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Mapping invasive Phragmites australis in highway corridors using provincial orthophoto databases in Ontario

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Abstract

We mapped the distribution of invasive Phragmites australis (European common reed) in MTO-operated roadways of southern Ontario using airphotos from a provincial database, the Southwestern Ontario Orthophotography Project (SWOOP), which covers all highways from Windsor east to Norfolk/Niagara and north to Tobermory. We mapped all available SWOOP images acquired in 2006, 2010 and 2015. In addition, we delineated invasive Phragmites along MTO-operated roadways within the footprint of the Southcentral Ontario Orthphotography Project (SCOOP acquired in 2013) and the Central Ontario Orthophotography Project (COOP acquired in 2016); the mapping excludes the Greater Toronto Area but includes Prince Edward county, roads through the city of Barrie, and north to Parry Sound. Based on available orthophotos for SWOOP only, total areal cover of invasive Phragmites expanded an order of magnitude between 2006 and 2010 (26.8 to 259.7 ha, respectively); between 2010 and 2015, there was only an increase of 7.2% (278.4 ha), presumably because of ongoing herbicide treatments that began on selected roads beginning in 2012. Expansion rate differed between road types, with 400-series highways having significantly greater expansion rates than non-400 highways (24.5 vs 6 times, respectively). Areas covered by SCOOP images had an areal cover of 152 ha in 2013, while that for COOP images had an areal cover of 7.8 ha in 2016. This inventory is freely available for anyone to update using provincial orthophotos or medium to high-resolution satellite imagery such as Sentinel 2.

Keywords Invasive Phragmites, early detection, road maintenance, remote sensing

Distribution Unrestricted.

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Executive Summary

We have successfully mapped the distribution of invasive *Phragmites australis* (European common reed) in roadways of southern Ontario using airphotos from a provincial database, the Southwestern Ontario Orthophotography Project (SWOOP), which covers all highways managed by West Region of MTO (Windsor east to Norfolk/Niagara and north to Tobermory). This is the first time a project of this scale has been conducted to map the presence of *Phragmites* in roadway corridors, and the first time the airphoto dataset has been used for remote sensing. No other dataset provided the scale and resolution (20cm/pixel) necessary for identifying historic distributions of *Phragmites*. This study includes all available SWOOP images acquired in 2006, 2010 and 2015. In addition, we delineated *Phragmites* along MTO-operated roadways within the footprints of the Southcentral Ontario Orthphotography Project (SCOOP acquired in 2013) and the Central Ontario Orthophotography Project (COOP acquired in 2016). This study area excludes the Greater Toronto Area but includes Prince Edward County, roads through the city of Barrie, and north to Parry Sound.

Using eCognition software (Trimble), we conducted an automated image classification with the 2006 and 2010 datasets to map *Phragmites* (and 7 other land-cover classes) within an 80-m buffer of the centre-line of all MTO roads. We used this approach to map *Phragmites* in county roads within the West Region to increase our dataset for more robust analyses. For automated image classification, we ensured that a minimum total accuracy of 80% was achieved for *Phragmites*, with minimum total scene accuracy of 75%. Accuracy was assessed by comparing classified features to those that were manually digitized from airphotos. We were unable to use the automated classification approach to map *Phragmites* in photos acquired after 2010; therefore, *Phragmites* stands in the 2015 SWOOP, 2013 SCOOP and 2016 COOP images were manually digitized. For manual digitization, two technicians were trained to digitize the same road segments until they achieved minimum 80% accuracy. No other land cover classes were classified, and accuracy assessments were made by confirming the presence of delineated stands by comparing against Google Streetview, since no field data were available for this purpose. To preserve consistency in manual delineations, all images were digitized by these two technicians.

Based on amount of *Phragmites* mapped in the SWOOP airphotos, *Phragmites* expanded greatly between 2006 (26.8 ha) and 2010 (259.7 ha); the rate of increase was reduced between 2010 and 2015 (331.47 ha), presumably because of extensive herbicide treatments on selected roads that commenced in 2012 (see Chow-Fraser & Marcaccio 2018). Most of the change between years occurred when *Phragmites* expanded into areas occupied by “grasses”, that are essentially low-lying vegetation in road corridors (species could not be further distinguished beyond this category). We saw a statistically significant but weak influence of surrounding land cover (e.g. agriculture, urban, forest) on the expansion rate of *Phragmites* between 2006 and 2010; the only significant predictors were agriculture, grass, and traffic volume (all positive but explained very little of the overall variation). This may mean that *Phragmites* invasion is still in its early stages, and that the only limiting factor is available habitat. There were differences in expansion rate between road types, with 400-series highways having

significantly greater expansion rates than did non-400 series highways, especially those with low traffic volume. Between 2006 and 2010, the 400-series highways expanded 24.5 times (from 5.4 ha to 132.7 ha) compared to only 6 times for all other highway categories combined (from 21.4 ha to 127.1 ha). This may be related to the presence of medians in the 400-highways that provided more habitat for *Phragmites* to colonize than on two-lane highways.

Presence of *Phragmites* in the 2013 SCOOP dataset (152 ha) was lower than that for the 2010 SWOOP dataset; however, this is expected to increase since the demand for recreational property is increasing rapidly northward from Barrie to Parry Sound. Not surprisingly, the total mapped area covered by the 2016 COOP images was relatively low (7.8 ha); however, given that treatment is more successful when stands are small and sparsely distributed, we strongly recommend that MTO implement a treatment program as soon as possible to prevent *Phragmites* from expanding further westward and northward within Ontario. The *Phragmites* inventory that we have created should be updated at regular intervals, either with airphotos from future acquisitions of SWOOP and SCOOP, or with medium to high-resolution satellite image data such as Sentinel 2.

Introduction

Invasive Phragmites

Phragmites australis (Cav.) Trin. ex Steudel (the common reed) is a perennial grass that grows in many habitat types throughout the world. There are 27 genetically distinct groups (haplotypes) worldwide, of which 11 have been found in North America (Saltonstall 2002). Over the past two decades, Haplotype M, which originated from Europe, invaded coastal and inland wetlands throughout southern Ontario, replacing native vegetation and generally reducing biodiversity (Chambers et al. 1999; Markle and Chow-Fraser 2018). This invasive haplotype aggressively colonizes exposed mud flats sexually (through seeds), and then expand asexually (through rhizomes) to form dense monocultures. Its rapid spread has been attributed to it being a superior competitor against other emergent vegetation (Rickey and Anderson 2004; Uddin et al. 2014) and to being more tolerant of disturbances (e.g. road maintenance and changes in hydrologic regimes) and stress (e.g. increased salinity due to road de-icing salts) (Marks et al.,1994; Chambers et al. 1999; Saltonstall 2002).

Past studies have shown that transportation corridors provide excellent invasion pathways for species such as invasive *Phragmites*. Linear ditches along roadsides or in the median can be readily colonized by invasive *Phragmites* (Leong et al. 2007; Brisson et al. 2010), because they are able to tolerate high salinity from road salts and require little moisture in comparison to other aquatic vegetation (Medeiros et al. 2013). Ministry of Transportation of Ontario (MTO) has acknowledged the destructiveness of invasive *Phragmites*, both with respect to the road infrastructure, as well as to adjacent ecosystems, and has been developing a control strategy. Since 2012, MTO has sprayed highway corridors with glyphosate, a broad-spectrum herbicide used to control the growth of *Phragmites* and other weeds (Figure 1).

The primary goal of this project is to create a database (McMaster Invasive *Phragmites*Database; MIPD) to map and update the areal cover of invasive *Phragmites* on MTO-managed roads in Ontario. Using the Southwestern Ontario Orthophotography Project (SWOOP) database, we used object-based image classification software to delineate the extent of *Phragmites* in MTO's western region in 2006 and 2010. We conducted a change detection analysis to determine roads associated with the highest rate of expansion, and to elucidate significant landscape-level factors that may influence *Phragmites* colonization. Additional image data from the Southcentral and Central databases (SCOOP 2013 and COOP 2016 respectively) allowed us to increase our mapping effort of invasive *Phragmites,* although there are no land cover maps for these areas, and the data that are available do not exist for multiple years. We should also mention that our maps do not distinguish between native and invasive haplotypes of *Phragmites*; that said, it is very unlikely that native *Phragmites* would occur in densities as high as what we have been mapping in the present study.

Orthophoto databases

We used the SWOOP database (Southwestern Ontario Orthophotography Project), which was organized and funded cooperatively by multiple government agencies (municipal, provincial and federal) who wanted to obtain seamless aerial photos of the southwestern portion of the province at regular intervals (approximately every 5 years; 2006, 2010, 2015, 2020, etc). This dataset covers an area from Windsor east to Brantford/Niagara (2006/2010 & 2015) and north to Tobermory (**Figure 1**).

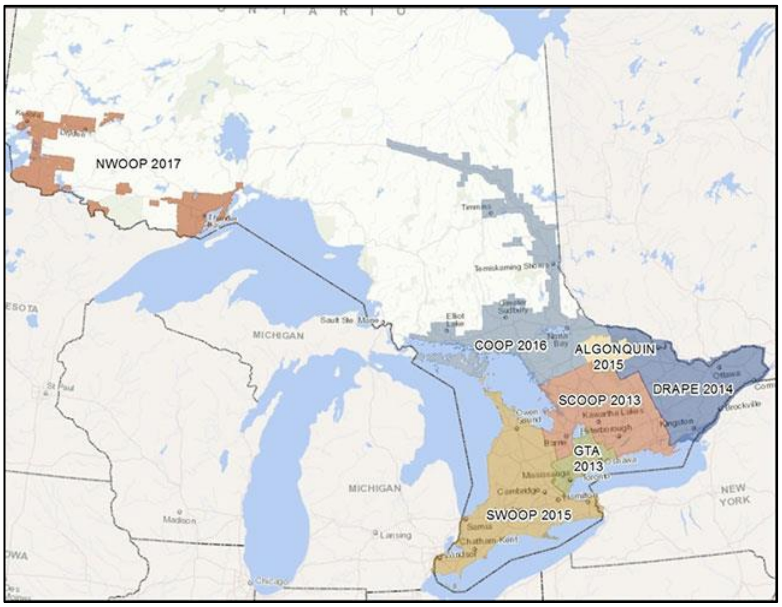

Figure 1: Area covered by various Ontario orthophotography project databases. The area covered by SWOOP for 2015 and 2010 is the same; that for 2006 did not include portions around Hamilton and Niagara.

We also used the SCOOP database (Southcentral Ontario Orthophotography Project; 2013) which covers an area from Prince Edward county, west to Barrie (excluding the GTA) and north to Parry Sound, as well as the COOP database (Central Ontario Orthophotography Project; 2016), which follows the shoreline of northern Georgian Bay and the North Channel and includes Manitoulin Island (Figure 1). The Ontario Ministry of Natural Resources and Forestry (OMNRF) has set forth a plan to acquire spring orthophoto image data at regular intervals across the province; eastern and northern regions have also been imaged and are planned to be acquired every five years. Because these projects were developed primarily for planning purposes, the image data were acquired during spring when leaf-off conditions allowed for unobscured view of buildings and roads (April-May, weather dependent). SWOOP, SCOOP and COOP images are freely available to participating stakeholders and to research agencies and universities; the cost would have been prohibitive otherwise. Since SWOOP data are captured from a plane rather than from a satellite, the surface of the earth is much closer to the sensor, and the true colour image had a spatial resolution of 20 cm with red, green, and blue bands. Such high-resolution imagery would allow for a minimum mapping unit of <1m and is therefore suitable for mapping *Phragmites* stands within roadway and/or highway ditches.

Previously, *Phragmites* has been mapped on a large scale with satellite-based imaging sensors in true colour, near-infrared, radar, and combinations thereof (Bourgeau-Chavez et al. 2015; Pengra, Johnston, & Loveland 2007; Young, Young, & Hogg 2011). These sensors typically have a ground-based resolution of 10-30 m per pixel and can often return their orbit to a specific location within two weeks. Due to the nature of these sensors, any feature (e.g. *Phragmites*) that is to mapped must be approximately four times the size of the pixel to ensure that, regardless of orientation, the feature would fall completely within one pixel. Hence, the satellite-based sensors require a minimum mapping unit of 40x40 to 120x120 m, and this exceeds the dimension of the average highway ditch, which for these sensors is too narrow to be appropriately mapped. By comparison, aerial photos, or orthophotography (imagery taken from an airplane) can provide a much smaller minimum mapping unit (<1m). The trade-off for this high resolution however, is the requirement for costly flights to be flown, and involvement of many thousands of images to cover an area the size of the province of Ontario. In the SWOOP dataset, approximately 50,000 images must be acquired per year, and the SCOOP & COOP datasets are of comparable size.

One of the major challenges of this project was managing the tens of thousands of images acquired over the study period. To save time and money in the classification of these images, we created subsets of images together that had been acquired at approximately the same time of day and during the same time of year within similar geographic locations (e.g. Cambridge, Hamilton). Such aerial images should have similar spectral characteristics and will produce acceptable results when the same classification scheme is developed and applied.

Methodology

Use of eCognition to map Phragmites

High resolution data such as that found in SWOOP can be difficult to process. Large data files can severely slow processing time for image viewing and even moreso for image classification. High resolution data can also have many mixed pixels, where two abutting objects are found in the same pixel and the signal is a mix of both. In a typical pixel-based method, the unique colour values associated with each pixel is used solely to guide classification. This can often lead to inaccuracies because of variation in the dataset; in addition, it can result in single pixels being misclassified within a group of similar pixels. To process the large amount of high-resolution data, we used eCognition, an object-based classification software (Trimble Navigation Limited, Colorado, USA). Object-based approaches avoid the above problem by first splitting the image into segments that are spectrally similar and/or have a consistent parameter (e.g. shape, length, volume) associated with them. This reduces the number of single pixels that can be misclassified and allows other intrinsic values from remote sensing to be used (e.g. size, shape, perimeter).

To make our task manageable, we first clipped out a small strip of land (buffer) beside each road to be analyzed (Figure 2) and performed the classification only on these buffer strips. We also included all other roads with posted speed limits above 60km/h in the SWOOP dataset (data obtained from OMNRF shapefile; Figure 3). This excluded local roads that were usually maintained by property owners and/or have little to no ditch in their easement. The buffer varied according to road speed and road type (e.g. larger buffer was used for 400 series highways compared to two-lane highways). We extracted the image data within the buffer using FME (Safe Software, Surrey, BC, Canada), and inserted them into eCognition for image processing.

We created a base classification for identifying invasive *Phragmites* as well as other land cover-land-use types (see Table 1). Some classes such as "shadows" have no ecological meaning but are necessary for us to correctly classify the other land cover types without confusion. These classes were subsequently used in our change-detection analyses to determine the land-cover type that invasive *Phragmites* were more likely to colonize.

We created a base classification using 5% randomly selected images within a particular image subset. We conducted multiple accuracy assessments for these images until our base classification met or exceeded our accuracy threshold of 70% for total accuracy and minimum 80% for *Phragmites*. We then applied this base classification to remaining images in the subset. The literature has shown that classifications created in one image can be transferred to another with a small decrease in total accuracy (Rokitnicki-Wojcik et al. 2011). While other studies have completed accuracy assessments for every image used, this was not logistically feasible given the large number of images we had in our dataset. To improve total accuracy of the classification when the dates of image acquisition are not similar, we started with our previous base classification and then modified it to incrementally improve the accuracy until an acceptable level could be attained. No field data were needed to supervise this classification because of the high resolution of the images.

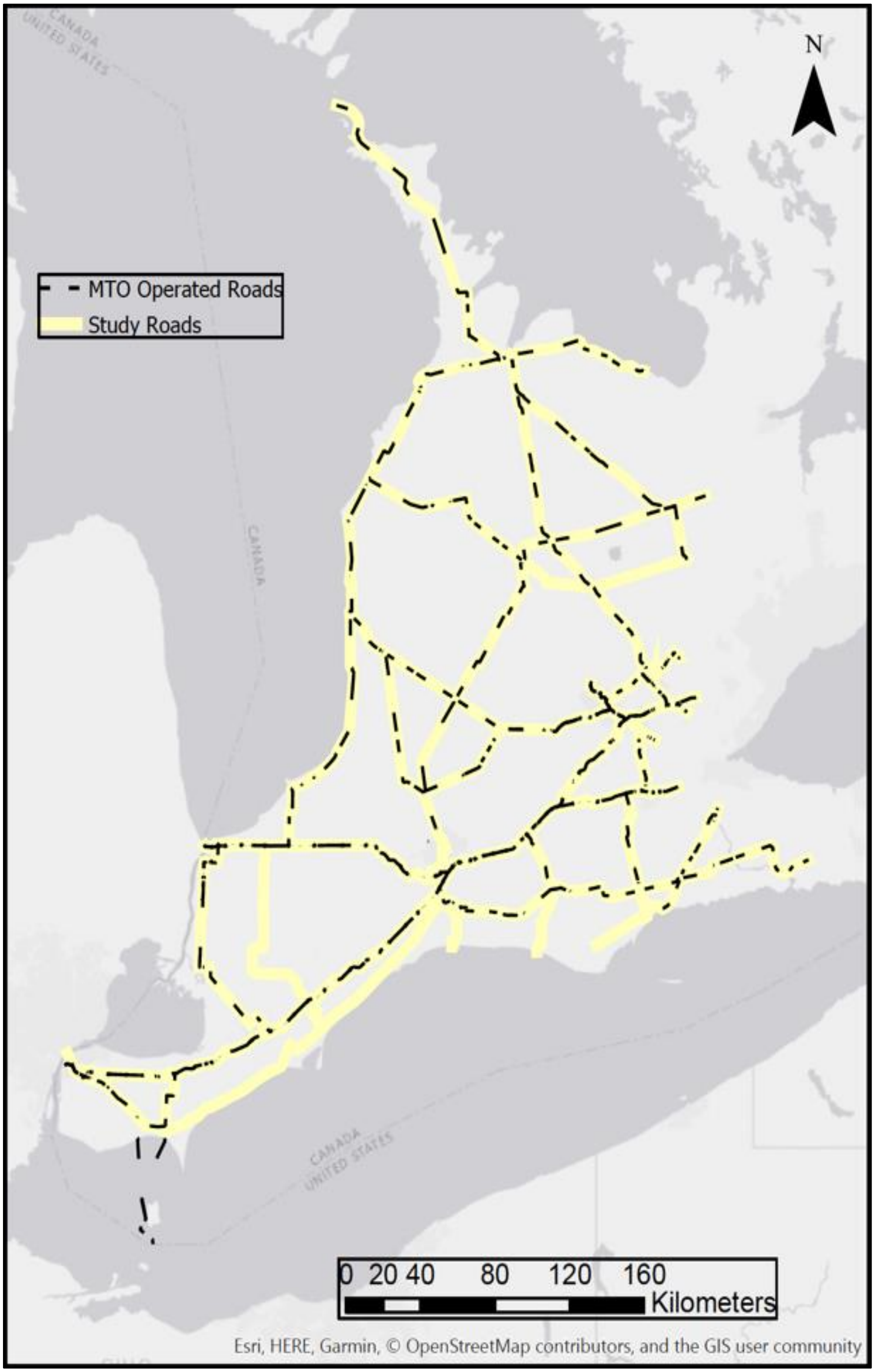

Figure 2: Roads analyzed in the MTO Western Region

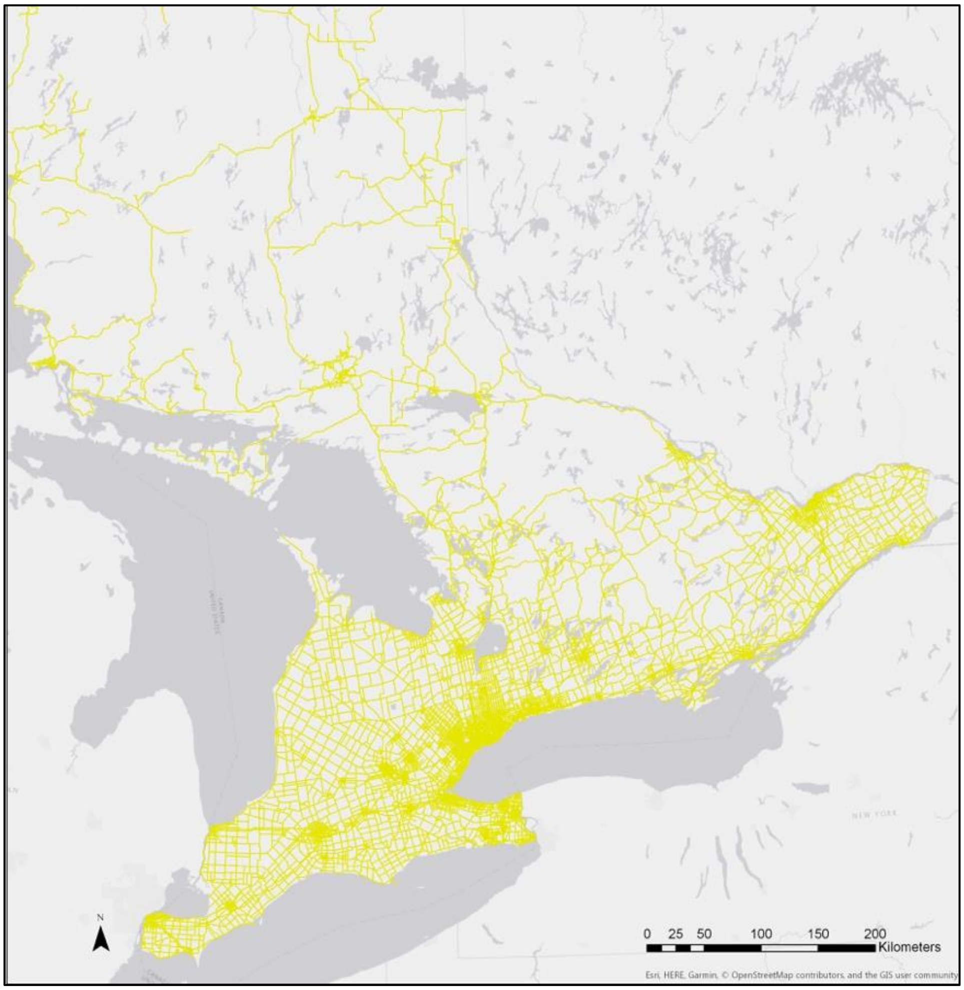

Figure 3: Roads over 60km/h in Ontario

Table 1: Classes included in the image classification process

Classes	**Explanation**
Phragmites	Class of interest
Grasses	Small ground-covering plants that occupy majority of land cover
Shrubs	Small plants that are woody/more robust than grass
Deciduous Trees	Bare leafless tree, generally indicating it is deciduous
Coniferous Trees	Conifers; still green in early spring orthophoto
Paved	Any built-up surface, such as road, building, sidewalk, etc.
Water	Streams near roads
Shadow	Land cover obscured by shadow, resulting in dark/black area

We had difficulty using eCognition to classify habitat classes in the 2015 SWOOP, 2013

SCOOP and 2016 COOP image data. We attribute this to changes in the sensor and/or post-processing that had been employed to produce the 2010 and 2006 SWOOP image data. We found insufficient spectral data to conduct an accurate image classification. The images had a large peak in blue band values that resulted in very low contrast among objects (Figure 4).

Manual digitization of invasive Phragmites

Two trained technicians were responsible for digitizing all of the *Phragmites* within MTO-operated roadways in the SWOOP 2015, SCOOP 2013 and COOP 2016 datasets. Both technicians had been trained to identify *Phragmites* as part of the eCognition classification procedure. To minimize differences in digitization between the two technicians, every road segment was digitized by both individuals and the overlap between the two was output to the final product. A typical accuracy report could not be generated for this protocol because all of the data had been manually digitized, and this was the normal method used to assess the accuracy of the automated classification. We compared the overlap to mismatch from each technician and found the ‘accuracy’ to be acceptably high (80%). Most of the error were due to small differences in boundary delineation, and how carefully technicians followed the outlines of stands with their cursor. In general, manual digitization tended to produce fewer but larger polygons whereas eCognition was able to pick out many of the smaller stands that could easily be missed by the human eye. Knowing this bias, we refrained from conducting a large-scale change detection between methods. The only way to validly compare these dates would have been to manually digitize all road segments in the 2006 and 2010 SWOOP images as well as other land cover classes. This was clearly not feasible given the amount of time we had to complete the project. Even with these differences, we could inspect the classified images to assess large-scale changes in the distribution of invasive *Phragmites* between time periods.

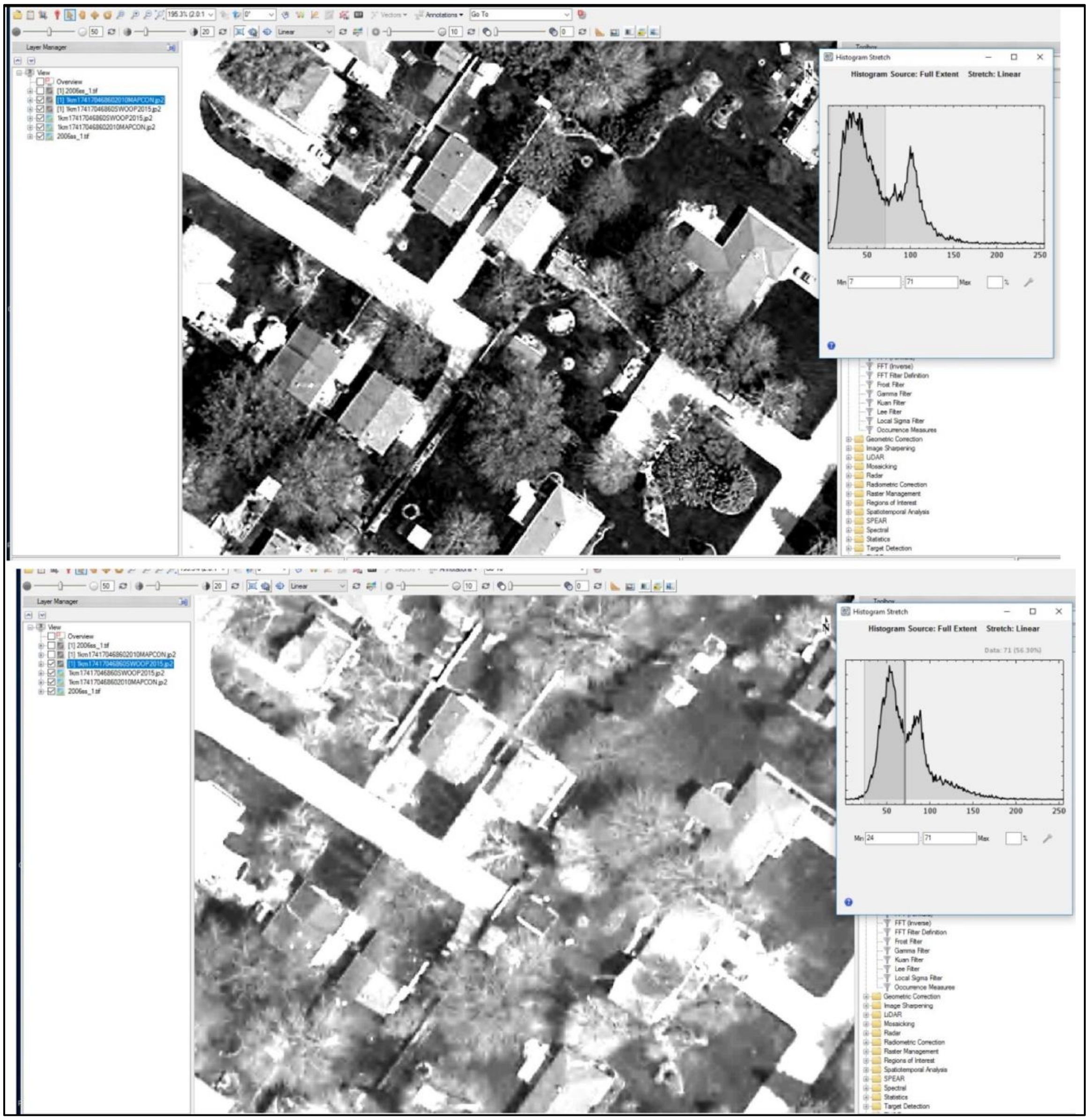

Figure 4: Photo of parcel of land taken in 2010 (top) and 2015 (bottom). Note the reduced contrast in the 2015 image and the peaking of values (bottom-right histogram) that led to our inability to perform automated image classification.

Modelling expansion of invasive Phragmites

With the data obtained from the automated image classification, we conducted stepwise regressions and multiple ANOVAs to determine what landscape factors contributed to the expansion of invasive *Phragmites* between 2006 and 2010. We omitted 2015 data from this analysis because herbicide treatments had been applied to various roadway corridors between 2012 and 2015 and would have altered the outcomes of our modelling (see Chow-Fraser & Marcaccio 2018). SCOOP and COOP data were also omitted because they were only available for a single time period in 2013 and 2016, respectively. We included land-cover data at both the micro- (habitat classes derived for the automated image classification) and the macro-scale (derived from the Southern

Ontario Land Resource Information System 2.0 (SOLRIS; 2009-2011, Ontario Ministry of Natural Resources and Forestry). We also added traffic volume as an additional explanatory variable to determine its effect on *Phragmites* distribution.

A description of the landcover classes comprising the micro-habitat scale can be found in Section 2.1 (Methods: Use of eCognition to map invasive *Phragmites*); both 2006 and 2010 data were used as inputs. SOLRIS is a database compiled by the Ontario Ministry of Natural Resources and Forestry (OMNRF) that covers southwestern and southeastern Ontario. The minimum mappable unit (the smallest discernable unit of land cover in the dataset) is 0.5 ha. Land cover classes are based on the Ecological Land Classification System (ELC; Lee et al. 1998). Independent databases created by the OMNRF were used as training data and applied to an image classification using Landsat 8 image data from 2009-2011. Multiple image years were required to ensure proper seasonality and lack of image artifacts (such as cloud cover). A list of complete land cover classes can be found at the source website (www.ontario.ca/data). For our modelling, we grouped multiple layers together to reduce the degrees of freedom, only used ecologically relevant classes, and excluded land cover classes that had very low areal cover in our dataset. Our final class layers consisted of agriculture, wetland, mixed forest, coniferous forest, deciduous forest, built-up area, aggregate extraction and open water. Traffic volume data were obtained from MTO and corresponded to the 2010 dataset.

All statistical modelling was conducted in JMP (SAS Institute, North Carolina, USA; v.13). The data were extracted as database files from ArcGIS (v. 10.4; ESRI, California, USA) and analyzed in JMP. Relevant spatial statistics (i.e. area, location) were applied in ArcGIS before data export. To appropriately analyze the data and reduce error associated with automated classification, the data were split into 1-km segment for each road, and the data were aggregated at this level. In this way, each road had multiple (>30) data 'points' with areal cover of each land cover class. SOLRIS data were extracted from a 2.5-km radius buffer around each 1-km segment; this was deemed an ecologically relevant distance while maintaining a good overview of the surrounding mosaic of landscape.

Results

Areal cover of invasive Phragmites in highway corridors

The GIS database assembled in this study includes data that span a decade between 2006 and 2015 for the southwestern region, and to our knowledge, is the only inventory of invasive *Phragmites* in highway corridors within Ontario. It also includes the distribution current to 2013 for MTO-operated roads in south central Ontario, and to 2016 for central Ontario. In most cases, we successfully classified *Phragmites* with eCognition to achieve an accuracy of 80% for the 2006 and 2010 images; however, for reasons that we have explained earlier, we were unable to obtain comparable accuracy for the other sets of image data.

In 2006, total areal cover of *Phragmites* was 26.8 ha (Figure 5). The greatest amount of *Phragmites* cover was found on Hwy 6 (5 ha) and Hwy 401 (3.4 ha). While there is a pattern of longer roads harbouring more *Phragmites*, Hwy 6 contained more *Phragmites* per kilometre than all other roads in 2006 (0.02 ha/km). While Hwy 403 had the second highest *Phragmites* density per km, Hwy 401 and 402 had closer to average densities during this early period (0.012 ha/km, average 0.011 ha/km). By comparison, Hwy 26, 9, and 40 had much lower densities per kilometre than did other highways (0.003, 0.003, 0.004 ha/km, respectively).

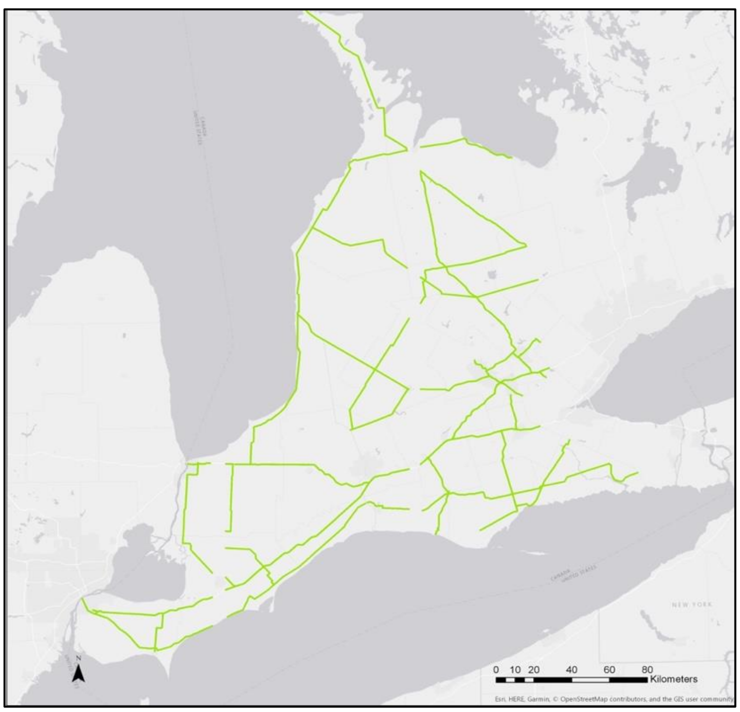

Figure 5: 2006 Phragmites distribution. The outlines of polygons have been thickened to allow them to be visible at this scale.

In 2010, total areal cover of *Phragmites* was 259.7 ha (Figure 6), a substantial increase compared to that in 2006. The average density also increased ten-fold to 0.11 ha/km, although the range of values also increased from 0.02 to 0.40 ha/km. During 2010, Hwy

6 had a median density (0.07 ha/km) while Hwy 403 had the highest density (0.40 ha/km). Hwy 402 and 401 also had high densities (0.22 & 0.29 ha/km), similar to that on Hwy 85 (0.32 ha/km).

Figure 6: 2010 Phragmites distribution. The outlines of polygons have been thickened to allow them to be visible at this scale.

By far, the greatest change in areal cover between 2006 and 2010 was associated with Hwy 401 (76.87 ha) which was double that of the next highest increase, Hwy 21 (31.81 ha) (Figure 7). The largest percent change came from Hwy 40 (2768%) and Hwy 85 (2430%). The largest change in density was seen in Hwy 403 (3.84 ha/km) which was much larger than that in Hwy 85 (3.05 ha/km), Hwy 401 (2.78 ha/km), and Hwy 402 (2.07 ha/km) (Figure 8).

The total areal cover of *Phragmites* in 2015 was 331.47 ha (Figure 9). The greatest amount of *Phragmites* was found on Hwy 401 (107.22 ha) at a density of 0.04 ha/km. The changes in areal cover and density between 2010 and 2015 had also been impacted by strategic herbicide applications that started in 2012; see Chow-Fraser & Marcaccio 2018 for a more detailed review of these data.

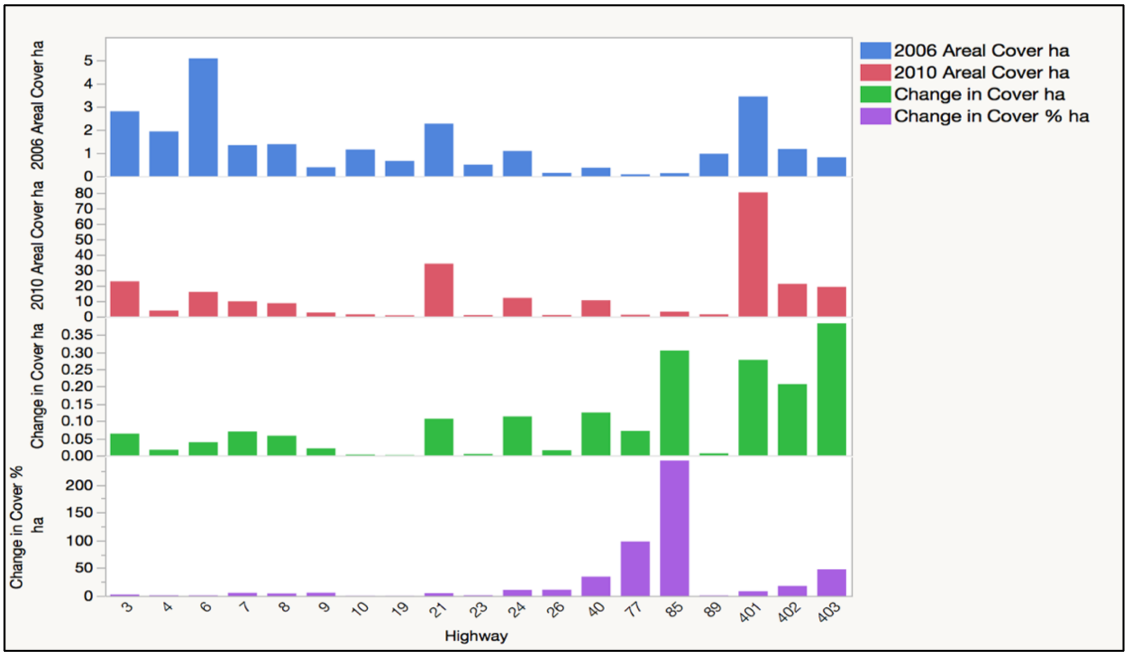

Figure 7: Change in Phragmites distribution between 2006 and 2010. The total kilometres analyzed may not represent the actual number of roadway kilometres as only segments with Phragmites were assessed.

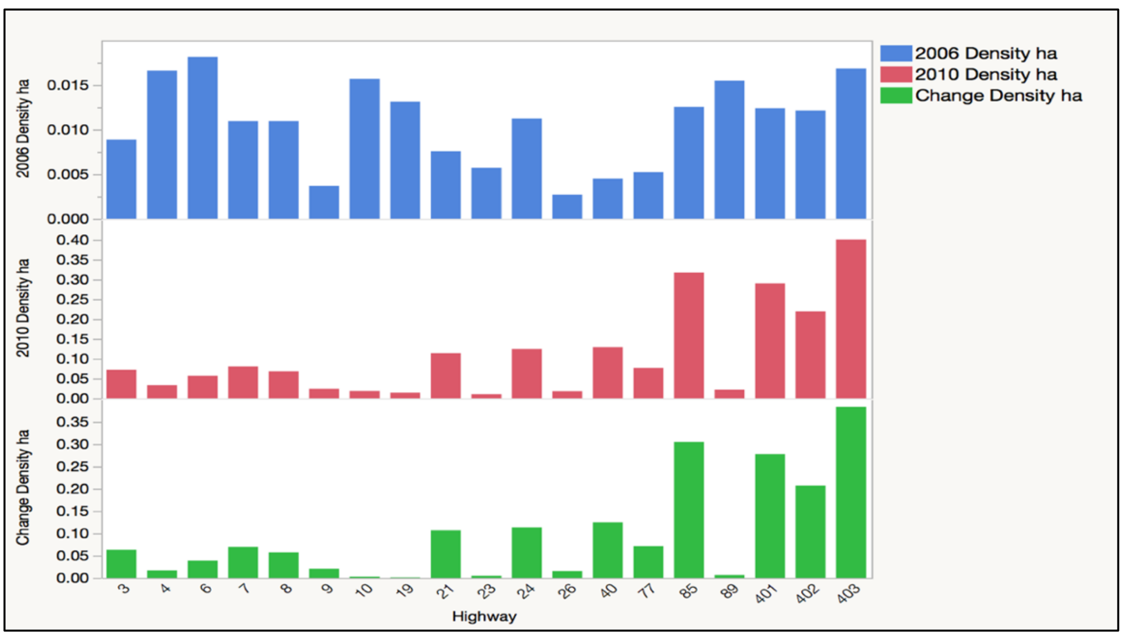

Figure 8: Change in Phragmites density between 2006 and 2010. The total kilometres analyzed may not represent the actual number of roadway kilometres as only segments with Phragmites were assessed.

Figure 9: Phragmites distribution in 2015. The outlines of polygons have been thickened to allow them to be visible at this scale.

Of all road types, the 400-series highways appeared to be most vulnerable to colonization because of their medians (Figure 10), which had been become densely colonized by 2010. Hwy 40 connects Hwy 401 and Sarnia at the western terminus of Hwy 402 (Figure 11). This is a heavily trafficked non-400-series highway that runs close to a heavily invaded marsh in the Walpole Island wetland complex. Hwy 85 is a short collector highway found in the city of Kitchener-Waterloo, and its highway corridors had very high densities throughout both time periods (Figure 12). This highway runs through a highly populated neighbourhood and serves as a northern corridor into Kitchener-Waterloo. We inspected these highway stretches and found many commission errors that may be attributed to the unique land cover in this region (Figure 13). For instance, in this stretch of highly urbanized highway, we saw unique habitat classes such as sound barriers and shadows cast by these barriers that had been misclassified as *Phragmites*. The highway was relatively short and had many unique land cover classes that contributed to errors of commission.

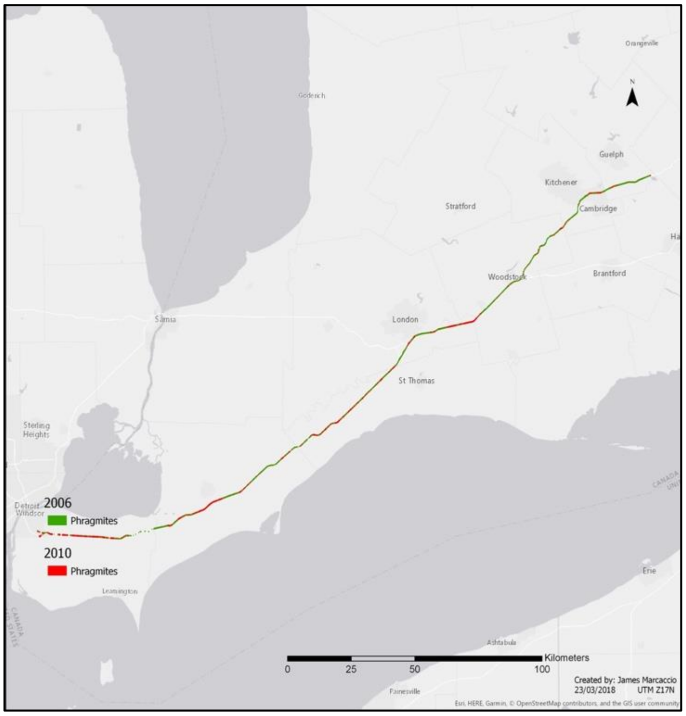

Figure 10: Phragmites along Hwy 401, which had the largest areal cover of Phragmites in our dataset.

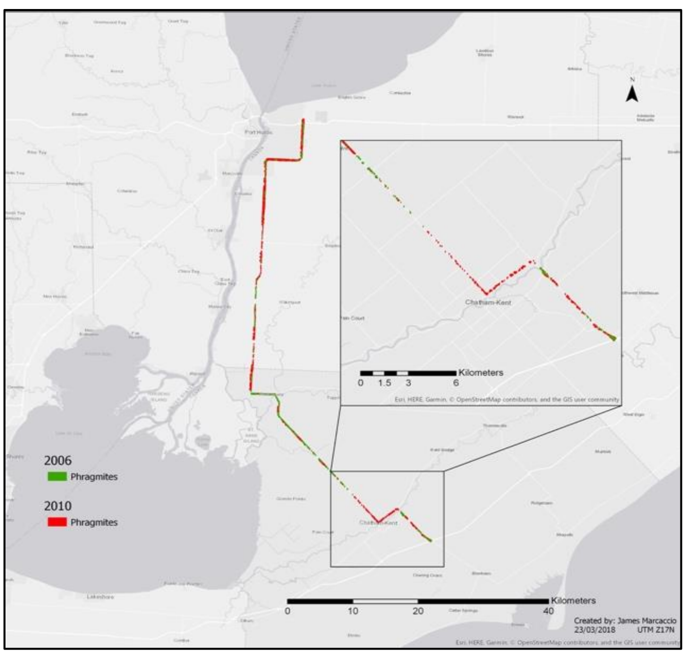

Figure 11: Phragmites on Hwy 40, one of the most densely populated roads in this dataset.

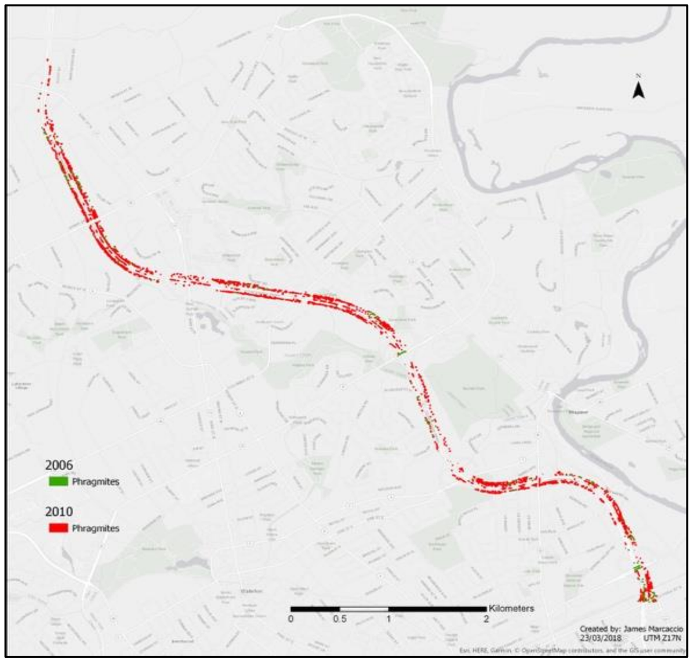

Figure 12: Hwy 85 passes through Kitchener-Waterloo and has very unique land cover compared to roadsides of other highways.

Figure 13: Sample of orthophoto over Hwy 85 showing Phragmites classified in red. Although some error is expected and some Phragmites had been accurately classified, the unique configuration of the built-up area led to numerous errors of commission.

Within the SCOOP 2013 database, we mapped 151.95 ha of *Phragmites* (Figure 14). The greatest areal cover was associated with Hwy 400, Hwy 11 and Hwy 7 (Figure 15). The greatest densities were found on Hwy 612 and 632, which are significantly higher than that on any other road in this dataset, but still lower than that found in the SWOOP dataset.

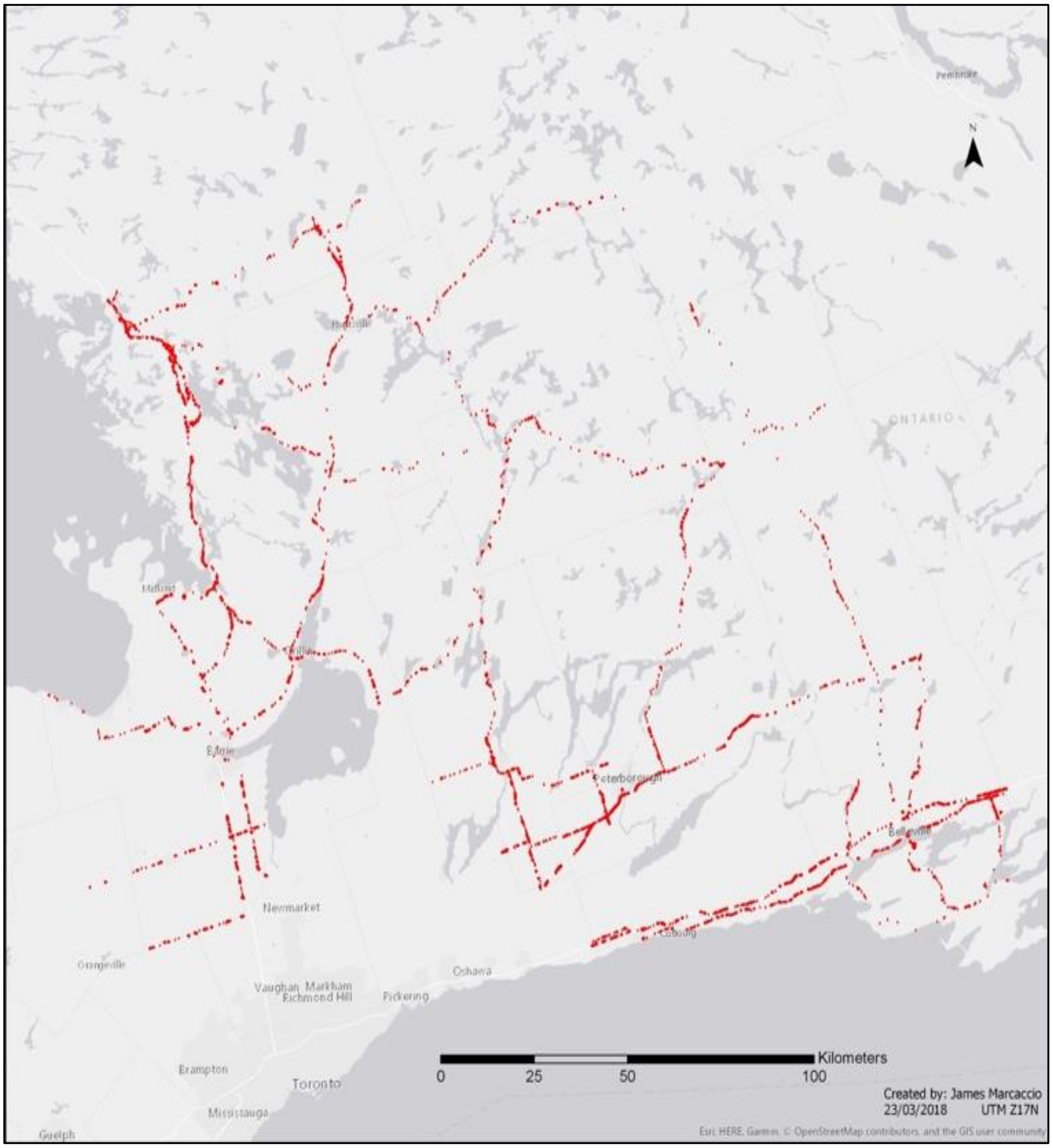

Figure 14: Phragmites distribution within the SCOOP dataset (2013).

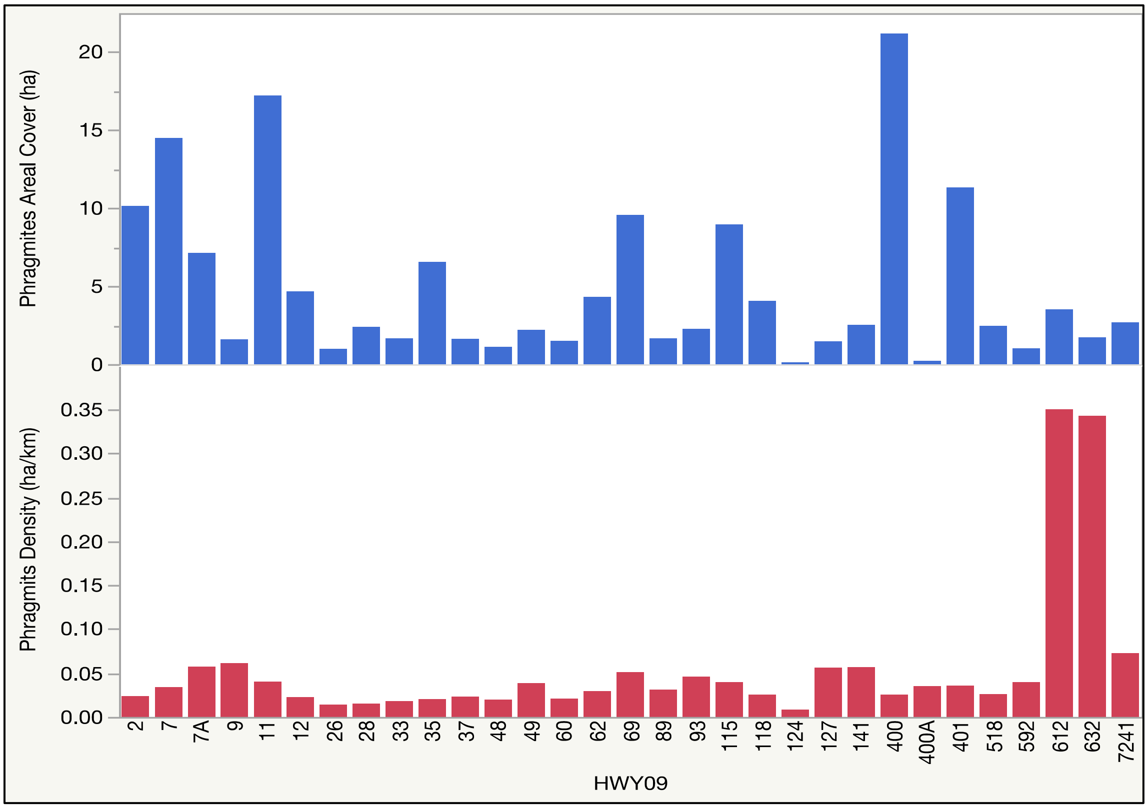

Figure 15: Areal cover of Phragmites within the SCOOP 2013 dataset.

The total *Phragmites* cover within the COOP dataset was very low (7.78 ha; (Figure 16) and this most likely reflects a very early stage of invasion. Hwy 11 had the greatest areal cover in this dataset (Figure 17). The very high density reported for Hwy 539A is an artefact, an inflated number due to only 2 kilometres having been analysed for this dataset. Figure 18 shows a better visualization of density, where Hwy 522B, 94, and 639 have the highest densities.

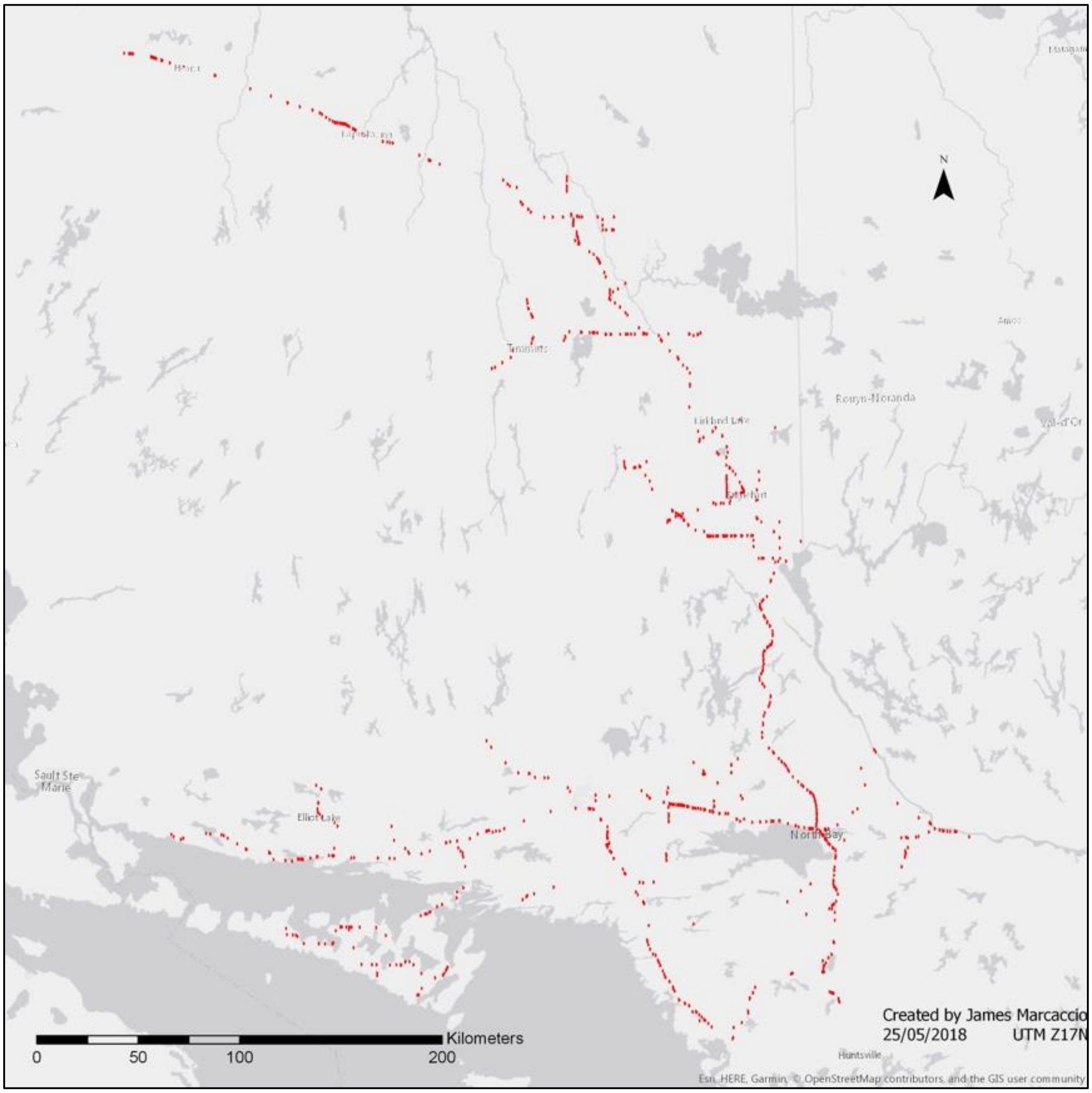

Figure 16: Phragmites distribution within the COOP dataset (2016).

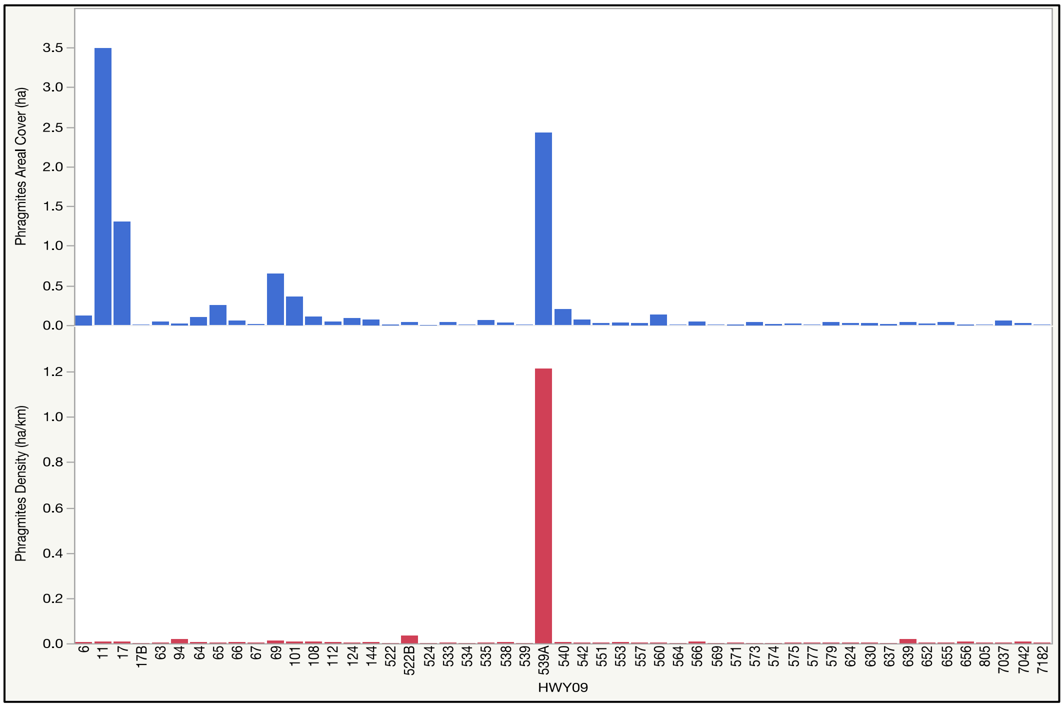

Figure 17: Areal cover and density of Phragmites within the COOP 2016 dataset.

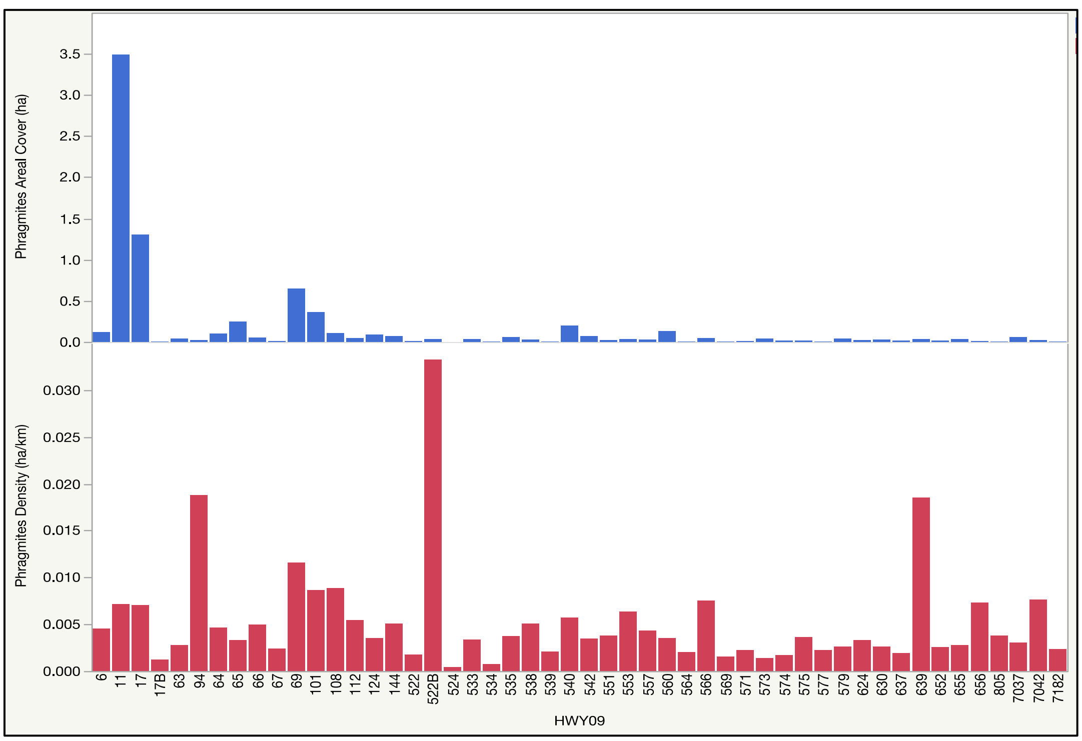

Figure 18: Areal cover and density of Phragmites within the COOP 2016 dataset, with Highway 539A removed.

Based on the most recent datasets, we have mapped 491 ha of *Phragmites* across Ontario, of which the northern datasets (SCOOP and COOP) only account for a third (160 ha combined). This lower distribution may be due in part to lower traffic volume (see Section 3.2), and perhaps to more harsh landscapes of the Canadian Shield that have less available and suitable soils. Nevertheless, if this area is not managed soon, *Phragmites* may overtake a large portion of available habitat and make it much more difficult to eradicate. Assuming that the rate of expansion (2.14/y) from 2006 to 2010 in southwestern Ontario could be applied throughout the province, the estimated 491 ha of *Phragmites* in the province could grow to 4,283 ha by 2018 and 6,660 ha by 2020 if we do not implement a comprehensive control program.

Modelling expansion of invasive Phragmites

Using a stepwise regression, we determined the variables that contributed most to explaining the variation in *Phragmites* abundance in 2010. At the micro-habitat scale, grasses, deciduous stands and *Phragmites* abundance in 2006 had the strongest positive effects while at the macro-habitat scale, agricultural and forested lands, as well as wetlands were the strongest determinants. We excluded *Phragmites* abundance in 2006 since this did not explain any additional variation in the data ($p > 0.05$) after other variables had been accounted for. Because of the large number of observations, all land-cover variables were statistically significant, although the total explained variance was low because of the large geographic area included in this analysis (Table 2). The strongest effect came from abundance of grasses in 2006. Traffic volume was also a significant predictor of *Phragmites* abundance, but only explained as much as did land cover.

Table 2: Phragmites invasion habitat modelling. Asterisks (*) indicate significance.

Model	Method	Intercept	Grasses	Conifers	Agriculture	Forests
Grasses	Bivariate	410.30*	0.03*			
Conifers	Bivariate	1439.14*		-0.04		
Agriculture	Bivariate	1651.30*			-1.33e-5*	
Forests	Bivariate	1069.84*				-4.02e-5
All	GLM	-559.62	0.06*	0.09	5e-6	-2e-5*

We had to convert roads into 1-km segments in order to standardize the observations since some roads were very long (e.g. Hwy 6), while others were very short (e.g. Hwy 85). We did not experiment with other road lengths, and it is possible that at even smaller spatial scales, some of the variables might have emerged as being more important. Previous studies have noted that land cover and geography may influence the presence of *Phragmites* on roadsides (Lelong et al. 2007, Maheu-Giroux et al. 2005, Brisson et al. 2010). These studies, however, were relatively small in geographic scope, and did not consider the areal cover of *Phragmites*. Another difference is that these other studies had been conducted in Quebec where invasive *Phragmites* had been established for quite some time, whereas it is relatively new to roadway corridors in Ontario.

One interpretation of the outcome of our modelling is that the landscape in Ontario is in an earlier stage of the invasion process compared with the Quebec situation, where roadways have already become saturated. Unfortunately, historical high-resolution image data are not often available to test this hypothesis. Future studies could determine if genotypes of invasive *Phragmites* in highway corridors differ between Quebec and Ontario; we would expect *Phragmites* occurring in close proximity to have the same genotype (spread clonally) while those that are located far apart are more likely to have different genotypes (spread by seed). Based on this information, investigators may be able to develop new control methods that take advantage of gene editing.

Conclusions

Invasive *Phragmites* is present on all MTO-operated roads in southern Ontario, and it continues to expand throughout these road networks. Divided highways with medians offer more habitat than other road types, which typically leads to greater areal cover of *Phragmites* but not necessarily the densest per kilometre. The greatest amount of *Phragmites* currently occurs in the southern portion of the province, where there are both major highways and large wetland complexes. We are aware that small populations of the less aggressive native haplotype exist within southern Ontario, and do not exhibit invasive behaviours and therefore do not need to be treated or removed. The current remote-sensing techniques, however, cannot differentiate between native and invasive haplotypes. We speculate that invasive *Phragmites* is still at an early stage of invasion and will likely continue to expand into any and all available habitat unless they are treated with suitable herbicides (see Chow-Fraser & Marcaccio 2018). This is necessary to prevent the roughly ten-fold expansion that occurred between 2006 and 2010 in southwestern Ontario.

Recommendations

Due to the change in post-processing of the Ontario Orthophotography Project databases, we do not recommend using these image data to update the McMaster Invasive *Phragmites* Database in 2020. Our data serves as an important historical assessment of roadways in Ontario that could not have been achieved with other data sources. In the future, newer technologies and sensors should be explored for image classification along roadway corridors (see Rupasinghe & Chow-Fraser 2018). Results of our modeling confirms that *Phragmites* is at an early stage of invasion with respect to roadsides. Any areas that have suitable habitat (high moisture, no existing woody plants) are likely to be colonized in short order, and existing stands will continue to expand until they meet a physical barrier.

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