Assessing Efficacy of Invasive *Phragmites* Removal in Highway Corridors with Orthophotography & Satellite Image Data: The Ontario Case Study

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Abstract

Roadside easements are a unique linear habitat that can be easily invaded by invasive *Phragmites australis.* While many North American jurisdictions have initiated control programs, few have established associated effectiveness monitoring programs. Here, we propose and apply three methods to determine effectiveness of a regional treatment program undertaken by the Ministry of Transportation of Ontario (MTO) in southwestern Ontario. We utilized 1) high-resolution spring orthophotography, 2) medium resolution multi-seasonal satellite image data and 3) high-resolution multispectral satellite image data to assess the effectiveness of MTO's treatment program. Using digitization and image classification, we deduced effectiveness of treatment programs in over 3,900 km of roadside habitat between 2010-2015 (orthophotography) and 2016-2018 (satellite data). Net decreases in areal cover of *Phragmites* were over 95% for all road types other than for major expressways, which saw decreases between 80-95% between 2010 and 2015 but only 20-55% between 2016 and 2018. The areal cover of *Phragmites* also increased more rapidly within untreated expressway habitat compared with other road types over the same time period. Although orthophotography (20-cm resolution) acquired in spring yielded good results for identification of invasive *Phragmites*, it is only available once every five years on a provincial scale. By comparison, medium resolution satellite data (Sentinel-2) provided good results within large expressways (with larger and wider easements/habitat area) but was poor for all other road types (<2 lanes). These data miss small patches which are confirmed through high-resolution satellite data (Worldview 3; <1.5m). We advocate for use of medium-resolution satellite data for annual baseline information on expressways, and high-resolution satellite data before and after treatment programs to directly assess effectiveness at smaller spatial scales.

Introduction:

Phragmites australis (Cav.) Trin. ex Steudel (invasive 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). One sub-species known as *Phragmites australis americanus* is native to North America and the rest are from Eurasia (Saltonstall 2003). Over the past two decades, Haplotype M (hereafter referred to as invasive *Phragmites*), which originated from Europe, invaded North American wetlands along the Atlantic and Great Lakes coastlines, replacing native vegetation and generally reducing biodiversity (Meyerson et al. 2000; Markle and Chow-Fraser 2018). In Canada, this haplotype was relatively confined to the St. Lawrence river until a population explosion in the 1970s, which coincided with highway construction in Montreal, Quebec (Lelong et al. 2007). Using genetic analyses, Catling & Corbyn (2006) confirmed that the *Phragmites* in road networks is the invasive rather than the native subtype.

There are only a few documented studies of the distribution of invasive *Phragmites* in highway corridors within Canada, but these have confirmed the explosive nature of this weed in road networks. Individual patches of *Phragmites* in roadsides have been observed to expand by 1.0 – 5.6 metres per year (Brisson et al. 2010). Jodoin et al. (2008) reported that 67% of 1-km segments of road in Quebec had been colonized by invasive *Phragmites* in 2003. Recently, Marcaccio and Chow-Fraser (CH 2) found that within all road types in southwestern Ontario (covering nearly 17,000 km of roads), growth of *Phragmites* increased from 275 ha to 634 ha between 2006 and 2010, an overall expansion of 230% or 58% per year. Within well-travelled highways over the same time period, there was an increased expansion rate of 969% (26.8 ha to 259.7 ha). The density of invasive *Phragmites* per kilometer of road was also over two orders of magnitude higher in highways than any other road type. With such substantial areal cover and growth, it is vital to control invasive *Phragmites* along Ontario highways to successfully manage and eradicate this species within the province.

Much more is known about the traits that have led to the successful invasion of invasive *Phragmites* in wetlands and roadside habitats. First, it is a superior competitor against other emergent vegetation (Rickey and Anderson 2004; Uddin et al. 2014) because it is 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) (Chambers et al. 1999; Saltonstall 2002). Secondly, high nutrient loading (especially in agricultural landscapes) can disproportionately benefit invasive *Phragmites* compared with other species because of its superior ability to sequester nitrogen and phosphorus (Rickey & Anderson 2004; Ge et al. 2017). It can also increase its range through secretion of allelopathic chemicals (volatile monocarboxylic acids) from its roots and rhizomes that prevent other vegetation from growing near it (Armstrong & Armstrong 2001). Finally, its ability to colonize sexually through thousands of wind-dispersed seeds (Gervais et al. 1993; Kettenring & Whigham 2009; Meyerson et al 2000), and grow clonally along linear networks (Brisson, de Blois & Lavoie 2010) allows it to aggressively colonize exposed wet habitat and then quickly expand to form dense monocultures that can extend into deep water (Armstrong et al. 1999). Taken together, increased salts, nutrients, and disturbance put other wetland plants at a competitive disadvantage compared with invasive *Phragmites* in brackish marshes (Minchinton & Bertness, 2003) and road ditches (Chambers et al. 1999; Bart et al. 2006; Brisson et al. 2010).

Environmental agencies throughout North America have used various strategies to eradicate/control invasive *Phragmites* (see Table 1). Besides mechanical treatment such as cutting, drowning, rolling, burning and covering them to prevent access to light, almost all agencies have used herbicides alone or with other mechanical control. The herbicide used most often is glyphosate, a broad-spectrum herbicide sold commercially as Roundup, Weathermax, Rodeo or Aquamaster. Effectiveness of glyphosate in controlling invasive *Phragmites* populations in greenhouse experiments (Derr 2008) and experimental plots have been reported (e.g. Reimer 1976), but these are relatively small artificial settings that do not necessarily reflect the many kilometers of invasions occurring along the linear wetlands in highway corridors. Due to the high cost (both economically and socially) associated with diverting traffic in order to safely service roadways, the only option available is to use herbicides alone. Without knowing how invasive *Phragmites* responds to glyphosate applications administered as part of routine road maintenance programs, managers cannot justify the relatively high cost of implementing such treatment programs given competing demands on dwindling budgets.

The primary objective of this study is to investigate approaches to quantify the effectiveness of treatment programs for invasive *Phragmites* occurring in highway corridors. Since these habitats are long and narrow, and occur for many kilometers, conventional remote sensing methods that have been used to map invasive *Phragmites* do not apply. For instance, large-scale mapping of common reed in the Great Lakes basin has been successful with satellite-based imaging sensors in true colour, near-infrared, radar, and combinations thereof (Pengra, Johnston, & Loveland 2007; Young et al. 2011; Bourgeau-Chavez et al. 2015;). These sensors typically have a ground-based resolution of 20-30 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. This exceeds the dimension of the average highway ditch which precludes mapping any feature of interest within their boundary. By comparison, the new medium-resolution (10 m) and high-resolution (>1.5m) satellite sensors and orthophotography (imagery taken from an airplane) can provide a much smaller minimum mapping unit. With these capabilities we can accurately assess the distribution and cover of invasive *Phragmites* throughout roadsides habitats.

Invasive *Phragmites* has been present within Ontario for many decades and the Ministry of Transportation of Ontario (MTO) has acknowledged the destructiveness of invasive *Phragmites*, both with respect to integrity of road infrastructure and to the health of adjacent ecosystems. Given the reported success of glyphosate in controlling invasive *Phragmites* populations in wetland habitats (Reimer 1976), MTO, like other agencies in North America (see **Table 1**) has sprayed highway corridors with this broad-spectrum herbicide to control *Phragmites* and other weeds in the West Region since 2012 (**Figure 1**). Since then, treatment has been ongoing on an annual basis but is limited by budget and timing with other construction projects taking precedence.

Here, we propose and apply three methods to determine effectiveness of a regional treatment program undertaken by the Ministry of Transportation of Ontario (MTO) in southwestern Ontario. We utilized 1) high-resolution spring orthophotography, 2) medium resolution multi-seasonal satellite image data and 3) high-resolution multispectral satellite image data to assess the effectiveness of MTO's treatment program. This study is the first large-scale multi-year assessment of the effectiveness of repeated glyphosate applications to control invasive *Phragmites* in highway corridors, and should yield important insights on how best to implement future effectiveness monitoring programs for Ontario and other jurisdictions in the Great Lakes basin.

Methods:

Ontario's southwestern region encompasses over 100,000 kilometres of roadways of varying size, construction type and management. In this paper, we examined the 16,900 kilometres of highways managed by the provincial Ministry of Transportation of Ontario's (MTO's) West Region which includes two-lane highways, divided highways, and large divided expressways. All of these roads have some easement associated with them that often includes a vegetated depression (ditch) which is primarily designed for hydrological reason (efficiently removing water from the roads' surface). These easements are of different sizes depending on the road (and portion within) and some expressways also have vegetated medians (as opposed to concrete/barriers).

Highways in this large study area are of two basic types, the 400-series highways (401, 402, and 403) which are expressways with multiple lanes and speed limits of 100 km/h, and the non-400 series highways that are primarily two-lane roads although some have four-lanes segments or passing lanes and are 60-80 km/h. The lengths of each road also vary greatly with Highway 6 running north-south for 472 km while Highway 77 is very short at 22.6 km. The 400-series highways are associated with much higher traffic volumes than the non-400 series highways (Marcaccio & Chow-Fraser 2019; CH 2).

Treatment data were obtained from the Ontario Ministry of Transportation (MTO) from a GIS database. These treatments were conducted by private contractors using glyphosate (concentration: 5%, spray rate: 8L/ha) on boom arms from vehicles. All treatments were completed with one application between August and October of the year indicated and included both sides of the roadway as well as the median if present. Since direct GPS data of sprayed areas were not available, we have assumed that all stands of *Phragmites* within the area delineated by the contractors were treated. In some instances, ditching may have also occurred, a process wherein a segment of the topsoil is removed to re-establish appropriate hydrological patterns to ensure proper flow of water within the easement. In these instances, all plants including *Phragmites* would be completely removed from the landscape and replaced with new soil and seedlings. Additionally, occasional cutting treatments have been conducted throughout the study area but the focus of these were for road safety and drainage maintenance rather than removal. As the amount of mechanical treatment was low compared to herbicide treatment (<40 km), these were not considered as a separate treatment group within the dataset.

An automated image classification was conducted for the 2010 Southwestern Ontario Orthophotography Project (SWOOP) image data (see Marcaccio & Chow-

Fraser, 2019; CH2 for details), and manual digitization was employed for the 2015 SWOOP image data. All 2015 data were digitized by two technicians and only polygons that were within agreement between both technicians were included. In lieu of field data, a third technician compared the digitization against Google Earth and Google Streetview data from the same time periods to ensure accuracy. These data only include *Phragmites* as a land cover class as delineating other classes was too time consuming. Although these datasets had the same resolution, we could not directly compare individual polygons as each method of identifying invasive *Phragmites* (image classification in 2010 versus manual digitization in 2015) produced similar areas but different polygon sizes.

For the 2016 and 2018 comparison, Sentinel-2 (10 metre resolution) image data were processed in ENVI (v. 5; Harris Geospatial, Colorado, USA) with the multi-temporal support vector machine (SVM) tool. For each year, three images were acquired in spring, summer, and fall and these were combined to enhance our ability to distinguish *Phragmites* from other land-cover classes. Worldview-3 (1.25 metre resolution) data were also acquired from the summer (August) of 2016 and GeoEye (1.25 metre resolution) from summer 2018 and were manually digitized to determine the accuracy of the Sentinel-2 classification (**Figure 2**). Due to the difference in pixel size between products, we assessed the level of agreement between datasets based on the *proportion* of patches in the high-resolution datasets that were successfully identified in the medium-resolution datasets, rather than the absolute areas. Additional comparisons between these datasets were conducted to determine the geometric differences in patches from medium-resolution data versus the patches from high-resolution data.

Within each dataset, a change detection was conducted by splitting each road into 1-km segments and determining changes within these segments to standardize units of measure and to account for errors and misaligned pixels between years (which would result in false changes in boundaries for each invasive *Phragmites* patch). Areal cover in the earlier year that decreased (was no longer visible) in the later year was interpreted as having been successfully treated, while a stable (remained) or increasing areal cover was deemed to have been unsuccessful. We only report increases and decreases by road within the area that was treated and not the entire length of the road due to the differences in geographic distribution and length of some roads.

Details on the results of the 2010 image classification with spring orthophotography have been documented elsewhere (Marcaccio & Chow-Fraser 2019; CH2). The 2015 image data had been manually digitized due to use of a different sensor and pre-processing method that resulted in compressed data that were no longer suitable for automated image classification. For our comparison between 2010 and 2015, 16,900 km of roads and their habitat were mapped (Figure 3). This represented all roads that MTO currently manage, along with additional portions of roads where data on completion of treatment had been provided by MTO for use in this project. Although the 2010 and 2015 image data were from spring, we were able to clearly identify invasive *Phragmites* stands because they do not senesce and collapse like other vegetation, but remain tall and visible throughout the winter and spring. Since the 2015 data represent growth through 2014 (and not 2015), we only considered treatments conducted in 2012, 2013, and 2014.

Results

In total, between 2010 and 2015, MTO treated 2,331 km of unique road segments (Figure 3), and removed 213 ha of invasive *Phragmites* (Figure 4). Despite this, the total area of invasive *Phragmites* still increased by 18 ha, presumably because of growth and expansion of *Phragmites* that had not been effectively treated. While treatments were effective for all roads, lower efficacy was observed for Hwy 401, 402, and Hwy 40 (a bypass road between the western portion of Hwy 401 and 402; Figure 5). While the 403 had a high removal rate, the total length of roadway within this study area was quite short (only 48 km) compared to Hwy 401 and 402 (255 km and 94 km, respectively). Compared with the 400-series highways, removal rates for all other highways were significantly higher (t-test, $P<0.001$; Figure 6). Timing of treatment also appeared to affect efficacy; road segments that had been treated more recently were associated with higher removal rates. In this study, repeat treatments did not have a significant effect on the outcome of removal because of confounding effects of road type (i.e. only 400-series highways were treated twice). A major driver of the expansion of invasive *Phragmites* was the total areal cover that had been present in 2010 (Figure 7a). Similarly, resistance to treatment was also a function of historic areal cover (Figure 7b).

Between 2016 and 2018, only the 400-series highways and a short length of smaller roads were treated and as such we conducted our analyses on only the 400-series highways (Figure 8). Using Sentinel-2, we found many areas of net decrease where treatments had taken place, but these did little to diminish the total expansion of invasive *Phragmites* across the entirety of the roadways (Table 2). Repeated treatment over two years on Highway 401 led to the best results for removal within these areas, but they did not approach those levels seen in our earlier analysis (Figure 8a). According to previous analyses (2010-2015), smaller patches of *Phragmites* responded best to treatment. Given we used the Sentinel 2 image for the 2016-2018 analysis, the 10-metre pixel resolution could not be used to accurately identify patches larger than 100m^2 (Figure 9), which is much larger than the 1 m^2 patches identified in orthophotos (20 cm pixel, with minimum object size in eCognition equal to 4 pixels) and manual digitization of 1.5 m image data (Table 3).

By comparison, our high-resolution satellite data (WorldView-3 & GeoEye) could be used to identify much smaller patches similar to that obtained through orthophotography (Table 3). Of the 163ha in 2016 and 138 ha in 2018 of study area mapped, 90 ha of these overlapped spatially and all of the invasive *Phragmites* in this area had been treated. In addition to the inherent difference between manual digitization and automated image classification with respect to polygon size, these products were also different in terms of areal cover. Sentinel-2 overestimated by 142% in 2016 and 213% in 2018 (Table 3). Treatment effectiveness in this study area as determined by Sentinel-2 showed only a 27% decrease. With high-resolution data, however, treatment effectiveness showed a 51% decrease, which is closer but still lower than that obtained in the 2010-2015 analyses (>80%). This confirms our earlier finding that smaller stands of *Phragmites* are more easily eradicated with glyphosate treatment. If patches < 100m^2 (smallest size of Sentinel-2 patch) are removed from the high-resolution data, the change in invasive *Phragmites* areal cover is small. These findings indicate that the

Sentinel-2 data had overestimated areal cover of *Phragmites* because of its coarser pixel size.

Discussion

Roads have been hypothesized to be a major long-distance transporter of invasive *Phragmites* (Lelong et al. 2007), and Marcaccio and Chow-Fraser (2019; CH2) have shown how rapidly it can expand within southwestern Ontario from 2006 to 2010 when they are left untreated. From road ways, they can also expand quickly to other adjacent disturbed habitats (Ailstock, Norman, & Bushman 2001). Therefore, the unchecked growth of invasive *Phragmites* is a problem not only for the integrity of road infrastructure, but also for biodiversity conservation in natural ecosystems.

Due to management constraints and logistics, all treatment programs took take place in late summer, when efficacy was typically lower for glyphosate applications (Mozdzer et al. 2008). Because there had been no baseline mapping of invasive *Phragmites* prior to 2015, MTO carried out their treatment program without knowing the full extent and distribution of infected corridors. Even with these constraints, we have found good rates of removal across the study area. Due to the extent of the invasion in 2012 and lack of previous management, any removal efforts were likely to produce positive results in the short-term. The uniform recommendation by all agencies to repeat treatment (see Table 1), which are well supported by the literature (Riemer 1976, Turner & Warren 2003, Derr 2008, Lombard, Tomassi & Ebersole 2012) means that appropriate and consistent mapping must also be carried out to ensure that management actions are appropriately allocated and continue to be effective.

Overall, the results of our 2010-2015 analyses were acceptable in terms of invasive *Phragmites* removal; however, despite the effectiveness, we found an increase in distribution of *Phragmites* in 2015 that was primarily from new growth and regrowth from treated stands that varied from <1 to 27%. Both new growth and regrowth were more prolific on the 400-series highways. We also found that patch size of *Phragmites* had a significant influence on both efficacy of glyphosate treatment and the colonization rate, and that the 400-series highways tended to have larger patch size than other road types. We had no evidence of complete eradication, and this may be due to the large size of patches in particular road types, and the low frequency of invasive *Phragmites* treatment between years.

We have also found that smaller stands on the fringes of the invasion front (north in this study) are more easily removed than dense stands on invaded highways (Figure 4). Removing these fringing stands can help limit the spread of *Phragmites* into novel habitat as this plant can reproduce effectively over large distances by seed (Fér & Hroudová 2009; Kirk et al. 2011). Since these small stands are difficult to identify with traditional satellite-based remote sensing products, more effort should be focused on finding an effective strategy for early detection. Future studies can and should consider developing a landscape-level model for *Phragmites* expansion and management in roadsides similar to what Duncan et al. (2017) and Long, Kettenring & Toth (2017) created for wetland systems; the unique spatial attributes of roadsides may require different parameters and considerations for a successful modelling approach to be created.

We found a reduction in effectiveness on large freeways with larger easements and greater habitat availability. These roads often have much larger patches of *Phragmites*; we cannot determine through remote sensing methods whether these come from one clonal stand or convergence of multiple unique genetic individuals. Larger *Phragmites* patches are extremely difficult to fully eradicate and thus may limit the apparent effectiveness of any control program along well colonized roadsides when viewed on shorter (< decadal) time scales (Quirion et al. 2017). While a decrease in total areal extent is possible, it is likely that roads such as the 400-series highways will need to be managed for decades longer before they are fully eradicated. In addition, these roads were only treated once in 2012 compared to others which had been treated closer to 2015 and/or treated multiple times.

The 400-series highways are associated with higher traffic speeds (100 km/h vs <=80km/h) and much higher traffic volumes than other road types (Marcaccio and Chow-Fraser 2019; CH 2). These roads also have large on/off-ramp complexes that are difficult to manage due to their depth and width (limiting the area possibly treated by roadside vehicles) and the creation of artificial wind vortexes which affects the distribution of airborne particles of glyphosate (MTO, personal communication). The combination of these factors has been hypothesized to lead to increased frequency and distance of seed-borne dispersal through artificial winds and direct attachment to vehicles (Ailstock et al. 2001). This would make repeat treatments an absolute necessity as even small patches of invasive *Phragmites* left behind could easily repopulate long stretches of these roads.

A notable anomaly in our dataset was Hwy 40, which had similarly low efficacy to those reported for Highways 401 and 402, but is a two-lane highway (**Figure 5**). The invasion pattern on this road was similar to those of other non-400 series highways and was also constructed in a similar fashion to other highways (two lanes with no divided median). We speculate that high volume of traffic on this road and source populations of invasive *Phragmites* may explain this anomaly. Hwy 40 was constructed as a west-end link between two very busy highways (Hwy 401 and 402) before they crossed two international border crossings near Sarnia and Windsor, Ontario. It is also located east of and in close proximity to the St. Clair river, Lake St. Clair, and the Walpole Island wetlands, which is currently densely populated with invasive *Phragmites* (Wilcox 2012). With the predominant winds being westerly in this area and a flat, agricultural landscape, it is possible that the wetlands act as a source of invasive *Phragmites* seeds that continuously invade Hwy 40 and the western ends of Hwy 401 and 402. Genetic analyses could help test this hypothesis and elucidate the underlying causality.

As mentioned earlier, the 2010-2015 comparison did not bear out the merit of repeated treatments on these highways. We were, however, able to support this using the 2016-2018 comparison (Table 2). Our data also showed that regrowth of invasive *Phragmites* can outpace the efficacy of treatment programs, especially if viewed on a road-by-road (not kilometre-by-kilometre) basis. Care must be taken to consider smaller units of roadway to accurately assess impacts especially when roads are relatively long and only a small subset of the road is actually treated.

The degree of expansion in 2015 appears to be directly related to the amount that had been present in 2010, and this is consistent with observations that *Phragmites* expands clonally (Figure 7a, Jodoin et al. 2008, Bellavance & Brisson 2010). While we cannot directly compare individual patches due to the differences in how the data were processed, our data are consistent with clonal expansion of invasive *Phragmites* that had existed historically. We do not believe that seed-based dispersal had occurred over these small distances, since high winds generated by traffic across these landscapes are expected to be associated with longer seed dispersal distances. Similarly, our finding that degree of resistance to treatment (amount of *Phragmites* that remained unchanged following treatment) was directly related to the amount that had been present in 2010 (Figure 7b) again points to difficulties in eradicating more heavily infested landscapes.

We emphasize the importance of using the same type of image data to permit valid comparisons. This was the most challenging aspect of monitoring across different time periods in this study. The only way to use SWOOP image data (scheduled to be acquired in 2020) for future comparisons would involve labour-intensive and tedious manual digitizations, and we do not recommend this approach. Instead, we recommend using multi-season image classification of Sentinel 2 or 3 satellite data on large highways (such as the 400-series highways) for periodic updates. Unfortunately, the relatively narrow and linear nature of roads mean that even 10-metre resolution is simply too coarse in most circumstances. Along a typical highway in southwestern Ontario the easements can be 5 metres, which results in an abundance of mixed pixels.

Although effectiveness monitoring was acknowledged as a necessary component of treatment programs by all agencies that we surveyed (see Table 1), none of the agencies documented how to accomplish this using either remote sensing or field surveys. Of the three approaches used in this study, those involving satellite image data are directly transferable to other jurisdictions. Nevertheless, we only recommend using the high-resolution satellite data (e.g. Worldview 2, 3 or Geo-Eye) to map individual *Phragmites* stands for a select number of smaller highways. As these high-resolution data are not freely available, their use will be limited to agencies with available budgets and expertise. By conducting image classifications before and after treatment, areas in need of repeat treatment can be identified and efficacy can be determined. As we and others have noted, repeat spot treatments are extremely effective in reducing *Phragmites* cover throughout the landscape and only manual field work or high-resolution data will suffice for this purpose.

Our results are reported solely as areal cover and give no indication of biomass or density of invasive *Phragmites* present within each patch. The density of patches is known to have a significant influence on treatment efficacy because patches with higher stem counts are less responsive to treatment (Quirion et al. 2017). This may account for some variability in treatment effects in this study. Preliminary data suggest that *Phragmites* stands on the 400-series corridors are not only larger, but also much denser (DeBoer and Chow-Fraser, unpub. data). Although biomass/density determinations may require multi-spectral image data, the results would prove especially useful for managers to estimate amount of glyphosate that is required to effectively treat the amount of *Phragmites*.

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Table 1. Targeted survey of current control programs for invasive *Phragmites* in roadways and wetlands throughout N. America

Authors/Agencies	Type of habitat	Herbicide Used/Options	Mechanical Treatment Used or Recommended	All Treatments Used	Recommendation for spraying in consecutive years	Disposal Methods	Post Treatment Monitoring	Results of Effectiveness After Year 1	Results of Effectiveness After Year > 2
BMPs from Canada									
Kincardine (2013)	**Wetlands and shoreline**	Glyphosate 4-5% (Weathermax)	Burning	ATV spraying, backpack spraying, hand-wicking, prescribed burns	Yes	Rolling/Burning	Yes	Speaks of U.S. combining Glyphosate and Imazypyr for 80-100% kill	N/A
Ontario Ministry of Natural Resources and Forestry (2011)	**Generic habitats**	Glyphosate	Cutting, tarping, solarization, drowning, rolling,	Spraying, cutting, tarping, solarization, drowning, rolling	Yes	Bagged in thick plastic, then dried out in the sun. Once dry can be burned or disposed of	Yes	N/A	N/A
Ontario Phragmites Working Group. (2015)	**Roadways**	Glyphosate 4-5%	Rolling, cutting,	Spraying, wicking, wet blade, rolling, cutting, burning,	Yes	Burying, covering (3m deep), covering with heavy plastic, burning, or dispose in an open agricultural field where emerging plants can be treated	Yes	70-95%	For most cells, complete control can be expected after two treatments
BMPs from USA									
Brigham City, Utah (2007)	**Wetlands**	Glyphosate 2%	N/A	Spraying and Burning	Yes	Burning	Yes	N/A	N/A
King County (2010)	**Roadways and generic habitats**	Glyphosate (Rodeo and Aquamaster) and Imazapyr (Habitat)	Spading young plants, repeated cutting before tasseling	Spading, cutting, wick wiping, herbicide spraying, burning	Yes	Place roots, rhyzomes, and seed heads in sturdy plastic bags and dispose. Stems left on site for compost or burning	Yes	N/A	N/A
Michigan State and Partners n.d.	**Roadways and generic habitats**	Glyphosate (six pints per acre), Imazapyr (six pints per acre), or even mix	Hand tools, weed whips, small mower	Spraying, burning, flooding, mechnical treatments,	Annual maintenance	N/A	Yes	N/A	Annual spot treatments of pioneer colonies 100%
New York State DOT Adirondack Park (2014)	**Roadways**	No specific mention in the BMP	Spading young plants, pulling, digging	Spraying, cutting, pulling, digging	Yes	Drying/liquefying, Brush Piles, Burying, Herbicide	Yes	N/A*	N/A*
Janice Gilbert for Lake Huron Centre for Coastal Conservation (2016)	**Roadways and generic habitats**	Glyphosate	Covering, smothering, rolling, drowning, cutting, spading	Spraying, hand wicking, burning mechanical control	Yes	N/A	Yes	N/A	N/A

N/A = not available *In a webinar (October 2017), reported that probability of eradicating (i.e. no growth after 3 y) decreased drastically with treatment area; 83% for 0.36 sq. m vs 26% for 45 sq. m vs 1% for >3000 sq. m. Also noted that 60% returned after one year of treatment; minimum 20% returned after 2 consecutive years of treatment and <5% after 3 consecutive years.

Table 2: Changes in areal cover (ha) of invasive *Phragmites* for 400-series highways based on automated image classification of Sentinel-2 satellite image data. Highways were classified as either “Treated” or “Untreated”, depending on whether they received glyphosate or not, respectively during 2016.

Hwy series	Type	Total area analyzed	Area in 2016	Area in 2018	% change from 2016
401	Untreated portion	1200	137.5	172.6	+25.5
	Treated portion	875	63.0	28.9	-54.1
	Entire highway	2075	210.5	201.5	-4.3
402	Untreated portion	606	57.2	74.0	+29.3
	Treated portion	616	41.0	33.3	-18.8
	Entire highway	1222	98.2	107.3	+9.3
403	Untreated portion	195	6.4	7.0	+9.4
	Treated portion	450	11.3	8.2	-27.4
	Entire highway	645	17.8	15.2	-14.6

Table 3: Comparison of spatial attributes of invasive *Phragmites* patches identified with Sentinel-2 (S2), Worldview-3 (WV3), and GeoEye (GE) data.

	Medium resolution (S2)		High resolution (WV3 and GE)	
Total Study Area in 2016 (ha)	163.3		163.3	
Total Study Area in 2018 (ha)	138.0		138.0	
Intersected Study Area (ha)	90.4		90.4	
Phragmites 2016 (Total ha)	16.2		10.8	
Phragmites 2018 (Total ha)	9.1		3.5	
Phragmites 2016 (Intersected/Treated ha)	9.5		6.7	
Phragmites 2018 (Intersected/Treated ha)	6.93		3.3	
All Change 2016 - 2018 (Intersected, ha)	2.57		3.4	
Mean polygon size (2016) (Intersected, ha)	0.052		0.050	
Standard Deviation (2016)(Intersected, ha)	0.084		0.104	
Mean Polygon size (2018)(Intersected, ha)	0.029		0.042	
Standard deviation (2018)(Intersected, ha)	0.035		0.067	
Minimum Polygon size (Intersected, ha)	0.0100		(WV3) 0.000927	(GE) 0.001897
Area from (<minimum polygon size of S2) (Intersected, ha)	0		(WV3) 0.2738	(GE) 0.1143
Area from (>min size S2)(Intersected, ha)	(2016) 9.5	(2018) 6.93	(WV3) 6.3767	(GE) 3.1451

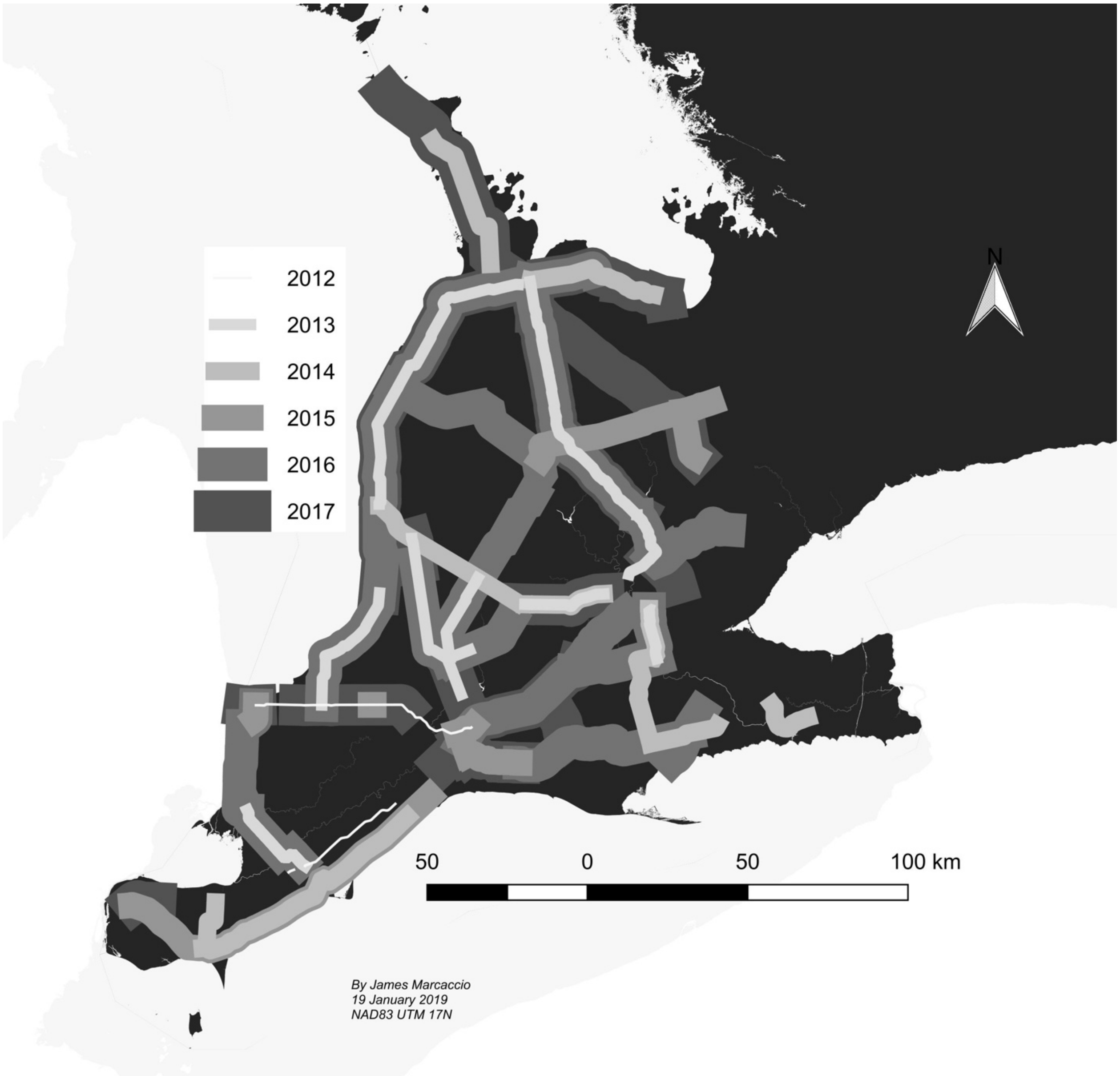


Figure 1: Roads in West Region that had been treated with glyphosate between 2012 to 2017.

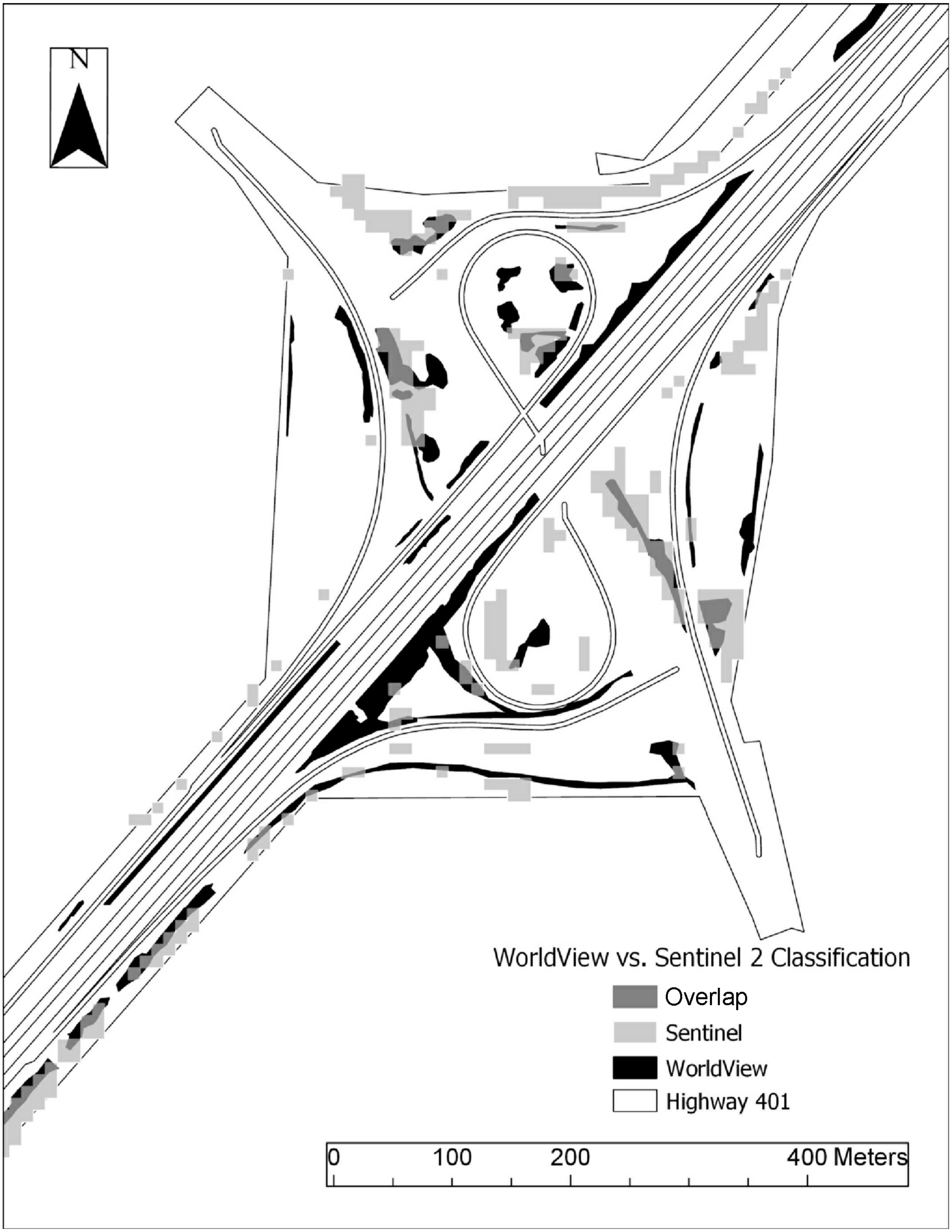


Figure 2. Automated image classification identifying invasive *Phragmites* (light grey) compared to manual digitization of invasive *Phragmites* (black).

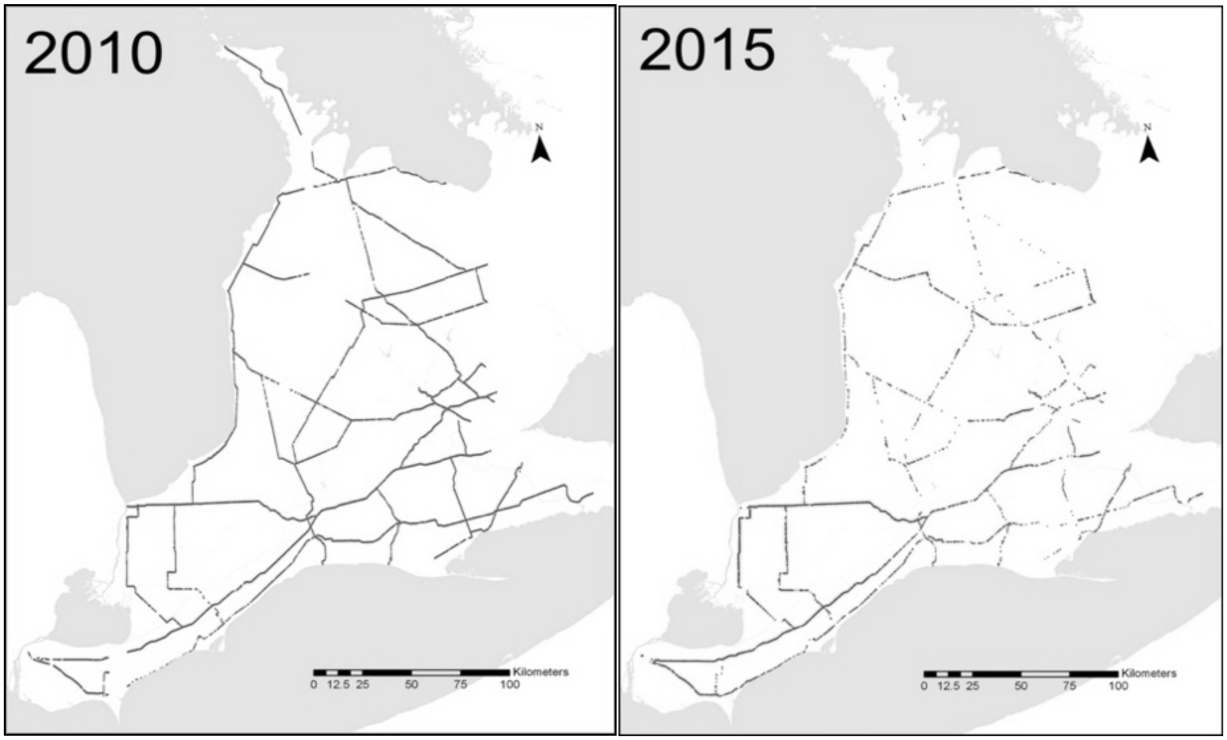


Figure 3: Comparison of 2010 and 2015 distribution of invasive *Phragmites* (black) in highway corridors.

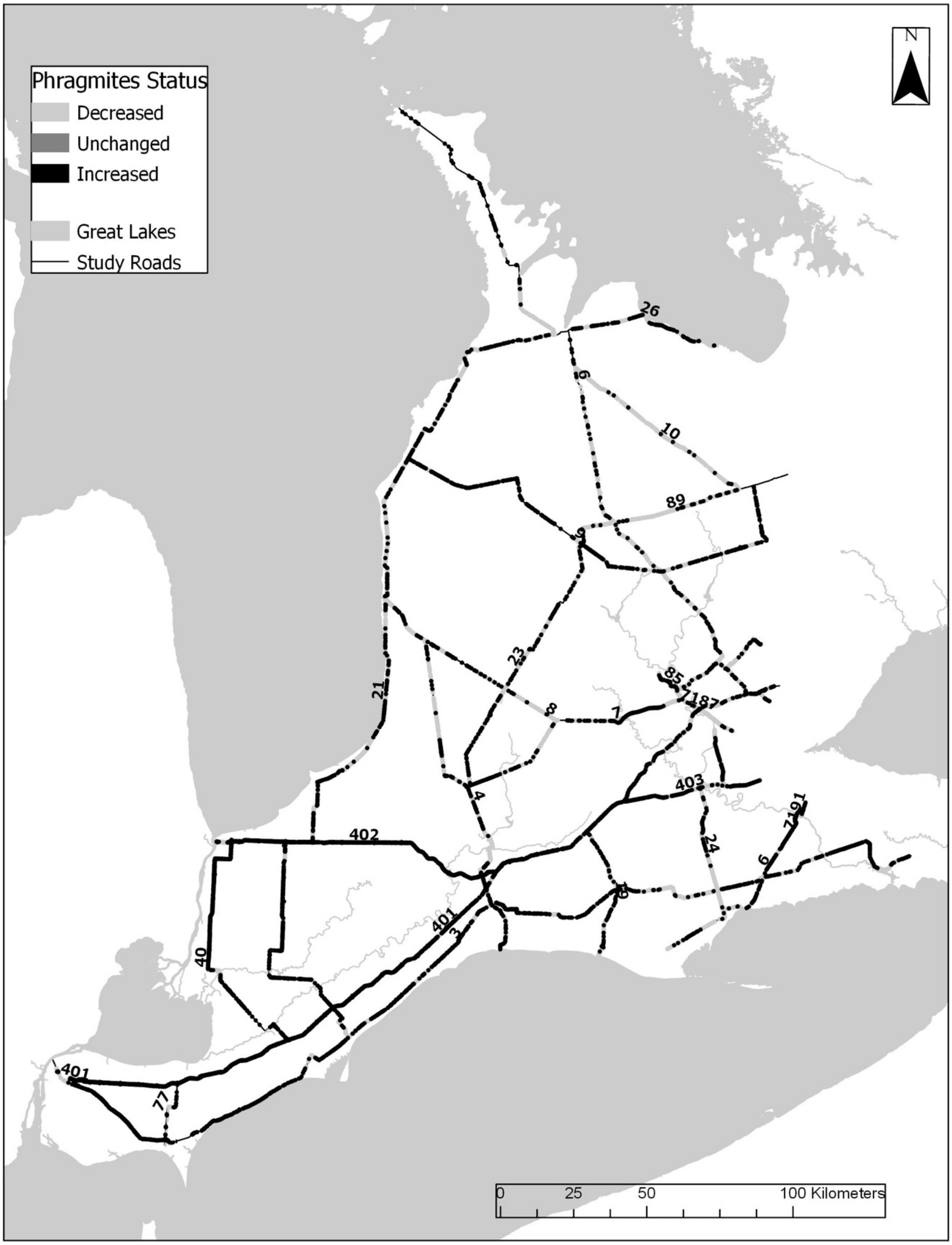


Figure 4: Results of a change detection of invasive *Phragmites* occurring in highway corridors of southwestern Ontario between 2010 and 2015, based on SWOOP image data only.

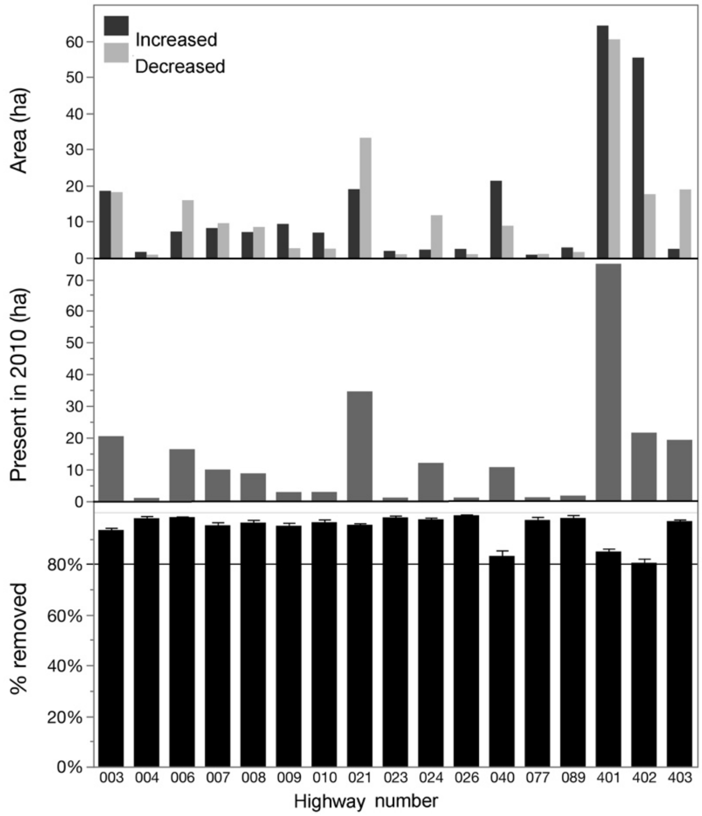
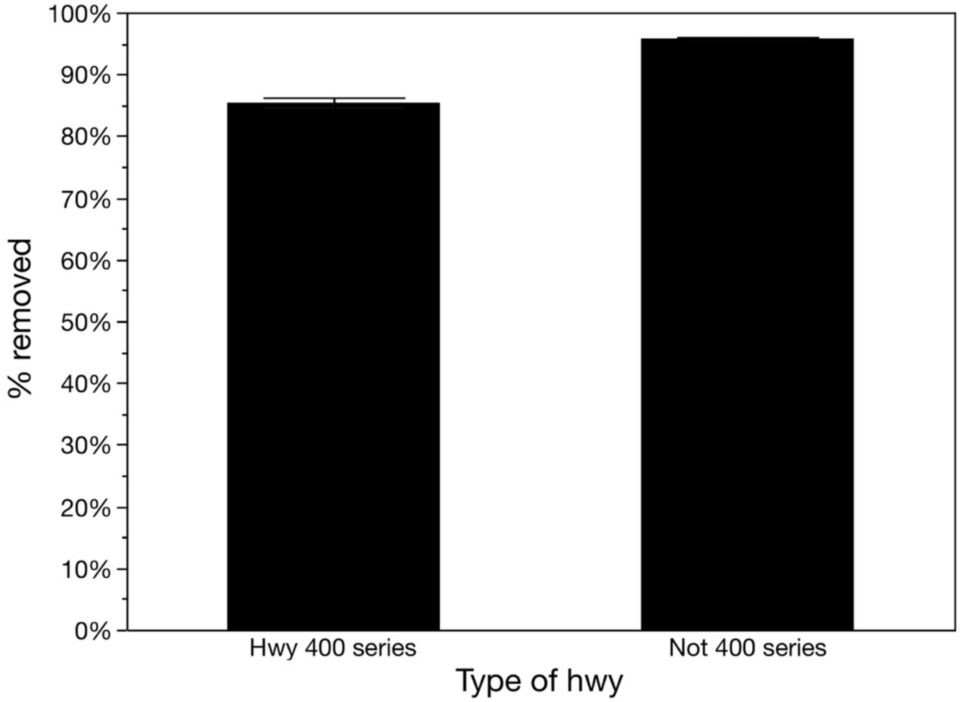


Figure 5. Top: Invasive *Phragmites* areal cover that had increased/grown (black) and decreased/removed(grey) between 2010 and 2015, by road. Middle: Invasive *Phragmites* present in 2010 by road. Bottom: Invasive *Phragmites* removed by road. The black line corresponds to an 80% removal rate.

a)



b)

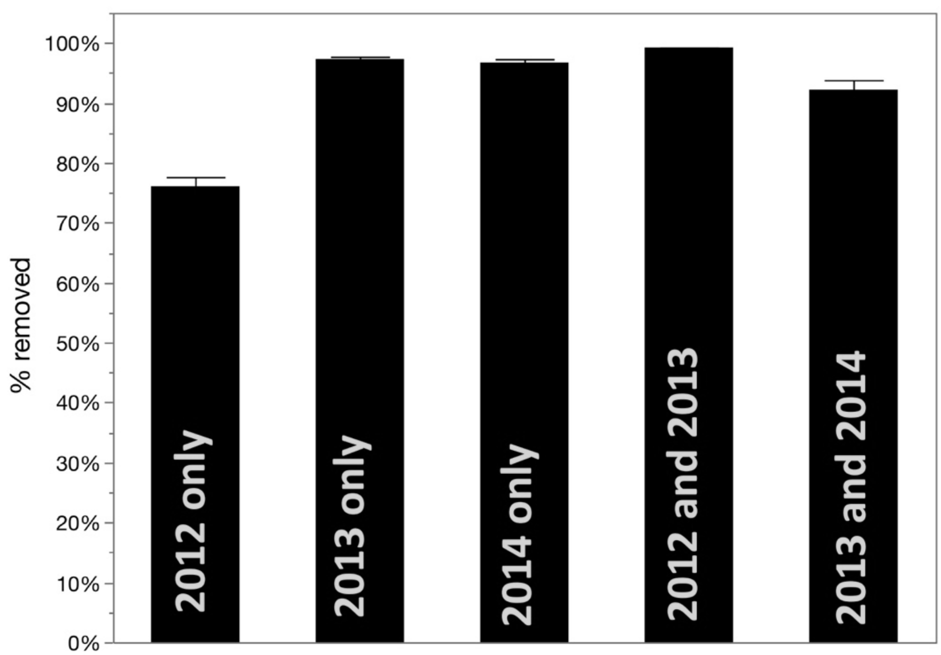


Figure 6. Percentage *Phragmites* removed for a) 400-series and non-400 series highways and b) roads grouped according to when they had been treated.

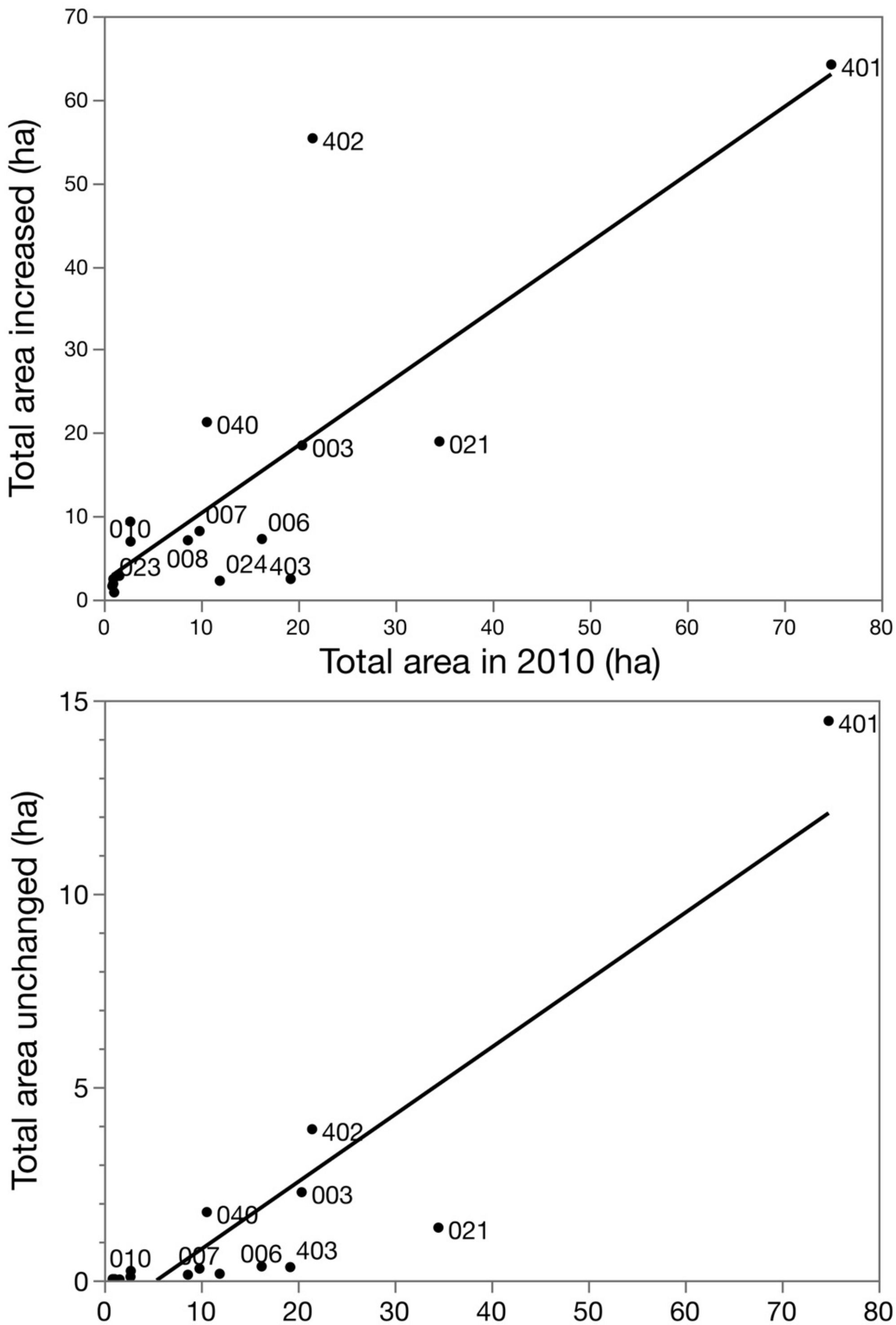


Figure 7: a) Total area that had changed as a function of original area in 2010 and b) Total area that remained unchanged as a function of original area in 2010.

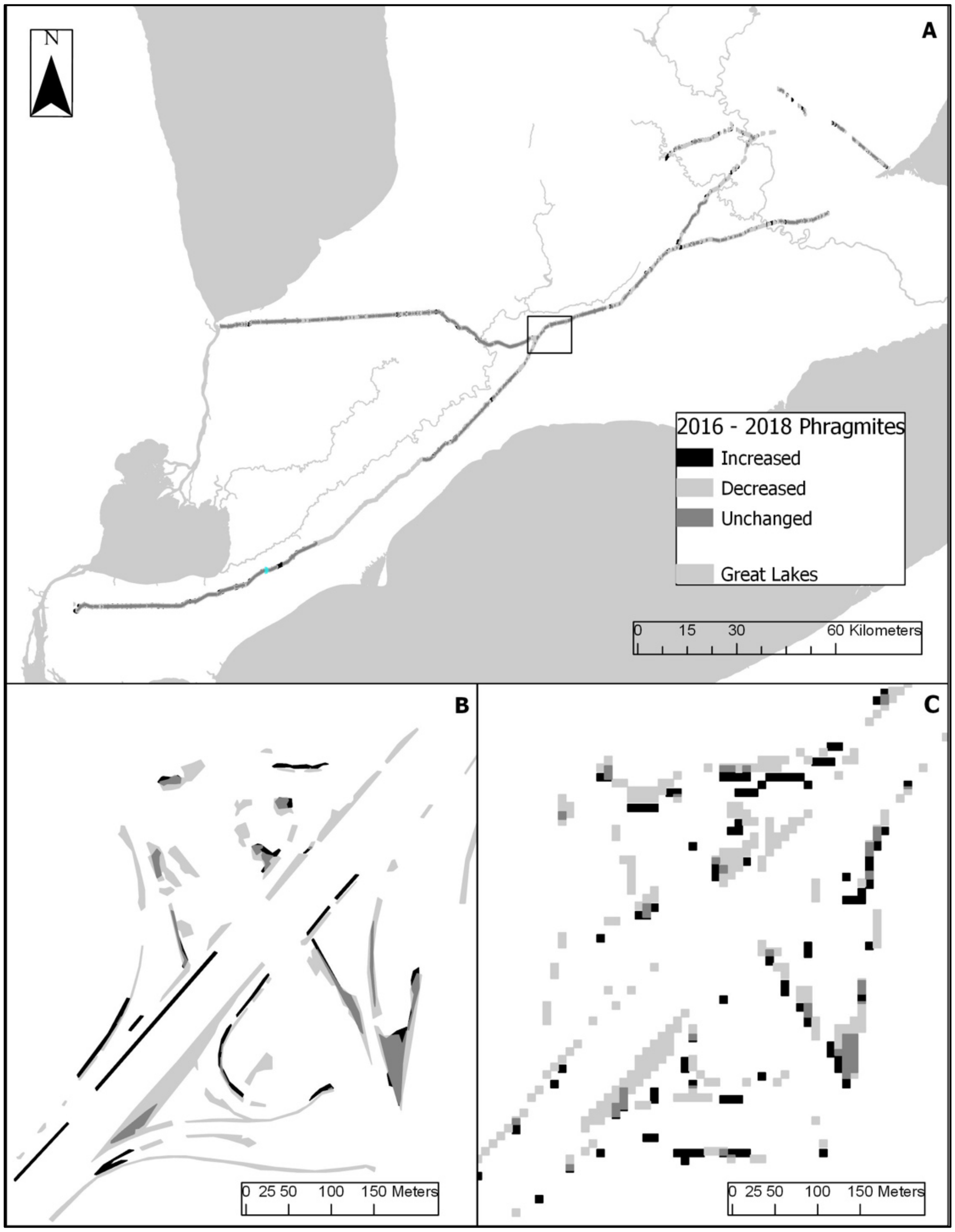


Figure 8: a) Results of a change detection of invasive *Phragmites* occurring in large highway corridors between 2016 and 2018, based on Sentinel-2 image classification. Shown in insets, b) enlargement of the above; c) showing the results of a change detection of invasive *Phragmites* between 2016 and 2018 based on manually digitized high resolution satellite data (2016: WV3; 2018: GE)

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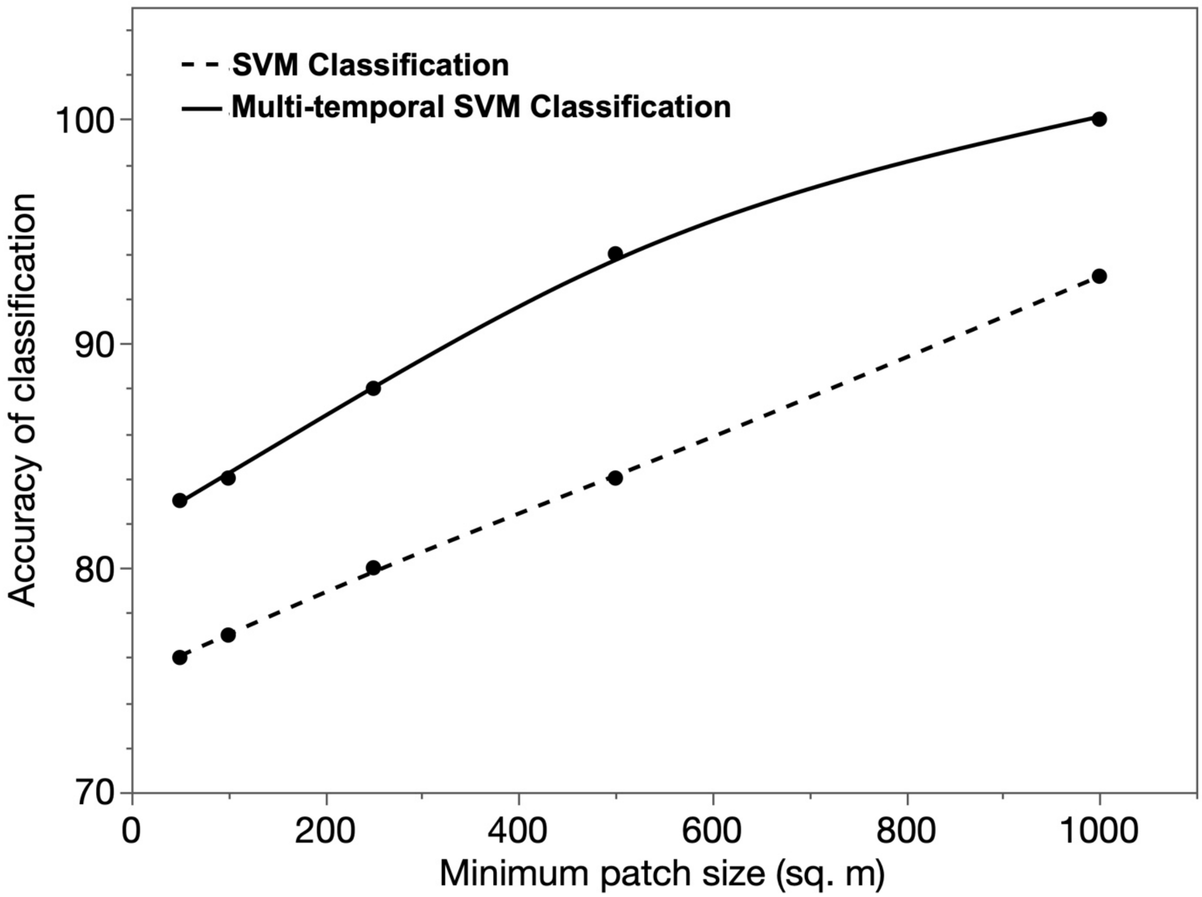

Figure 9: Dependency of Sentinel-2 accuracy on minimum patch size along highway corridors for two classification protocols.