International Journal of Applied Earth Observation and Geoinformation 44 (2016) 113–123

Contents lists available at ScienceDirect

International Journal of Applied Earth Observation and Geoinformation

journal homepage: www.elsevier.com/locate/jag

Measuring and monitoring linear woody features in agricultural landscapes through earth observation data as an indicator of habitat availability

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ARTICLE INFO

Article history:
Received 30 June 2015
Received in revised form 24 July 2015
Accepted 26 July 2015
Available online 25 August 2015

Keywords:
Linear woody features
Hedgerows
Windbreaks
Landscape
Biodiversity
Indicators
Line intersect sampling
Earth observation
Monitoring

ABSTRACT

The loss of natural habitats and the loss of biological diversity is a global problem affecting all ecosystems including agricultural landscapes. Indicators of biodiversity can provide standardized measures that make it easier to compare and communicate changes to an ecosystem. In agricultural landscapes the amount and variety of available habitat is directly correlated with biodiversity levels. Linear woody features (LWF), including hedgerows, windbreaks, shelterbelts as well as woody shrubs along fields, roads and watercourses, play a vital role in supporting biodiversity as well as serving a wide variety of other purposes in the ecosystem. Earth observation can be used to quantify and monitor LWF across the landscape. While individual features can be manually mapped, this research focused on the development of methods using line intersect sampling (LIS) for estimating LWF as an indicator of habitat availability in agricultural landscapes. The methods are accurate, efficient, repeatable and provide robust results. Methods were tested over 9.5 Mha of agricultural landscape in the Canadian Mixedwood Plains ecozone. Approximately 97,000 km of LWF were estimated across this landscape with results useable both at a regional reporting scale, as well as mapped across space for use in wildlife habitat modelling or other landscape management research. The LIS approach developed here could be employed at a variety of scales in particular for large regions and could be adapted for use as a national scale indicator of habitat availability in heavily disturbed agricultural landscape.

1. Introduction

The conservation of wildlife and their associated habitats is becoming an issue of increasing concern around the world. The loss of natural habitats and the loss of biological diversity is a global problem affecting all ecosystems ranging from, for example, boreal forests (Wilcox and Murphy, 1985; Schmieglow and Monkkonem, 2002), marine environments (Worm et al., 2006) as well as agricultural landscapes (Burel et al., 1998). Monitoring human impacted ecosystems is essential in order to ensure their proper functioning is not impacted in terms of ecosystem processes, which is supported by ecosystem's biological diversity. The quantification and assessment of baseline conditions along with regular ecosystem monitoring can provide warning of undesirable changes and additionally provide a means for evaluating the success of various management strategies with respect to protecting biodiversity (Pereira and Cooper 2006; Cabello et al., 2012).

Many agricultural landscapes are heavily managed for cultivation. These landscapes are considered to be highly disturbed environments with very little natural or semi-natural landcover remaining amongst a matrix of heavily managed crop land, pasture and man-made structures. It is well established that the amount and variety of available habitat on agricultural landscapes is directly correlated with biodiversity levels (Fuller et al., 1997; Fahrig et al., 2011). Further, agricultural expansion, or land conversion, as well as intensification of agricultural practices is continuing to have negative impacts on wildlife attempting to inhabit agricultural landscapes, including as a result of habitat fragmentation (Fahrig, 2003; Fahrig et al., 2010). Within such heavily disturbed landscapes, remnant patches of natural and semi-natural landcover, including forest fragments, wetlands, riparian strips, abandoned agricultural fields, and field margins provide critical habitat to a wide variety of bird, mammal and invertebrate species that live within agricultural landscapes and as well as travel through them.

While perhaps not widely discussed in North American agricultural landscapes, linear woody features play a vital role in

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http://dx.doi.org/10.1016/j.jag.2015.07.008

supporting biodiversity. These features exist in a range of conditions from remnants of natural vegetation to planted and heavily managed features. Linear woody feature (LWF) is a general term which, depending on the geographic region and purpose, includes hedgerows, windbreaks, and shelterbelts. While it is difficult to assign a universal definition in terms of length, width and composition, for the purpose of this research, LWF refer to a line of trees and / or woody shrubs on an agricultural landscape between and along cropped fields as well as along roadways, lanes, rail corridors and watercourses. These linear features can be the remnants of pre-disturbance natural forest stands (Schmucki et al., 2002), the result of planting activities intended to mark property boundaries, keep livestock in or out of fields, as well as shelter agricultural fields from winds in order to prevent soil erosion and manage snow distribution. Additionally they are formed as the result of natural growth or regrowth in non-cultivated margins or field boarder areas (Burel 1996; Baudry et al., 2000).

Linear features have been recognized for the wide variety of essential ecosystem services which they provide. LWFs have been shown to help control and prevent runoff and flooding (Burel 1996), are a significant source of stored carbon (Huffman et al., 2015), support critical pollination services (Albrigo and Russ, 2002; Hannon and Sisk, 2009), and perhaps most importantly from the perspective of this research provide essential food, shelter and movement corridors for a wide variety of wildlife and enhance biodiversity across the landscape (Burel 1996; Davies and Pullin, 2007; Haenke et al., 2014; Jobin et al., 2014).

Field-based manual approaches have been and continue to be used to assess the overall length of hedgerows as well as detailed information on species composition and structure in some jurisdictions (UK Department for Environment, Food and Rural Affairs, 2007) however while potentially very accurate, this practice can be very resource demanding and requires an appropriate level of knowledge and skill to be conducted properly. Instead, LWF can be detected and mapped using a variety of approaches using aerial photography or high resolution satellite. Manual delineation of LWFs from imagery is possible, but similarly to field-based methods can be extremely labour intensive, especially across vast agricultural landscapes. Automated image classification approaches have been tested over small areas for detecting and mapping hedgerows and other linear woody features in agricultural landscapes. Such methods range from traditional reflectance based pixel clustering to multi data set object-based segmentation (e.g. Liknes et al., 2010; Aksoy et al., 2010; Pankiw and Piwowar, 2010; Atchison and Ghimire, 2012; Black et al., 2014). To date automated techniques have not generally been used beyond small local study areas and certainly have not been applied to large scale ecozone or ecoregion scale assessment.

Line intersect sampling (LIS), originally proposed by Canfield (1941), is one sampling approach commonly used for detecting and quantifying linear features on the landscape. LIS relies on intersections of sampling lines with the linear features of interest. While, LIS has historically been used for field-based vegetation surveys, more recently it has been adapted for use with remotely sensed images. For example, LIS has been applied for a variety of range of spatial distributed features including estimating the length of forestry roads (Matern 1964), agricultural crop residues (Laflen and Colvin, 1981), course woody debris (Van Wagner, 1964; Gregoire and Valentine, 2003) as well as forest edge and ecotone density (Corona et al., 2004; Esseen et al., 2006).

Under the UN Convention on Biological Diversity, participating countries have committed to developing and utilizing indicators to monitor and help prevent further loss in biodiversity as well as maintaining ecosystem integrity (United National Convention on Biological Diversity (UN-CBD), 1993). Indicators not only provide standardized measures that make it easier to compare and communicate changes to an ecosystem, but they can also provide indirect measures or correlates to variables or concepts, such as biodiversity, which are difficult, expensive, time consuming and often impossible to truly measure (Noss, 1999; Carignan and Villard, 2006).

The objectives of this research were to develop a rapid earth observation (EO) based method using line intersect sampling for quantifying and monitoring linear woody features in agricultural landscapes specifically as an indicator of habitat availability. The approach developed was tested and applied at a variety of scales including the full extent of a large Canadian ecozone, with the intention of future further application at a national scale. The intention of this research was not to detect and map individual landscape features, but rather provide a means for monitoring landscape units in terms of the density of linear woody features.

2. Materials and methods

While directly applicable to any farming region, for development and test purposes this study was restricted the Canadian Mixedwood Plains ecozone which spans the southern regions of the provinces of Ontario and Quebec (Agriculture and Agri-Food Canada (AAFC), 2015). EO based methods for quantifying linear woody features were developed and tested at various scales using various test sub-regions, before being applied to the entire ecozone. Fig. 1 provides an overview of the development of methodology and mapping application of LIS for detecting and estimating LWF. All GIS processing and data collection was carried out within ArcGIS 10.2 (ESRI, 2015).

2.1. Study Area

The Mixedwood plains geographic location, fertile soils, relatively warm growing season and abundant rainfall have made it Canada's most intensively managed and densely populated region. This region is home to over 52% of Canada's population in 0.86 Mha of urban area with 41% of the total ecozone land area occupied by cropland (composed of annual, perennial and forage cropping areas) (Statistics Canada, 2011) (Table 1). In pre-European colonization times the region was heavily forested supporting more species of trees than any other region of Canada, however, currently less than 10% of the original tree cover remains including many rare and endangered tree species (Ecological Stratification Working Group, 1996; Government of Canada, 2015). In terms of the total Canadian agricultural extent, the ecozone provides almost 13% of Canada's cropland area.

In Canada, ecozones are further divided to reflect variation in soils and climate resulting in ecoregions that are characterized by distinctive regional landforms, macro- or mesoclimates, vegetation, soils, water, and regional human activity patterns and uses (Ecological Stratification Working Group, 1996). The Mixedwood Plains ecozone is composed of four ecoregions; Lake Erie Lowlands, Manitoulin-Lake Simcoe, Frontenac Axis and the St. Lawrence Lowlands. For the purpose of this work, the St. Lawrence Lowlands ecoregion was sub-divided into two regions split by the provinces of Quebec and Ontario (Fig. 2).

2.2. Sampling design and methods development

Line intersect sampling is a relatively easy approach used for assessing and estimating the density of discrete landscape elements particularly linear elements (Canfield 1941; Matern 1964). The approach is based on the "needle problem" in which one attempts to calculate the probability of a needle intersecting parallel lines when dropped randomly (Buffon 1777; Barbiere 1860). Matern (1964) provided a more detailed discussion of the theoretical basis which is

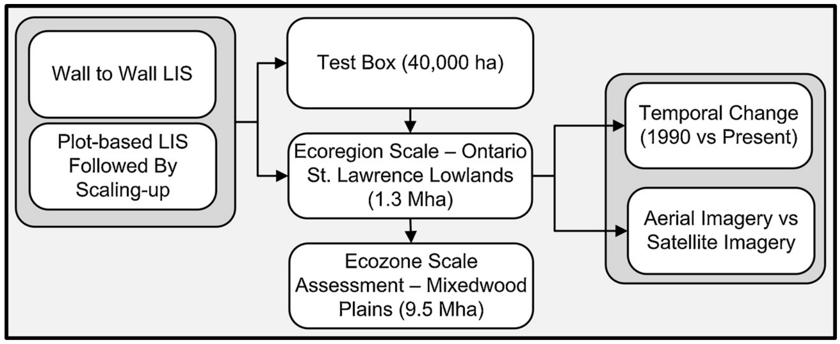

Fig. 1. General overview of methods development and mapping process.

Table 1
Population and agricultural land use information for the Mixedwood Plains ecozone, reported by individual ecoregions.

Ecoregion	Province	Total land[b] (km^2)	Cropland[c] (km^2)	Pasture[c] (km^2)	Woodland and wetlands[c] (km^2)	Cropland proportion (%)	Population density[d] (p/km^2)
St. Lawrence Lowlands	QC	27,707	11,487	630	2,919	41.5	157.7[a]
St. Lawrence Lowlands	ON	13,184	4,139	868	965	31.4	
Frontenac Axis	ON	818	155	75	62	18.9	28.7
Manitoulin-Lake Simcoe	ON	43,652	16,266	3,632	2,766	37.3	58.1
Lake Erie Lowland	ON	24,786	13,528	501	1,145	54.6	304.7

[a] Value for St Lawrence Lowlands ecoregion including both Ontario and Quebec portions.
[b] based on ecoframework soil landscapes of Canada land area.
[c] based on 2011 Census of Agr.
[d] based on 2006 Census of Pop. Estimates.

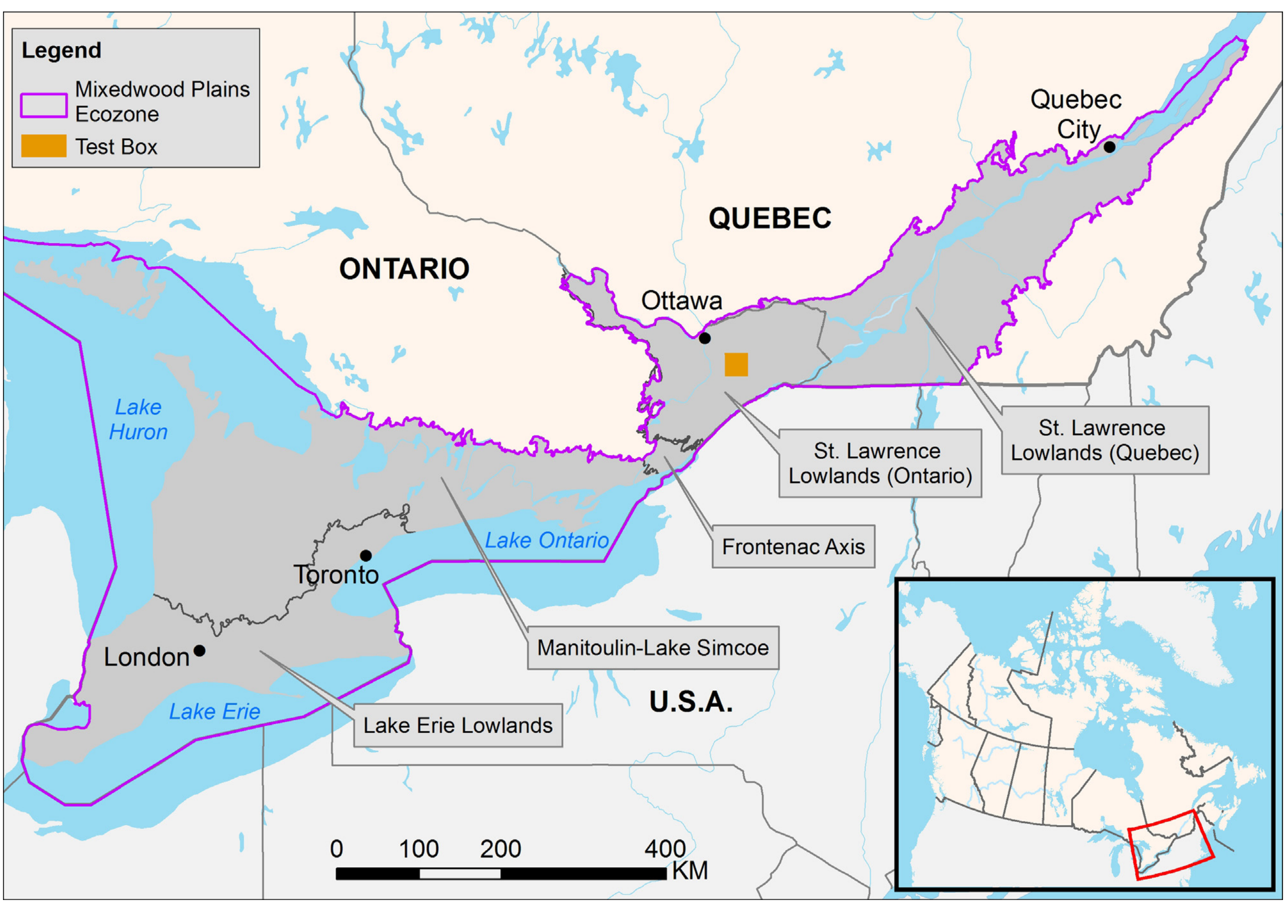

Fig. 2. Mixedwood Plains ecozone with four ecoregions and the location of the test box area indicated.

founded on the likelihood of a chain intersecting a network of lines when randomly placed over the network. Each link of the chain has a specific circumference of sampling and each link intersects a line at two points; if the links in the chain are made smaller and smaller the chain eventually becomes a line. Corona et al. (2004) applied the traditional line intersect sampling approach for use with earth observation data (Eq. 1) for detecting forest edges in a mixed land use landscape.

$$\mathrm{LFD} = \frac{10,000\pi}{2} \times \frac{P}{L} \tag{1}$$

Where the total linear feature density (LFD) (meters per hectare) is estimated by multiplying the proportion of the total number of intercept points (P) to the total length of sampling line (L) (meters) divided by two and multiplied a constant factor of the mathematically coefficient of π multiplied. The 10,000 value is simply a conversion factor for square meter area to hectares (Corona et al., 2004). Simply multiplying LFD by the area assessed provides the total estimated LWF for that region. Although the LIS has been applied successfully for assessment of a number of landscape features it has not been used for the specific activity of detecting and estimating LWF, as a result considerable testing and development activity was undertaken to ensure that it would be a suitable and effective approach for estimation and assessment of LWF in agricultural landscapes.

2.3. Methodological development test box

Initial testing and development of line intersect sampling (LIS) was carried out using a 20 km x 20 km test box (40,000 ha) within the Eastern Ontario portion of St. Lawrence lowlands ecoregion (Fig. 1). The box extent and boundaries were determined based on local knowledge of the region and previous work in this landscape (Pasher et al., 2013; Duro et al., 2014; Fahrig et al., 2015) and was representative of the Mixedwood Plains ecozone in terms of general landscape and land use activity. The land use activity in the test box was a mix of agricultural cropland types—intensive annual crop and livestock husbandry systems with as well urban and peri-urban activity in addition it contains considerable natural land in the form of forested and wetland areas. LIS was applied in the test box and all LWF were manually digitized using high resolution air photos to provide validation data for the sampling approach. In order to focus the analysis on agricultural landscapes and avoid assessing, for example, urban and forested regions for the presence of LWFs and at the same time avoid small isolated agricultural areas a course filter approach was applied across the region. Agricultural landscapes from here on refer to areas that were identified as having a minimum of 10% crop cover. This same process was employed consistently throughout this research to provide an agricultural landscapes mask when working in other regions at the ecoregion scale to provide both ecoregion and ecozone level estimates.

All linear woody features within the agricultural landscape were manually digitized at a scale in the range of 1:5,000–1:10,000 to provide a validation data set of LWF. The manual digitizing process used very high resolution true colour air photos available through a Bing image service covering the entire test box region of interest (Bing Aerial Imagery, 2014). Dates of the imagery varied slightly but the majority of the coverage was 2012. Generally speaking, interpreters digitized features that were a minimum of 20 m (i.e. continuous shrubs or trees) in length and not in excess of 20 m in width. All treed and shrubby features were digitized, which included those along fence lines, field boundaries, lane and roadways, rail lines as well as riparian features.

LIS relies on the use of sampling; a series of sampling grids with spacing of 250 m, 500 m, 1000 m, 2000 m and 5000 m were generated across the agricultural landscape of the test box region using a modified "Fishnet" tool in ArcGIS. It was recognized that the orientation of sampling gridlines could potentially impact the variance in estimates. Within the test box the grids were shifted and rotated using five different scenarios in order to attempt to quantify this variance. For all scenarios, intersection points were then generated at each location where a sampling line intersected a LWF using the manually digitized feature layer. The estimated density of linear features (LFD) for each grid was calculated using Eq. 1, multiplying this density by the total area assessed (agricultural landscape), providing an estimate of total LWF length which then could be compared to the actual total length manually digitized for the test box region.

A LIS wall-to-wall sampling approach has the benefit of providing a complete representation for which point density surface estimates can be developed. Such a density surface may be very useful for further work looking at the sub-ecozone regional variation in LWF. It does however require complete coverage with high resolution earth observation imagery. To assess the viability and comparative accuracy, sub-plot sampling was carried in addition to complete coverage sampling. A series of 16 2 km × 2 km sub-plots were generated and distributed throughout the test box along a regular 5 km spaced grid. From this set of 16 sub-plots (representing approximately 16% of the box area) sub sets of 12, then 8, and finally 4 were selected to test increasingly lower sampling densities. Within each sub-plot, line sampling grids were generated at a 250 m and 500 m spacing, and the intersections between the sampling lines and linear woody features were assessed. Obviously much finer scale line sampling would be necessary if sub plot-based sampling were employed given the much smaller area to be sampled. The estimated overall LFD across the plots was calculated. The estimated LWF found in the entire test box was calculated by multiplying the test box area by the density of lines as calculated within the sample plots.

2.4. Methodological assessment—ecoregion scale

As the objective of this project was to develop a method for full scale estimation of LWF for both local and large regions, testing activity was scaled up from the test box to the ecoregion scale. The Ontario portion of the St. Lawrence Lowlands ecoregion (~1.3 Mha, Fig. 2) was selected for this purpose. Building on the outcome of the results of the initial test box test, full coverage sampling lines spaced at a 2 km interval were generated across the agricultural landscapes within the region (1.05 Mha). Based on initial results from within the test box, the 2 km line spacing provided an optimal balance between effort required and accuracy of estimates of the total length of woody features. Sampling was carried out along the sample lines and an estimate of total LWF length was calculated.

2.4.1. Temporal change

Using this same region, high resolution air photos acquired in 1990 were obtained (NAPL National Air Photo Library, 2014) and georeferenced for all agricultural landscapes. The total area identified as agricultural land in the 1991 and 2011 agricultural censuses differed by less than 5%, indicating that at the ecoregion scale there is likely sufficient rationale to keep the study area mask (agricultural landscape mask). The identical 2 km spaced line sampling grid was used and an interpreter collected all the intersections between the sampling lines and the observed LWF.

2.4.2. Comparison of aerial imagery with high resolution satellite imagery

A national scale monitoring strategy may need to include a variety of earth observation data including both air photos and high resolution satellite imagery. To assess potential issues based on the

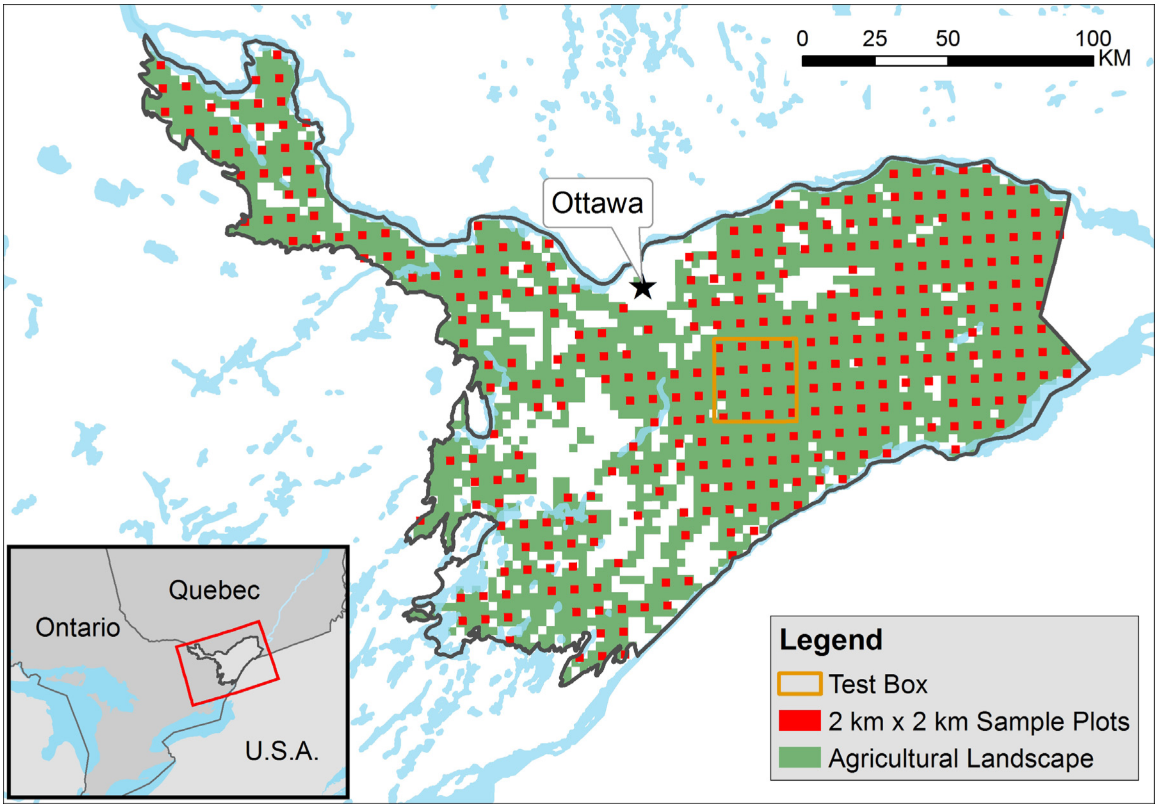

Fig. 3. Distribution of 2 km × 2 km plots across the agricultural landscape of the Ontario portion of St. Lawrence Lowlands ecoregion used for regional scaling up testing.

different imagery, the process was carried out using high resolution colour infrared satellite image composites (5 m spatial resolution) acquired in the summers of 2012 and 2013 by the RapidEye Sensor (Satellite Imaging Corp. RapidEye).

2.4.3. Plot-based sampling Ontario St. Lawrence ecoregion

Beyond the initial testing within the 20 km × 20 km test box, in order to further assess the use of sub-plots as an alternative to wall to wall, additional testing was conducted for the Ontario St. Lawrence Lowlands ecoregion. An approach employing sub-plot sample has the added benefit of potential easy integration into other national terrestrial monitoring framework activities in which all monitoring activities fall within a consistent sampling grid framework such as the national forest inventory (NFI) (Gillis et al., 2005). To provide a test for this approach and the potential for future integration with the NFI framework, 2 km × 2 km sampling plots were generated such that they were centered at the intersection of the 5 km grid position nested within the NFI grid. A total of 338 sample plots were used to cover the extent of the ecoregion (Fig. 3); this represented ∼12% (4800 ha) of the total agricultural landscape within the Ontario St. Lawrence ecoregion. Repeated random selections of the 338 sample plots were used to provide a representative sampling at 8% and 4% (210 and 105 of 338 plots) respectively as test sets for further reduced sampling densities. Random subsets were selected six times and the results were averaged together for each sampling density. For all of the 338 2 km plots the LWF were manually digitized to provide a validation data set and then sampling grids with spacing's of 250 m and 500 m were generated. All intersections between sample lines and woody linear features were extracted and the overall estimated WFD was calculated for the plots, and then scaled-up to the larger region they were selected to represent by multiplying the density by the area of the ecoregion.

2.5. Assessment of the entire Mixedwood Plains Ecozone

Using the wall to wall approach with 2 km × 2 km sample grid spacing, the four remaining ecoregion portions of the Mixedwood Plains ecozone were assessed using high resolution air photos. This included the Quebec portion of the Saint Lawrence Lowlands, the Frontenac Axis, Manitoulin-Lake Simcoe as well as the Lake Erie Lowlands ecoregions.

2.6. Calculation of error and variability in estimates

As with any process, errors were known to exist at various phases and an attempt was made to quantify these errors in order to be able to provide an overall estimation of the associated uncertainty for estimates total length of LWF using the LIS methodology developed here. Individual sources of error were combined to provide an overall estimate of uncertainty for LWF estimates based on the approach used for ecozone level estimation. Providing an uncertainty for these LWF estimates is desired by many potential users of the information and necessary for many official reporting activities (Intergovernmental Panel on Climate Change (IPCC), 2006). Uncertainty assessment also provides a useful guide for efficiently improving methodology. Two primary sources of error our assessment focused on were: the error of the LIS method compared to manual digitizing and the error related to interpretation of intercept points LWF when using the LIS method. To assess the error of using the LIS method, the relative difference of error between LWF estimates from the LIS method were simply compared with those generated through manual digitizing of features.

In order to quantify the error related to interpretation of LWFs, a series of test were done for each ecoregion sampling area using a random 5% set of the points that had been identified as woody features. This sampling of intercept points can be used to provide and assessment of commission error. These random subsets of points

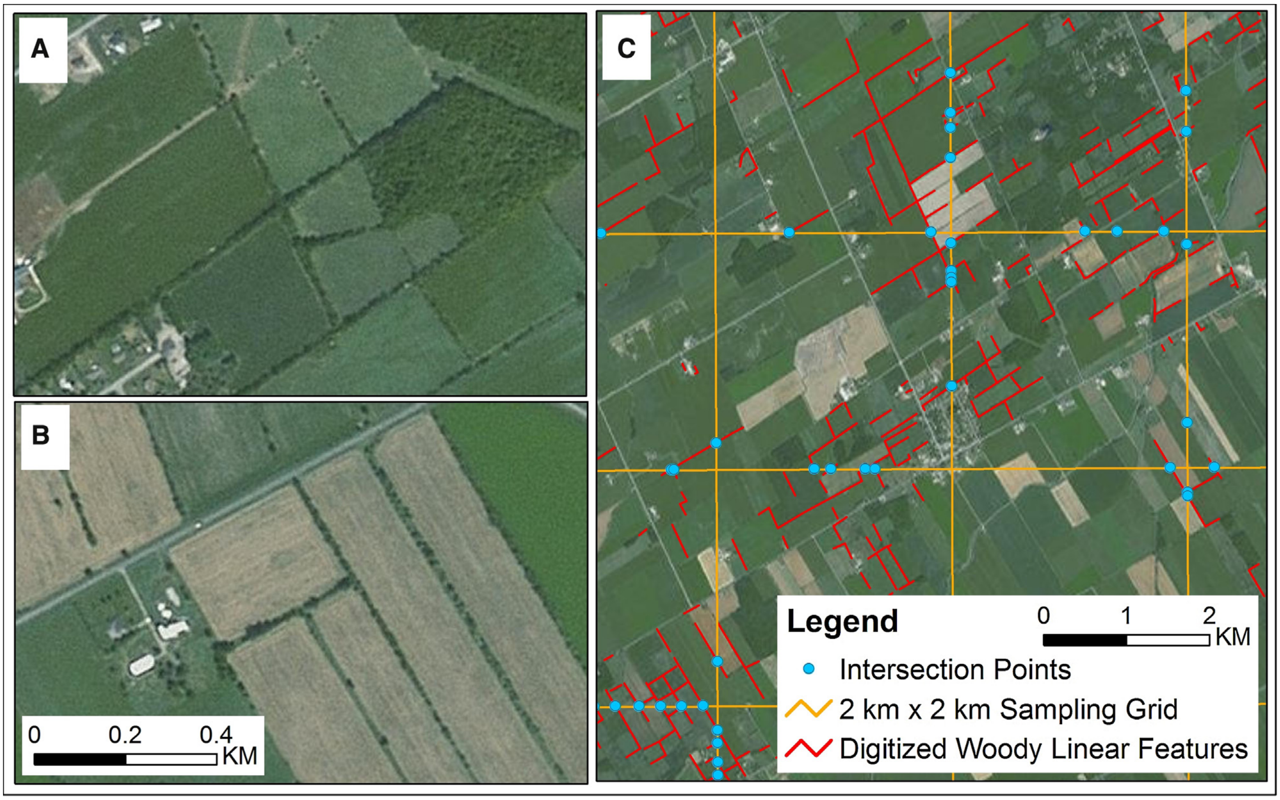

Fig. 4. Examples of linear woody features seen in colour air photos for Eastern Ontario. Common conditions seen during interpretation included (A) features surrounded by green vegetation and extensions of woodlots and (B) features surrounded by fields that don't appear green allowing easier identification. An example of Line Intercept Sampling (LIS) is shown with intersection points identified (C).

were checked by a second interpreter to confirm whether they were correctly marked. Additionally, an equal number of locations were randomly selected along the sampling lines, and at least 10 m from a marked woody feature, which represented locations where no woody feature was found. At each location the second interpreter marked whether there was a linear woody feature present, representing omission error, or if in fact there was no feature representing a correct interpretation. These tests were run for each ecoregion assessed, and the average error was used to provide an overall idea of interpreter error.

3. Results and discussion

3.1. Line intercept sampling development

Initial testing and development for the line intercept sampling (LIS) (Fig. 4) was carried out within the 20 km × 20 km test box within the Eastern Ontario portion of St. Lawrence lowlands ecoregion. Within this 40,000 ha area, 39,006 ha were identified as making up the agricultural landscape following the minimum 10% agriculture land cover criteria. Manual digitizing of all linear woody features in this area was completed in approximately 30 h, with a resultant vector layer containing a total of 608 km of LWF representing an overall density of 15.6 m/ha for the test region. LIS was carried out through human interpretation, to simulate a real world assessment, and this took less than 1 h, obviously a huge savings in time and effort required.

Wall to wall sampling across the test box provided accurate results for 250 m, 500 m, and 2000 m grid spacing's (Table 2). Perhaps most surprisingly, the 2000 m grid provided accurate results, yielding an error only twice that of the 250 m spaced sample grid (−5.9% compared with −2.5%), while requiring only one-tenth the effort (348 km of sample lines compared with 3076 km). The increasing underestimation of total length with progressively coarser grid spacing was a direct result of the LIS method missing the smaller features. For unexplainable reasons, the 1000 m grid was an anomaly, yielding the highest error, perhaps tied in with the calculation of feature density (Eq. 1), or an underlying landscape scale effect.

An average variance of 1.6% was found as a result of shifting and rotating sampling grids. This reflects the observation that LWF were found to follow a variety of landscape components. While the actual orientation of grids yielded different results, maintaining a constant grid across the landscape was deemed appropriate as the landscape patterns themselves varied based on roads, rail, cadastral, topographic and water features.

3.2. Assessment of the Ontario St. Lawrence Lowlands region

Wall to wall sampling using the 2 km × 2 km spaced grid involved manually assessing 10,651 km of sample lines resulting in 8342 LIS points. The LIS resulted in an estimated total length of 12,887 km of woody features across 1.05 M hectares of agricultural landscape (12.3 m/ha) (Table 3). This assessment required approximately 35 h of interpretation time, considered to be relatively little effort for such a large region (approximately the same amount of time needed to manually digitize all LWF in the 40,000 ha test box, an area 27 times the size).

Relative to the wall to wall sampling using the 2 km spaced grid which was done using high resolution air photos, the RapidEye satellite imagery interpretation resulted in a 6.5% lower estimate (Fig. 5). Although the satellite imagery provided near-infrared information, which the higher resolution air photos did not have, the coarser resolution imagery made detection of some features

Table 2
Results for LIS sampling within the 20 km × 20 km test box using a range of sampling densities.

	Sampling coverage (%)	Total grid length (km)	Estimate density of linear woody features (m/ha)	Estimated total length of linear woody features (km)	Relative error (%)
Manual digitizing	–	–	15.6	608	–
250 m grid	100	3,076	15.2	593	−2.5
500 m grid	100	1,522	15.1	588	−3.3
1000 m grid	100	743	13.5	528	−13.2
2000 m grid	100	348	14.7	572	−5.9[a]
5000 m grid	100	115	14.0	546	−10.3

[a] Average relative error calculated for the chosen grid density using multiple sets of sampling lines following shifts and rotations was found to be 1.6%.

Table 3
Results for LIS sampling across the Ontario St. Lawrence Lowlands region for current and historical conditions using air photos as well as RapidEye satellite imagery for comparison.

Region	Total Grid Length (km)	Total Intersection Points	Estimate Density of Linear Woody Features (m/ha)	Estimated Total Length of Linear Woody Features (km)	Relative Difference (%)
Current high resolution colour air photos	10,651	8342	12.3	12,887	–
Rapideye 5m resolution multispectral satellite	10,651	7787	11.5	12,030	−6.5
Historical (1990) panchromatic air photos	10,651	8347[a]	12.3	12,896	0.0

[a] Adjusted values to correct for poor 1990 image quality in some sections of the ecoregion.

Fig. 5. (A) High resolution colour air photo compared with (B) 5 m resolution RapidEye satellite image shown as colour-infrared composite.

impossible. Interpretation of the satellite imagery did however take less time to interpret compared to interpretation of higher resolution images. A detailed examination of 250 random linear woody features suggested that the average width of features found in this region were 10.5 m (Standard Deviation = 4.5 m), this would suggest that the majority of features should in fact be detectable in 5 m resolution imagery. In comparison to the high resolution colour air photos, the RapidEye interpretation was found to be 94% accurate using 389 points that were identified as linear woody features in the satellite imagery along with 389 locations where no feature was identified. Interpreters found it easier to work with the higher resolution imagery, however if wall to wall sampling was desired across a very large area, the satellite imagery can provide a feasible alternative to using higher cost air photos.

The temporal analysis yielded some surprising results. Initial sampling using the 1990 panchromatic air photos proved much more difficult than expected. This was a result of the variable resolution depending on the original acquisition and digital scanning. In addition the variable seasonality (leaf-on/leaf-off) and sun angle at the time of acquisition had a significant impact on interpretation accuracy. This resulted in a significant source of omission errors, mostly a result of leaf-off conditions in approximately 30% of the sampling area. In order to overcome this shortfall in the estimate, a series of sample regions were set out in areas that had both good and poor quality 1990 photos. Based on testing in regions with multiple 1990 air photos it was determined that on average 22% of intersection points, or 18 points per hectare, were missed. After translating this to the number of points missed per length of sample lines, the overall number of linear woody feature intersection points was increased from 7580 to 8347 (Table 3).

Over 20 years it appeared that the overall amount of linear woody features was stable across the landscape at the ecoregion scale; however there were pockets where existing woody features showed growth and new features appeared, while there were other locations where the features clearly disappeared. Linear feature removal was identified as being associated with either expansion of field or the conglomeration of multiple fields into single field units, or the result of abandonment of agricultural land which over time regenerated into larger forested or woody areas (Fig. 6).

Fig. 6. Examples of temporal changes seen in linear woody feature assessment using LIS between 1990 and 2012. (A,C) High resolution colour air photos with (B,D) 1990 panchromatic air photos for matching locations. Red arrows are shown pointing at reference locations comparable between image pairs.

3.3. Comparison of plot-based vs. wall to wall sampling

Sub-plot sampling employing a sampling grid of 250m and 500m within the test box resulted in linear woody feature estimates with very low relative error suggesting that plot-based sampling provided similar estimates to wall to wall sampling (Table 4). For the most part the 250m grid provided less deviation from the wall to wall estimates as those based on the 500m spaced grid, with the only exception occurring with the lowest sampling plot density of 4 plots, or 4% of the total box area. Across these eight tests within the test box, compared with digitized linear woody features, the plot-based sampling showed on average an overestimation of 5.1%.

For the analysis across the entire ecoregion, it was noticed that the scaled-up plot-based estimates yielded significantly higher estimates. However, the plot-based estimates were calculated using LIS points generated through automated intersections rather than human interpreted means. The automated intersections were done since the digitized woody features database existed for this region. An assessment of the difference showed that the automated intersections consistently yielded 10% more points compared with human interpretation. As a result of this systematic difference, an adjusted LWF estimate was generated for the Ontario St. Lawrence Lowlands in order to be able to compare the plot-based results to wall to wall sampling. The original wall to wall estimated 12,887 km (12.3 m/ha) was adjusted to 14,176 km of woody features (13.5 m/ha). Based on the adjusted values, the results of scaled-up plot-based line intercept sampling across the Ontario St. Lawrence Lowlands ecoregion yielded higher relative errors when compared to the digitized LWF ranging from 9.0% to 13.6% depending on the plot and line sampling density (Table 4).

In general plot-based results showed a general overestimation of the total length of woody features compared to wall to wall sampling. The plots perhaps did not perfectly represent the distribution of linear woody features across the region, causing an overall higher estimated total length than estimated through wall to wall sampling. Feature densities varied considerably through the 338 sub-plots from 0.46 m/ha to 46.8 m/ha (Average = 15.1 m/ha). These results suggest that for the assessment of smaller regions it is preferable to conduct wall to wall sampling rather than a plot-based one. In addition, wall to wall sampling may be preferable in cases where woody linear features are generally more evenly distributed throughout the region, or follow a regular structure based on road and field layout. This could possibly be the case for regions such as the Canadian Prairie region in which the Dominion Land Survey was conducted using a regular grid system for an extensive land area. An additional benefit of sampling the entire area of interest is that it facilitates future use of intercept points for spatial analysis such as the generation of contours and feature density maps.

On the other hand, plot-based sampling has two main advantages; the reduced amount of necessary imagery and the associated increased interpreter efficiency. Since sampling only occurs for a small portion of the overall area, not as much high resolution imagery is required to conduct the survey. This is a particular advantage when high resolution image must be purchased or require additional processing such as orthorectification/georeferencing is required prior to use. It may enable the use of higher quality imagery for a smaller region which would have a beneficial impact on overall accuracy. Finally, by using a plot-based approach, the total length of sample survey lines can be reduced.

Table 4
Results for plot-based LIS sampling within the 20 km × 20 km test box as well as across the Ontario St. Lawrence Lowlands ecoregion.

		Sampling coverage (%)	Total grid length (km)	Estimate density of linear woody features (m/ha)	Estimated total length of linear woody features (km)	Relative error (%)
Test box	Manual digitizing	–	–	15.6	608	–
	16 plots–250 m grid	16	431,933	15.6	609	0.1
	16 plots–500 m grid	16	183,971	16.1	629	3.5
	12 plots–250 m grid	12	26,996	15.9	619	1.8
	12 plots–500 m grid	12	11,469	17.4	677	11.3
	8 plots–250 m grid	8	27,374	15.9	620	1.8
	8 plots–500 m grid	8	11,331	16.6	647	6.3
	4 plots–250 m grid	4	25,992	17.1	669	9.9
	4 plots–500 m grid	4	10,996	16.6	647	6.4
Ontario St. Lawrence Lowlands	2 km × 2 km wall to wall	100	10,651	12.3	12,887	–
	Adjusted 2 km × 2 km wall to wall[a]	100	10,651	13.5	14,176	–
	338 plots 250 m[c]	12	8,797	15.1	15,760	11.2[b]
	338 plots 500 m[c]	12	3,788	14.8	15,451	9.0[b]
	210 plots 250 m[c]	8	5,459	15.4	16,108	13.6[b]
	210 plots 500 m[c]	8	2,377	15.2	15,915	12.3[b]
	105 plots 250 m[c]	4	2,739	15.3	16,036	13.1[b]
	105 plots 500 m	4	1,184	15.2	15,907	12.2[b]

[a] Adjusted for systematic interpreter underestimation in order to make comparable with automated intersection extractions done at the plot scale.
[b] Relative to adjusted 2 km × 2 km wall to wall estimate.
[c] Average results based on repeated random selections.

Table 5
Linear woody feature estimates for the Mixedwood Plains ecozone based on wall to wall 2 km × 2 km line intersect sampling.

Region	Province	Total sampling area (ha)	Total grid length (km)	Estimate density of linear woody features (m/ha)	EStimated total length of linear woody features (km)
St-Lawrence Lowlands	Quebec	2,398,749	23,051	7.7	18,381
St-Lawrence Lowlands	Ontario	1,047,516	10,651	12.3	12,887
Frontenac axis	Ontario	46,437	481	4.8	223
Manitoulin-Lake Simcoe	Ontario	3,852,207	38,674	11.2	43,242
Lake Erie lowland	Ontario	2,171,571	20,319	10.2	22,154
Mixedwoods Plains Ecozone	QC/ON	9,516,479	93,175	10.2	97,170

If monitoring is the sole objective, repeated plot-based measurements through time could suffice, even if it does not provide results as accurate in terms of quantifying the actual length of LWF.

3.4. Full ecozone assessment

A total area of over 9.5 M ha of agricultural land was assessed across the Mixedwood Plains ecozone (Fig. 2). Over 93,000 km of sampling lines on a 2 km grid were used to identify intercept points. This sampling resulted in a total length estimate of LWF of 97,170 km (Table 5). The Ontario portion of the St. Lawrence Lowlands ecoregion had the highest overall density; a significantly lower density was detected for the Quebec portion of the St. Lawrence lowlands. Smaller field sizes with a high variability of cropping practices were observed in the Quebec St. Lawrence which is a legacy of the Seigneurial system of land tenure implemented during original settlement in the mid 1600s. In addition large continuous forested patches occurred between farmland areas. The Manitoulin-Lake Simcoe ecoregion was by far the largest area to survey and interpret with the highest total number of line interception points; the region has an estimated total of over 43,000 km of LWF almost half of all found in the ecozone. Larger field sizes were observed in the Lake Erie lowlands ecoregion which resulted in a lower overall number of field boundaries and woody features associated with these boundaries. In the Frontenac Axis ecozone the fewest features were detected with more forested patches occurring within this agricultural region. This is the smallest of the ecoregions with the lowest ratio of cropland to total farmland and a higher proportion of agricultural land in pasture.

When conducting wall to wall sampling interpreters had some difficulty ensuring sampling and interpretation was consistent if imagery was of poor quality or varied a great deal. This was the case for the Lake Erie lowlands ecoregion where over 12% of the area selected for sampling proved difficult to sample due to cloud cover present in the imagery; as a result LWF are likely under estimated for this region. In some cases the only available cloud-free imagery was for snow covered winter periods; this imagery was suitable for interpretation but full colour imagery was preferred. This illustrates the difficulty in obtaining high quality imagery for very large areas and would suggest that a sub-plot sampling approach may be a more feasible option when conducting large scale assessment.

Based on standardized LIS data collection across the entire ecozone, the results are interpretable in a variety of formats. As an indicator, users might be interested in quantifying the estimated length of woody features within smaller landscapes used for management purposes. These measures could then be recalculated at a later time and used to track changes. An alternative to this would be to generate a continuous surface across the mapped region which could be used for various modelling exercises, including analyzing

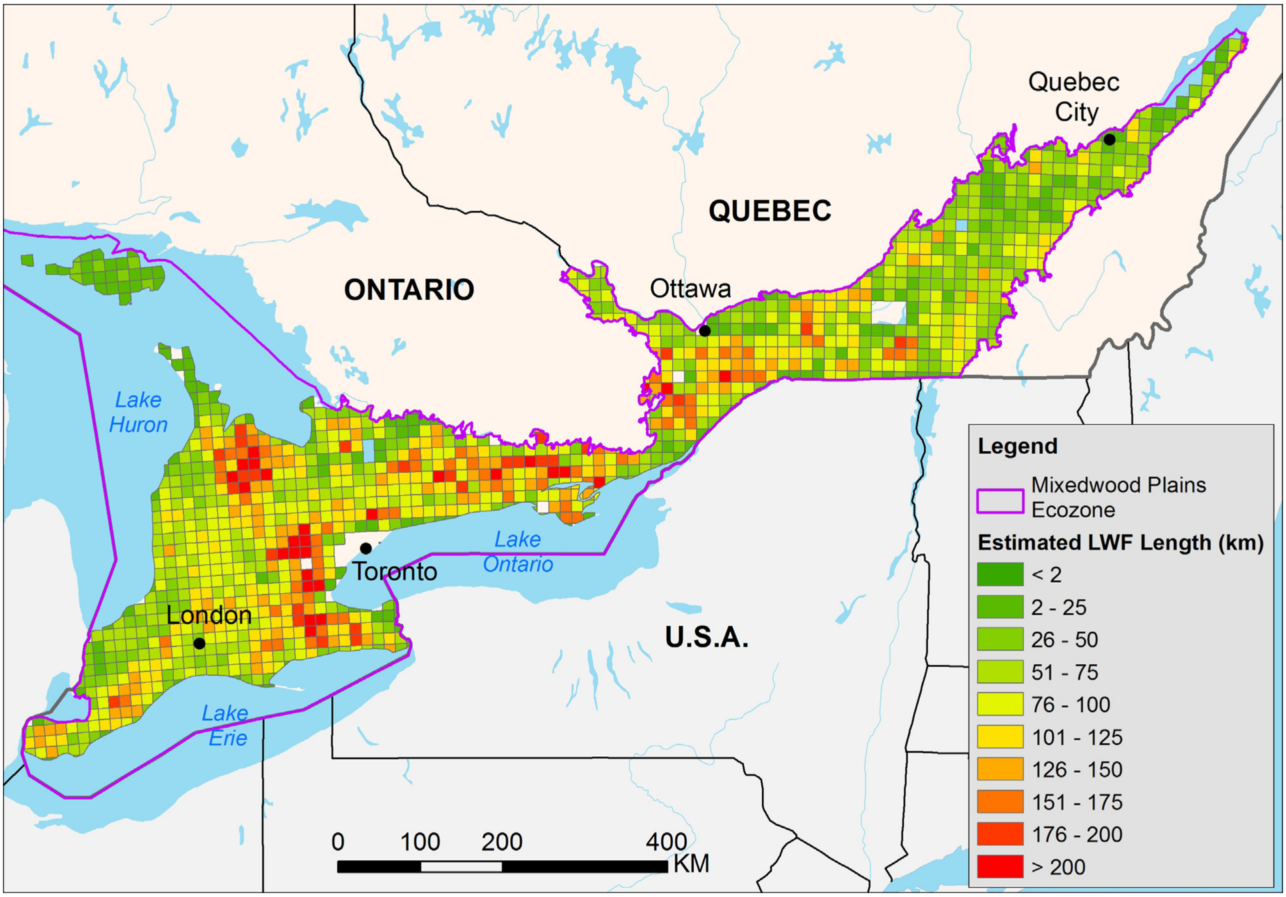

Fig. 7. Example of how a continuous surface can be generated representing the estimated LWF length across the Mixedwood Plains ecozone for use in reporting and modelling exercises.

relations between species survey data and woody feature presence or density. Fig. 7 demonstrates how this could be achieved. This example map utilized an arbitrary landscape size of 10 km × 10 km and within each cell the point density, LIS sampling length and area of agriculture was calculated and used to generate the estimated LWF length (kilometers) per 10 km × 10 km area. This could provide a means to compare conditions in terms of spatial variability across the region over time.

3.5. Consideration of errors and estimation of estimate uncertainty

In total almost 7000 points were evaluated for interpreter accuracy across all ecoregions using the high resolution colour aerial photography. Overall misclassification was found to be less than 1%. This small error can be maintained, or even reduced, through quality control and interpreter training as well as the use of very high quality fine resolution imagery.

With respect to quantifying the error of the LIS method compared to manual digitizing it was found that for the selected sampling density an error of 5.9% was calculated. Of course it is recognized that the comparison to manually digitized LWF that there are some errors in the manually digitized estimate if used as reference or "truth" value. This is the case even if this digitizing was conducted with the greatest care; some errors are to be expected. Taking into account both of these sources of uncertainty or variability, an overall estimate of uncertainty of 6% was calculated following standard error (S.E.) propagation methodology (Eq. 2).

$$S.E._{\text{Total}} = \sqrt{(S.E._{\text{LIS\_Method}})^2 + \left(S.E._{\text{Interpretation}}\right)^2} \quad (2)$$

4. Conclusions

Linear woody features are highly valued landscape features for a wide variety of reasons, including providing shelter, transit corridors and valuable habitat to a wide variety of species living in agricultural landscapes. Woody linear features can be detected and mapped using a variety approaches including manual field measurements, manual interpretation of remotely sensed imagery as well as through image classification or segmentation methods. The objective of this work was to develop an approach which could be employed a variety of scales in particular for large regions—ecozone scale, to provide an assessment of LWFs which could be conducted accurately, efficiently and rapidly.

Line intercept sampling was tested and used for both wall to wall assessments as well as plot-based assessments for estimating the density and total length of LWF across various agricultural landscapes. Elements of sample design as well as temporal analysis were conducted. Both the wall to wall and plot-based sampling yielded satisfactory results, each with its own benefits. Wall to wall sampling across 9.5 Mha resulted in a total length estimate of LWF of 97,170 km (± 5830 km). This is considered significant achievements given these features are rarely captured by landcover mapping or characterization and are significant habitat components and potentially critical for scientific investigations focused on wildlife—habitat interactions in agricultural landscapes.

The resultant LWF information across the mixedwood plains ecozone is being used to explore relationships between breeding birds in agricultural landscapes and various elements of landscape composition including LWF information, which to date has never been available at such a scale. Additionally, the LWF information will be utilized for exploring ecosystem service information such as pollination services and carbon accounting. A major goal of this research was to develop a national scale indicator of habitat availability. National scale assessments could involve both wall to wall and plot-based mapping. The wall to wall sampling method has been demonstrated to provide robust results across extensive agricultural landscapes and could easily be adapted for agricultural landscapes with different structures or histories, for example the Canadian prairie region which is significantly different from the Mixedwood Plains ecozone in terms of land parcel allocation, field size, road patterns as well as the ecoclimatic conditions, topography and land management practices.

Acknowledgements

The authors greatly appreciate advice and input provided by Dr. Greg Mitchell and Jason Duffe with Environment Canada and Dr. Scott Mitchell of Carleton University's Geomatics and Landscape Ecology Laboratory. Funding and support for this research was provided by the Landscape Science and Technology Division as well as the Pollutants Inventory Research Division of Environment Canada. Thanks as well to Lisa Koponen for GIS scripting support throughout this work.

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