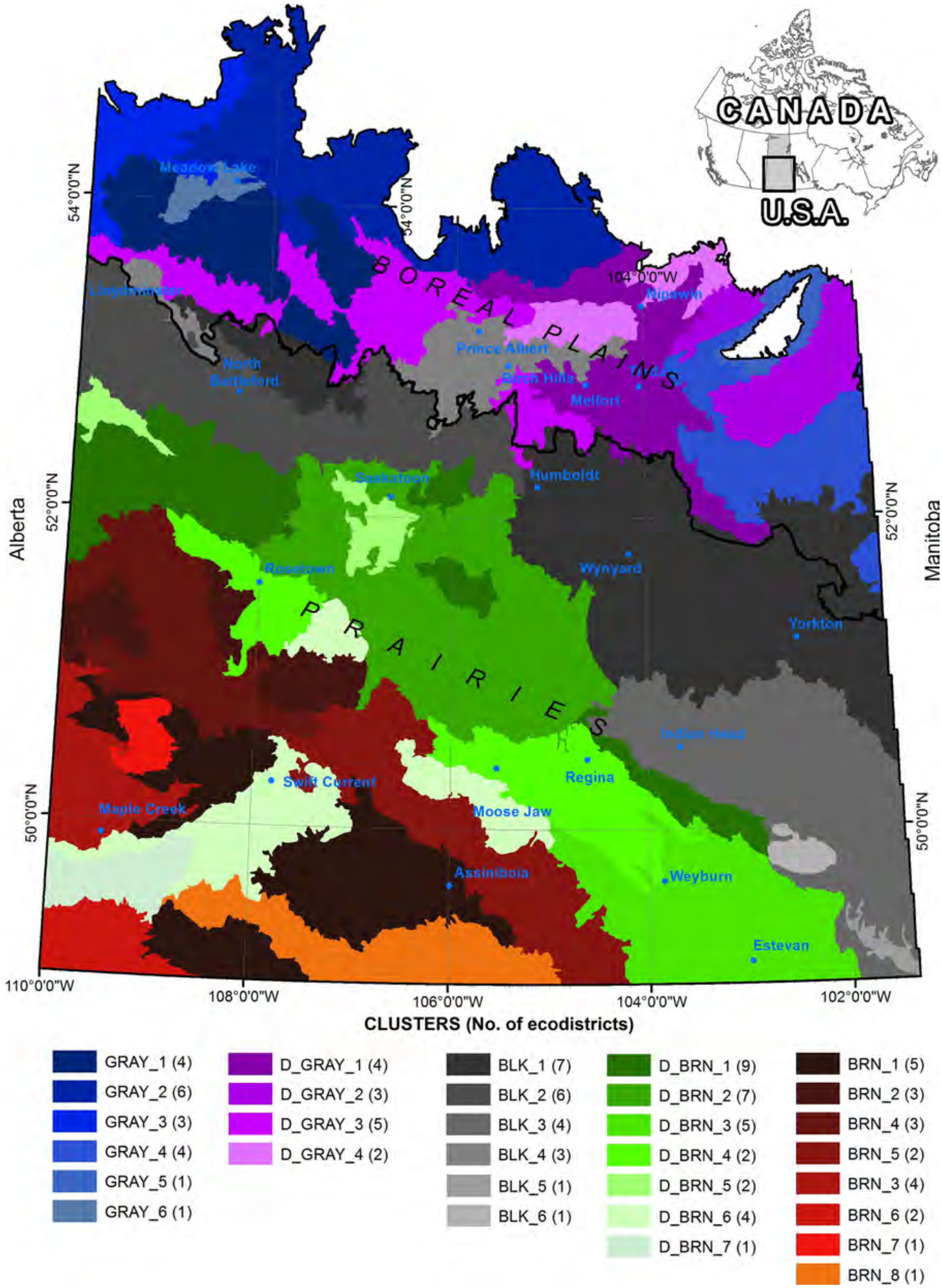
Cumulative shelterbelt lengths of 3,114 and 5,031 km were digitized for the correlation modeling set (i.e., 68 ten-km radius circle areas) and for the validation set (i.e., 67 ten-km radius circle areas), respectively. Overall, across all 10-km-radius circle areas of the correlation modeling set of digitized shelterbelts, the probability map correctly identified the location of 95 % of all shelterbelts. This was equivalent to accurately identifying the location of 2,959 km (of a total of 3,114 km) of all digitized shelterbelts, of any length, across 2.1 Mha of land spanning five soil zones in Saskatchewan. Although probability values in the shelterbelt map ranged from 25 to 100 %, the majority of observed shelterbelts were mapped with 60–70 % probability, which applied to 1,219 km (of total identified of 2,959 km), and 93 % of all digitized shelterbelts were mapped with >=45 % probability. A 45 % probability map value indicates there was a shelterbelt planted (of any length and any species) on 1-of-2 (i.e., one of any two) raster cells of the shelterbelt probability map.

Annually ordered trees for shelterbelt planting in Saskatchewan increased exponentially during the period 1925–1991, increasing from 1,000 trees year^{-1} to 9.2 million trees year^{-1}, respectively (Fig. 1). A moderate and steady decline of shelterbelt tree orders was observed in the post-1991 period where the 2009 annual tree orders, 2.5 million trees year^{-1}, were about a quarter of the number of trees ordered in 1991. On average, the number of different species annually ordered by landowners across Saskatchewan increased asymptotically from 5 (in the 1930s) to 37 (in the 2000s) through a gradual increase from 1935–1970, when a plateau was reached (Fig. 1). Notable annual peaks of shelterbelt tree orders in 1961, 1970, 1981 and 1991 are likely due to the result of landowners receiving relevant information (e.g. brochures and hand-outs) from the PSP Center at events such as agricultural fairs and shows, etc., organized in prior years, or following periods of prolonged drought (e.g., drought in the 1980s leading to the 1990 peak) (Kulshreshtha et al. 2011). The total number of six common shelterbelt species ordered in the period 1925–2009 by landowners across the province ranged from 1.5 to 64.6 million (in descending order) for CG > GA > HP > MM > SP > WS (Fig. 1).

The shelterbelt time-lapse series of maps reflected the relative temporal trends described above. The 1930s to 1960s maps indicated the initial localized small land areas of shelterbelt establishment sparsely distributed across four soil zones of Saskatchewan, excluding the gray soil zone in the northernmost agricultural land (Fig. 3). In the gray soil zone, there were relatively fewer quarter-section land locations with lower quantities of tree orders at that time period which was reflected by relatively lower shelterbelt probability areas on the maps. No distinct trends were observed for any soil zones in regard to shelterbelt establishment.

In the 1970s and 1980s, there was a dramatic increase in shelterbelt trees shipped to landowners through the PSP Center and the localized areas of initial shelterbelt establishment expanded further (Fig. 3). In the 1990s and 2000s, when the peak of shelterbelt tree shipments occurred, an order of magnitude more trees were sent to landowners compared to the 1960s, and more specific spatial shelterbelt distributions became obvious. More specifically, agricultural land across all of the dark brown and the eastern third of the brown soil zones were mapped with higher probabilities relative to the black, dark

Fig. 2 Map of sub-soil zone clusters in Saskatchewan ▶ where106 ecodistricts (Marshall et al. 1999) were clustered in 31 clusters by their similarity in 42 site, soil, and climatic variables listed in Table 1



CANADA
U.S.A.
Alberta
Manitoba
BOREAL PLAINS
PRAIRIES
54°0'0"N
52°0'0"N
50°0'0"N
104°0'0"W
110°0'0"W
108°0'0"W
106°0'0"W
102°0'0"W
Meadow Lake
Lloydminster
North Battleford
Prince Albert
Birch Hills
Melfort
Nipawin
Saskatoon
Humboldt
Wynyard
Rosetown
Yorkton
Indian Head
Regina
Swift Current
Moose Jaw
Maple Creek
Assiniboia
Weyburn
Estevan
CLUSTERS (No. of ecodistricts)
GRAY_1 (4)
GRAY_2 (6)
GRAY_3 (3)
GRAY_4 (4)
GRAY_5 (1)
GRAY_6 (1)
D_GRAY_1 (4)
D_GRAY_2 (3)
D_GRAY_3 (5)
D_GRAY_4 (2)
BLK_1 (7)
BLK_2 (6)
BLK_3 (4)
BLK_4 (3)
BLK_5 (1)
BLK_6 (1)
D_BRN_1 (9)
D_BRN_2 (7)
D_BRN_3 (5)
D_BRN_4 (2)
D_BRN_5 (2)
D_BRN_6 (4)
D_BRN_7 (1)
BRN_1 (5)
BRN_2 (3)
BRN_4 (3)
BRN_5 (2)
BRN_3 (4)
BRN_6 (2)
BRN_7 (1)
BRN_8 (1)

gray and gray soil zones (Fig. 3). Beginning in the 1970s and gradually becoming localized 'hot spots' of shelterbelt establishment in 1990–2009, the agricultural land areas around the cities of Saskatoon, SK and Indian Head, SK were distinctly mapped with the highest shelterbelt probability in the province. These hotspots are likely due to federal tree nursery being established in 1901 at Indian Head which was later joined by a sub-station, a second seedling nursery that operated from 1913 to 1965 at Saskatoon.

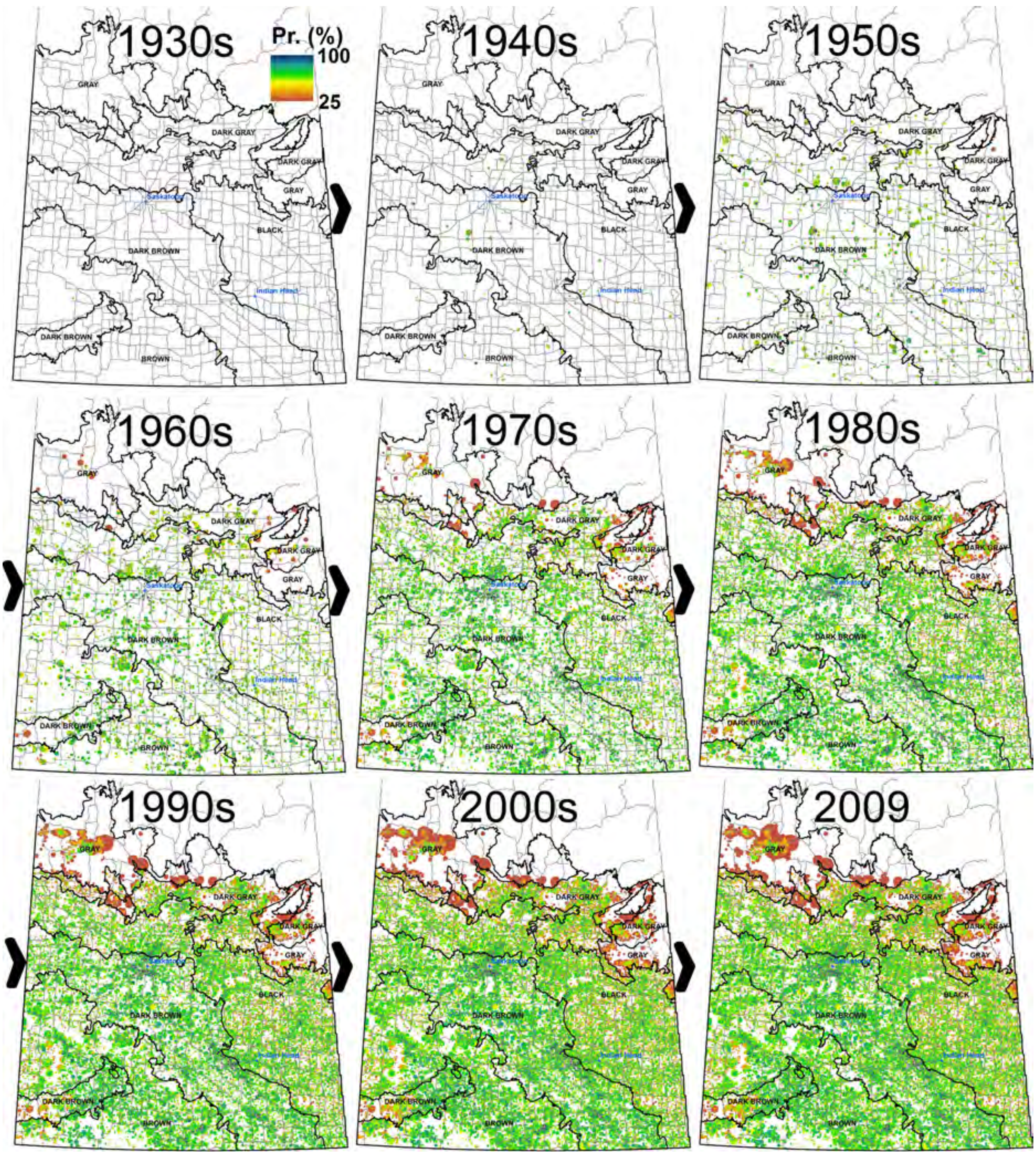


Fig. 3 Decadal time-lapse (1925–2009) series of probability (%) maps of expected shelterbelt establishment in Saskatchewan

Province-wide shelterbelt maps for six species

Using the shelterbelt probability map as a background layer, the expected total number of trees per 100 ha was mapped across the five soil zones of Saskatchewan (Fig. 4). The expected number of trees for each of the six species varied from 30 to 764, 13 to 592, 30 to 758, 8 to 313, 20 to 1,303 and 250 to 5,868 trees per 100 ha for HP, SP, MM, WS, GA and CG, respectively (Fig. 4). The estimated total agricultural area where HP, SP, MM, WS, GA and CG were used for planting shelterbelts was 7.1, 5.2, 4.7, 5.4, 11.5 and 9.7 million ha, respectively (Fig. 4).

Although the expected spatial distribution of the six species spanned across all five soil zones in Saskatchewan the relative number (per 100 ha) differed across the province. For example, relatively higher numbers of WS, SP and MM shelterbelt trees were mostly in the dark brown, black, and dark gray soil zones, while CG was predominantly in the brown, dark brown and black soil zones; and HP and GA uniformly existed in all five soil zones (Fig. 4).

The accuracies of all shelterbelt distribution maps analyzed for each of the six species, across the five map probability levels, are summarized in Table 2. The overall mapping accuracy (across any map probability) ranged from 52 to 74 % (in descending order) for WS (74 %) > SP (72 %) > MM = CG (69 %) > HP (57 %) > GA (52) (Table 2). The overall mapping accuracy accounted for an accurate match in two mapping classes: 'species in shelterbelt' class and 'no species in shelterbelt' class. The mapping accuracy of individual classes accounted for data omissions and commissions and was generally lower than the overall mapping accuracy.

In general, no specific trends were observed between shelterbelt probability levels and mapping accuracy since probability levels indicated the chance that shelterbelts (of any species) may be present on a given area while mapping accuracy indicated presence of a specific species (of the six species of interest). Identified areas with higher mapping accuracy, including estimated area and total number of planted shelterbelt trees (Table 2) of a given species, could be used as priority areas for site selection in future shelterbelt research.

Expected total shelterbelt length and priority ranking of clusters

The total shelterbelt length (of any species) ranged from 322 to 45,231 km for (in descending order) dark brown > brown > black > dark gray > gray soil zones (Fig. 5). The total length of shelterbelts in the dark brown and brown soil zones was an order of magnitude more than in the black and dark gray soil zones. The top five clusters with the largest shelterbelt length (6,509–13,561 km) were all located in the dark brown soil zone and the bottom five clusters with smallest shelterbelt length (<40 km) were located in the black and gray soil zones (Fig. 5).

The total area distribution of shelterbelts (of any species) was estimated as percent of the cluster (or soil zone) area (Fig. 5). On average, shelterbelts were planted on 34–75 % of the entire area of (in descending order) black > dark brown > brown > dark gray > gray soil zones. The shelterbelt distribution varied greatly across individual clusters ranging from 22 to 84, 43 to 77, 59 to 78, 52 to 75, and 52 to 72 % in the gray, dark gray, black, dark brown, and brown soil zones, respectively (Fig. 5).

The top ten clusters with largest expected shelterbelt length were identified as high priority areas for future shelterbelt research (Fig. 6). The cumulative shelterbelt length in these clusters (53,538 km) represented 88 % of the cumulative length of all shelterbelts in the province, which was estimated at 60,633 km (Fig. 5). The total area represented by the high priority clusters was nearly half (14.2 million ha) of the cumulative area of all 31 clusters, which was estimated 33.5 million ha.

The shelterbelt length prediction equations reported in this paper allowed for separate estimations of length of farmyard and field shelterbelts; length of field shelterbelts was estimated as the difference between the length of all and farmyard shelterbelts (Table 3). The estimation error associated with predicted length of farmyard shelterbelts (i.e., RMSE, %) was 24–60 % (in ascending order) for clusters in the brown < dark brown < black < gray = dark gray soil zones (Table 3). Bias of farmyard shelterbelt length predictions was from −110 to 10 % indicating both length overestimation, mainly in the dark gray and gray soil zones and underestimation, in the black and dark brown soil zones. The range of RMSE and bias, across soil zones, associated with predicted length of all (farmyard and field combined) shelterbelts was similar to farmyard shelterbelts (Table 3).

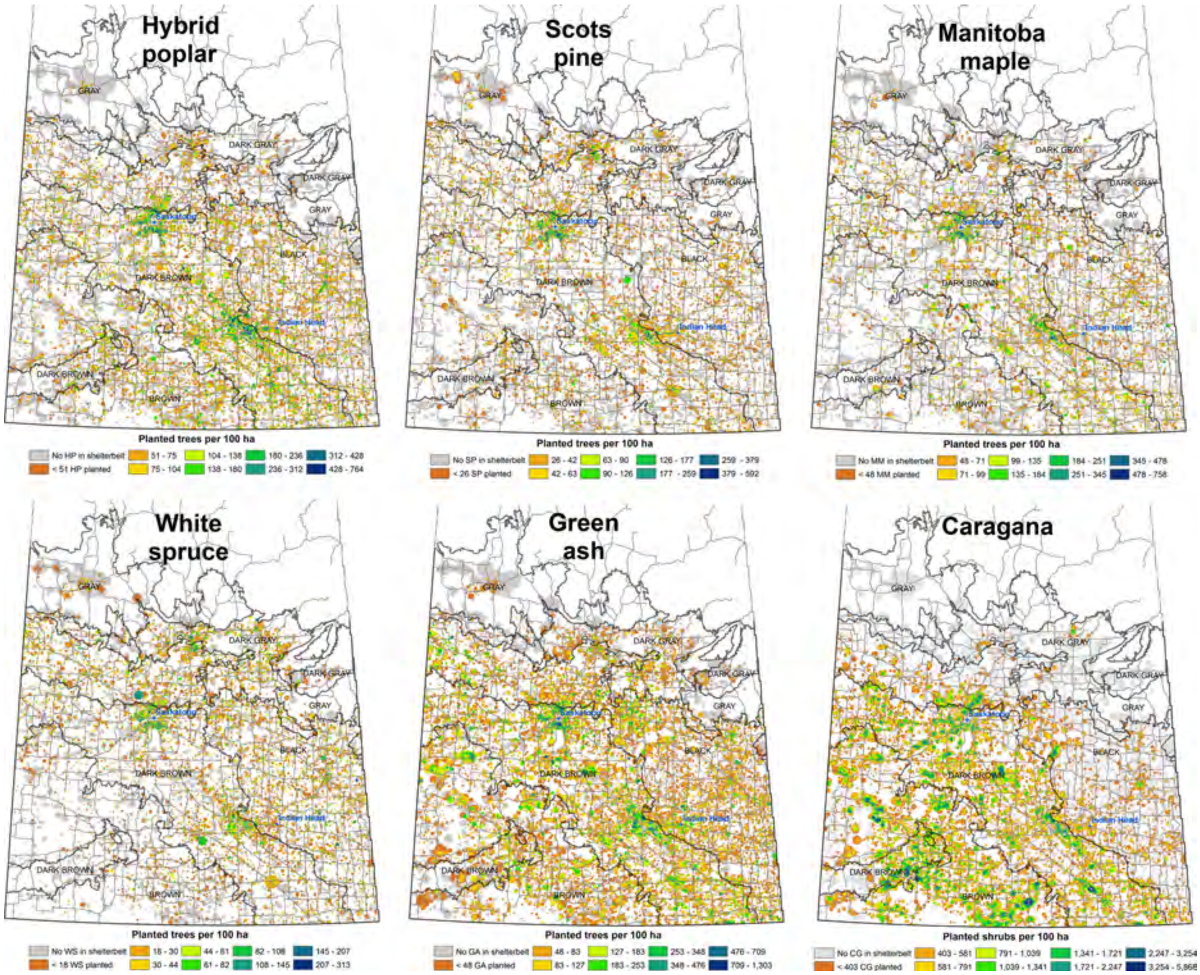


Fig. 4 Shelterbelt maps of estimated number of planted trees (or shrubs) per 100 ha of agricultural land in Saskatchewan, for six common shelterbelt species: *HP* hybrid poplar, *SP* scots pine, *MM* manitoba maple, *WS* white spruce, *GA* green ash, *CG* caragana

Discussion and conclusions

Clustering of ecodistricts

Similar to the clustering method presented in Amichev et al. (2012), the clustering approach used in this paper was necessary to group homogeneous ecodistricts in Saskatchewan, by their similarity in site, soil, and climatic characteristics, into a more manageable number of analytical units. In comparison to the approach by Amichev et al. (2012), the clustering method in this paper used an expanded number of variables (forty-two) and the smallest land units were ecodistricts.

There are 106 agricultural ecodistricts within Saskatchewan that span across five soil zones (Marshall et al. 1999). In general, the goal of the clustering procedure was to use the finer spatial resolution of an ecodistrict, relative to a soil zone, while reducing the number of analytical units (i.e., clusters) from the total of 106. A high similarity of ecodistricts within each cluster was achieved by treating unique ecodistricts as a cluster of their own which made the clustering approach applicable to other modeling projects.

Shelterbelt probability mapping

Similar to using satellite imagery data where visual or hyper-spectral sensor data is correlated with field data (Pankiw and Piwowar 2010), existing correlations

Table 2 Shelterbelt mapping accuracy assessment for six common shelterbelt species in Saskatchewan, Canada

Species	Mapped class	Map probability level (%)	Omissions (%)	Commissions (%)	Mapping accuracy (%)	Predicted area of planted trees (ha)	Predicted number planted trees (–)
Hybrid poplar (HP)	HP in shelterbelt	0–100	21	128	35	7,148,100	5,684,728
		0–50	50	100	50	329,600	240,070
		50–60	67	167	13	3,002,300	2,130,159
		60–70	0	375	21	2,488,800	2,099,107
		70–100	14	50	57	1,327,400	1,215,392
	No HP in shelterbelt	0–100	53	9	43	–	–
		0–50	50	0	50	–	–
		50–60	43	17	48	–	–
		60–70	63	0	38	–	–
		70–100	54	15	40	–	–
	All HP classes	0–100	–	–	57	–	–
		0–50	–	–	67	–	–
		50–60	–	–	52	–	–
		60–70	–	–	46	–	–
		70–100	–	–	67	–	–
Scots pine (SP)	SP in shelterbelt	0–100	39	117	28	5,237,300	1,966,654
		0–50	92	33	25	463,200	155,512
		50–60	20	60	50	2,126,600	718,762
		60–70	40	160	23	1,702,000	664,290
		70–100	40	180	21	945,500	428,090
	No SP in shelterbelt	0–100	26	9	68	–	–
		0–50	8	17	79	–	–
		50–60	13	4	84	–	–
		60–70	35	9	60	–	–
		70–100	41	9	54	–	–
	All classes	0–100	–	–	72	–	–
		0–50	–	–	80	–	–
		50–60	–	–	86	–	–
		60–70	–	–	64	–	–
		70–100	–	–	59	–	–
Manitoba maple (MM)	MM in shelterbelt	0–100	37	51	42	4,672,000	3,236,917
		0–50	80	10	27	202,900	141,052
		50–60	50	67	30	1,874,900	1,178,435
		60–70	27	55	47	1,667,800	1,185,282
		70–100	0	88	53	926,400	732,148
	No MM in shelterbelt	0–100	28	20	60	–	–
		0–50	20	140	33	–	–
		50–60	17	13	73	–	–
		60–70	35	18	55	–	–
		70–100	37	0	63	–	–
	All MM classes	0–100	–	–	69	–	–
		0–50	–	–	47	–	–
		50–60	–	–	76	–	–
		60–70	–	–	68	–	–
		70–100	–	–	74	–	–

Table 2 continued

Species	Mapped class	Map probability level (%)	Omissions (%)	Commissions (%)	Mapping accuracy (%)	Predicted area of planted trees (ha)	Predicted number planted trees (–)
White spruce (WS)	WS in shelterbelt	0–100	52	44	33	5,400,500	1,544,914
		0–50	100	0	33	620,900	154,744
		50–60	56	33	33	2,316,400	630,415
		60–70	60	30	31	1,585,600	472,169
		70–100	20	120	36	877,600	287,586
	No WS in shelterbelt	0–100	17	19	70	–	–
		0–50	0	17	86	–	–
		50–60	15	25	68	–	–
		60–70	17	33	63	–	–
		70–100	27	5	70	–	–
	All WS classes	0-100	–	–	74	–	–
		0–50	–	–	87	–	–
		50–60	–	–	72	–	–
		60–70	–	–	68	–	–
		70–100	–	–	74	–	–
Green ash (GA)	GA in shelterbelt	0–100	22	128	34	11,489,500	9,916,161
		0–50	90	20	50	573,500	353,931
		50–60	27	109	35	4,979,300	3,692,724
		60–70	17	233	25	3,818,800	3,695,265
		70–100	10	140	38	2,117,900	2,174,241
	No GA in shelterbelt	0–100	61	10	35	–	–
		0–50	10	20	75	–	–
		50–60	67	17	29	–	–
		60–70	64	5	35	–	–
		70–100	82	6	17	–	–
	All GA classes	0–100	–	–	52	–	–
		0–50	–	–	80	–	–
		50–60	–	–	48	–	–
		60–70	–	–	46	–	–
		70–100	–	–	44	–	–
Caragana (CG)	CG in shelterbelt	0–100	35	49	44	9,727,700	64,573,630
		0–50	100	0	0	48,700	997,189
		50–60	33	56	43	3,551,100	19,578,719
		60–70	0	80	56	3,952,700	27,659,893
		70–100	27	45	50	2,175,200	16,337,829
	No CG in shelterbelt	0–100	29	21	59	–	–
		0–50	0	88	53	–	–
		50–60	25	15	65	–	–
		60–70	44	0	56	–	–
		70–100	31	19	58	–	–
	All CG classes	0–100	–	–	69	–	–
		0–50	–	–	53	–	–
		50–60	–	–	72	–	–
		60–70	–	–	71	–	–
		70–100	–	–	70	–	–

between PSP trees ordered and observed shelterbelt length (from digitized work) were used in this paper for shelterbelt mapping. The main difference between shelterbelt maps produced by using object-based satellite imagery classification (Pankiw and Piwowar 2010) and the probability map presented in the current paper is the resolution of analysis. Although the input data of thousands of shelterbelts digitized on-screen was derived from high-resolution aerial imagery (i.e., FlySask, 0.62 m), the resolution of the resulting shelterbelt probability map was 1 km. The choice for this relatively coarse map resolution was arbitrary, mainly aimed to increase data analysis efficiency, because the accuracy of the presented results was not affected by mapping resolution. The values in the shelterbelt probability raster layer indicated the chance (as percent) that one or more shelterbelts were present on the ground. Mapping the precise location of individual shelterbelts province-wide was not the goal for the shelterbelt probability map. Instead, the goal was to map historical shelterbelt establishment, total expected number of shelterbelt trees, and total expected shelterbelt length, all of which were completed at the provincial scale of analysis.

The probability map presented in this paper correctly predicted 95 % of all shelterbelts (approximately 3,000 km cumulative length) across a cumulative study area of 2.1 Mha. These results were similar to shelterbelt mapping projects done with higher resolution imagery on much smaller areas (Wiseman et al. 2009). Wiseman et al. (2009) were able of accurately (96 %) delineating shelterbelts on a 256 km^2 study area, and identifying the shelterbelt species planted via multivariate statistics analyses, using high-resolution aerial imagery (62.5 cm pixels) taken in the blue (450–495 nm), green (495–590 nm), and red (620–750 nm) electromagnetic spectra. Others evaluated the use of panchromatic SPOT 5 satellite imagery (2.5 m pixels), which were available for shelterbelt mapping on larger regions, including all of Saskatchewan (Pankiw and Piwowar 2010). Pankiw and Piwowar (2010) identified important limitations of

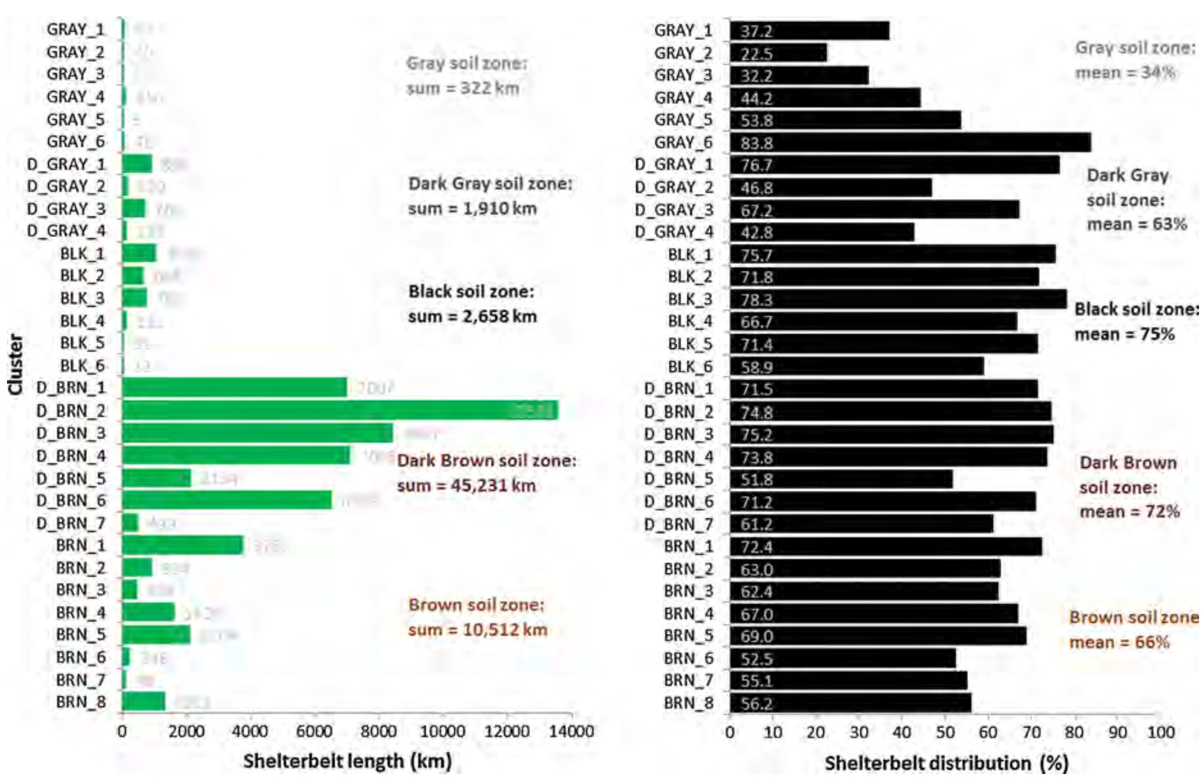
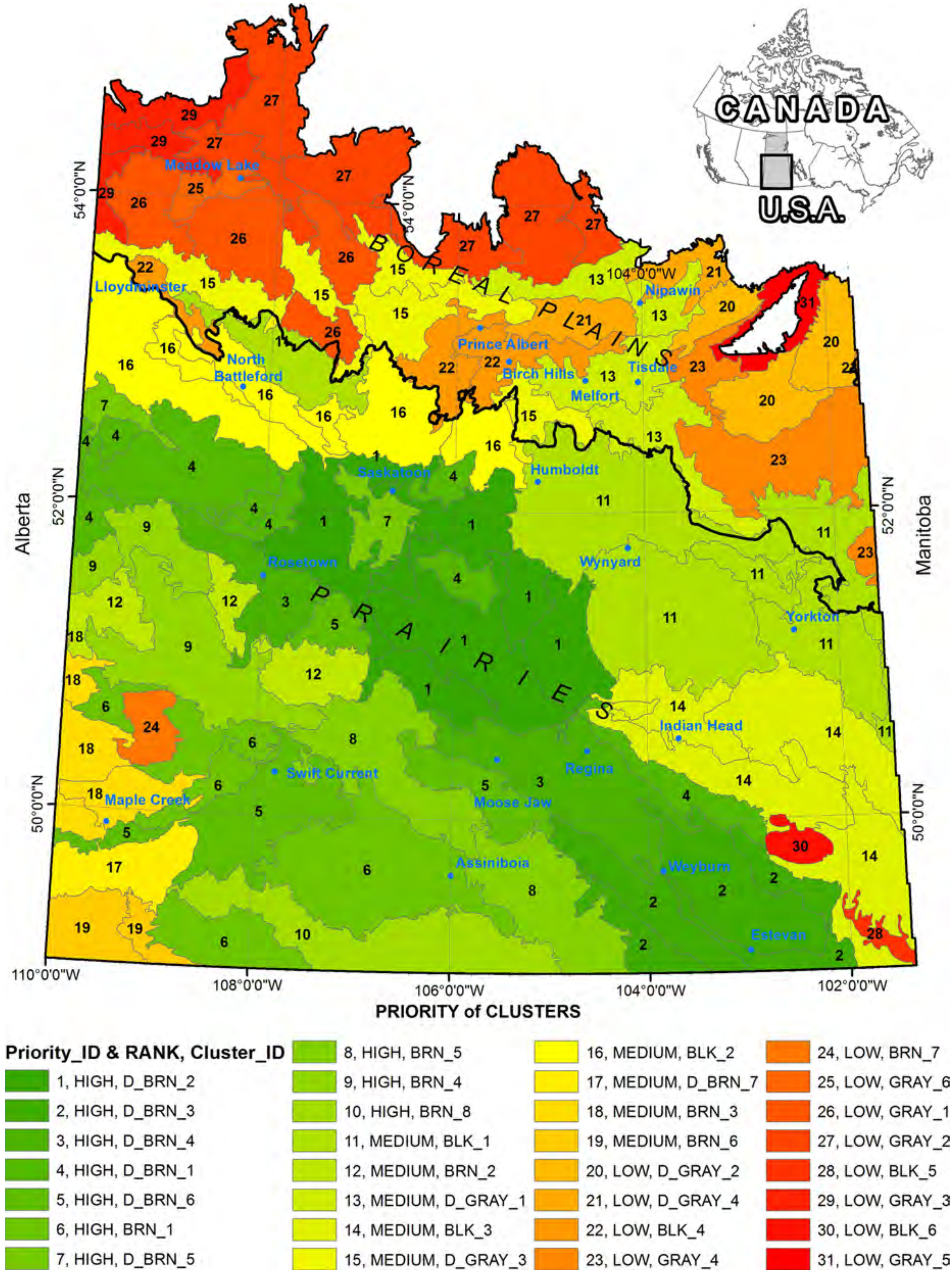


Fig. 5 Expected total length (*left*) and mean distribution (*right*) of planted shelterbelts across 31 clusters and soil zones in agricultural Saskatchewan


CANADA
U.S.A.
BOREAL PLAINS
PRAIRIES
Alberta
Manitoba
Meadow Lake
Lloydminster
North Battleford
Prince Albert
Birch Hills
Nipawin
Tisdale
Melfort
Saskatoon
Humboldt
Rosetown
Wynyard
Yorkton
Indian Head
Regina
Swift Current
Moose Jaw
Maple Creek
Assiniboia
Weyburn
Estevan
54°0'0"N
52°0'0"N
50°0'0"N
110°0'0"W
108°0'0"W
106°0'0"W
104°0'0"W
102°0'0"W
PRIORITY of CLUSTERS
Priority_ID & RANK, Cluster_ID
1, HIGH, D_BRN_2
2, HIGH, D_BRN_3
3, HIGH, D_BRN_4
4, HIGH, D_BRN_1
5, HIGH, D_BRN_6
6, HIGH, BRN_1
7, HIGH, D_BRN_5
8, HIGH, BRN_5
9, HIGH, BRN_4
10, HIGH, BRN_8
11, MEDIUM, BLK_1
12, MEDIUM, BRN_2
13, MEDIUM, D_GRAY_1
14, MEDIUM, BLK_3
15, MEDIUM, D_GRAY_3
16, MEDIUM, BLK_2
17, MEDIUM, D_BRN_7
18, MEDIUM, BRN_3
19, MEDIUM, BRN_6
20, LOW, D_GRAY_2
21, LOW, D_GRAY_4
22, LOW, BLK_4
23, LOW, GRAY_4
24, LOW, BRN_7
25, LOW, GRAY_6
26, LOW, GRAY_1
27, LOW, GRAY_2
28, LOW, BLK_5
29, LOW, GRAY_3
30, LOW, BLK_6
31, LOW, GRAY_5

◀**Fig. 6** Location of high, medium, and low priority clusters of agricultural land in Saskatchewan ranked in descending order of expected shelterbelt length

the utilized object-based classification method where portions of shelterbelts were not mapped at all even when the contrast between the surrounding landscape and the shelterbelt was increased by the use of winter SPOT 5 imagery with snowy background contrasting the darker trees in the shelterbelts. The main reasons for these inadequacies in mapping shelterbelts on high-resolution imagery (60 cm pixels) were small shelterbelt width and interference from shadow effects (Czerepowicz et al. 2012).

Decadal time-lapse shelterbelt maps

An important outcome of this paper is the time-lapse series of shelterbelt maps. These maps provided a unique presentation of the history of shelterbelt establishment across Saskatchewan, putting in perspective the expansive impact of the living legacy of the Government of Canada's shelterbelt program Center. In comparison to previous shelterbelt mapping projects that were based on satellite imagery (Czerepowicz et al. 2012; Pankiw and Piwowar, 2010), where data on each image is only 'one snapshot in time', the temporal attribute of the shelterbelt tree orders in the PSP database allowed shelterbelt mapping to be done across many decades. To our knowledge, these time-lapse, multi-decadal, shelterbelt probability maps for millions of hectares of the Canadian Prairies are presented for the first time in the current manuscript.

The time-lapse shelterbelt maps made it possible to identify important trends of shelterbelt establishment across Saskatchewan, such as the province-wide uniform shelterbelt planting that occurred until the 1960s relative to later decades (see Fig. 3). The uniformity of shelterbelt establishment up to the 1960s could be due to the expansive roadway network in Saskatchewan. In the 1970s and 1980s, the areas immediately next to major roadways and some intersections, as to restrict blowing snow across these roadways, were the locations where higher quantities of shelterbelt tree orders were recorded.

In comparison to previous decades, the concentration of shelterbelt establishment in the 1990s and 2000s was no longer focused in areas near major roadways and their intersections but rather it was

Table 3 Shelterbelt length (m) prediction equations as a function of number of trees ordered through the PSP developed for five soil zones in Saskatchewan–Black, Brown, Dark Brown, Dark Gray, and Gray; percent root mean square error (RSME %) and percent bias (Bias %) were used to evaluate the uncertainty of the shelterbelt length predictions

Shelterbelt type	Saskatchewan soil zone	Shelterbelt length†, L (m) = a × (Trees)^b					L (m) prediction uncertainty	
		a	b	R-square	*N*††	Range of trees‡	RMSE %	Bias %‡‡
Farmyard	Black	0.7032	0.8713	0.5918	19	62,575–293,905	41.2	10.5
	Brown	3.5499	0.7278	0.7378	12	6,965–441,745	24.5	−1.8
	Dark Brown	164.6500	0.4262	0.5606	11	42,990–506,358	37.2	10.4
	Dark Gray	0.1933	1.0000	0.4788	18	3,530–214,190	60.5	−36.1
	Gray	0.1744	1.0000	0.5393	10	80–71,595	60.2	−110.3
All	Black	0.0251	1.1750	0.5689	19	62,575–293,905	40.2	15.3
(farmyard + field)	Brown	0.2780	0.9962	0.8699	12	6,965–441,745	25.8	−7.8
	Dark Brown	2.4757	0.8295	0.6742	11	42,990–506,358	30.0	−10.9
	Dark Gray	0.3220	1.0000	0.5362	18	3,530–214,190	30.6	−35.2
	Gray	0.2225	1.0000	0.6083	10	80–71,595	61.2	−103.2

The length of field shelterbelt was computed as the length difference (All—Farmyard)

† Shelterbelt length is estimated as a function of the number of trees (Trees) through the PSP

†† *N* = sample size, i.e., number of 10-km-radius circle areas (31.4 kha) of surveyed land, used in equation development

‡ Range of trees = the range of the number of trees ordered through the PSP by landowners located within a given 10-km-radius circle area

‡‡ Bias % = negative bias indicates overestimation, while positive bias indicates underestimation

expanded well within agricultural land between major roadways. This expansion of shelterbelt establishment could be due to the positive trend and idea of shelterbelt planting becoming more mainstream among landowners. Additionally, by the 1990s, the knowledge-base associated with landowner assistance programs, including procedures and techniques for shelterbelt planting, and suggested shelterbelt designs, had reached greater numbers of landowners regardless of farm size (Kulshreshtha et al. 2011). All the above factors, in addition to historic drought cycles, appeared to have influenced a peak of shelterbelt establishment in the 1990s.

Due to the enormous number of shelterbelt trees planted annually in the 1990s and 2000s, the province-wide shelterbelt probability map appeared nearly unchanged in the period 2001–2009 despite the drastically reduced number of ordered shelterbelt trees in this period (see Fig. 3). The decreasing trend of shelterbelt tree orders from 1990 to 2009 is largely due to advances in direct-seeding technology leading landowners to believe that soil erosion could be rehabilitated without the use of shelterbelts (Kulshreshtha et al. 2011). Meanwhile, the use of larger field equipment may also be a reason for the recent trend of planted shelterbelts being removed across the province (J. Rempel, personal communication). Regardless of the species used in the shelterbelts, some landowners began removing well-established shelterbelts within their farms due to higher management costs relative to lower received benefits. These landowners were located mainly in the black and dark brown soil zones. Farmers who chose to maintain existing shelterbelts, especially in drier areas in the brown and gray soil zones, have noted appreciable ecosystem benefits from shelterbelts, such as shade and field moisture distribution.

Species-specific (6 species) shelterbelt maps

The purpose of the six species-specific maps was to show the expected spatial distribution and relative amount of each species across Saskatchewan, and to make these spatial and quantitative data available for future shelterbelt studies involving these species (see Fig. 4). The accuracy of the species-specific maps varied greatly across species and across mapped probability levels, with the majority of planted trees found on land with 50–60 % probability (i.e., 1-of-2 raster cells contain shelterbelts) for which the overall species mapping accuracy was 48–86 % (see Table 2). To our knowledge, there is no other work in the literature that attempted to map distribution of specific shelterbelt species across the Canadian Prairies. Although Wiseman et al. (2009) reported 95 % accuracy in mapping shelterbelt features (of any species) in Manitoba from high-resolution aerial imagery, no mapping accuracy was reported from their species identification part of the project which involved principal component analysis.

Expected shelterbelt length

For the majority of planted shelterbelts in the province, in terms of expected total length (i.e., dark brown and brown soil zones), RMSE and bias of length predictions were <37 % and within 11 % of the mean, respectively. To our knowledge, there is no other work in the literature that reports accuracy of shelterbelt length predictions in Saskatchewan that could be used for comparison with our results. The summaries of expected shelterbelt length by soil zone and by cluster in Saskatchewan are a powerful tool for extrapolation of shelterbelt tree growth and C flux results calculated per-unit length of shelterbelts.

One of the important additional uses of the expected shelterbelt length summaries was to identify priority areas for future shelterbelt research. The high priority clusters identified, encompassing 88 % of the cumulative length of all shelterbelts in the province, were located throughout the entire dark brown and parts of the brown soil zones, spanning from west-central to south-central and southeast Saskatchewan (see Fig. 6). The expected larger shelterbelt lengths in these areas, compared to the relatively wetter soils in the black soil zone to the north and east, are likely due to a wider use of shelterbelts as a means to deal with relatively drier land, especially in the brown soil zone. Although shelterbelts were planted on a relatively high proportion (52–78 %) of the agricultural land in the brown, dark brown and black soil zones, the shelterbelt planting density could be different. For example, using the equations in Table 3 we estimated that approximately 2,00,000 shelterbelt trees corresponded to about 40, 50, and 60 km of observed shelterbelts in the black, brown, and dark brown soil zones, respectively. Trends like this could provide important insights to policy makers with respect to the current state of shelterbelt establishment, maintenance, and diversity. However, in order to gain these insights, additional research is necessary to provide missing shelterbelt data, preferable from all soil zones, such as shelterbelt tree mortality, shelterbelt designs (i.e., spacing, width, number of rows), and prevalence of shelterbelts removal by landowners.

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