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Mapping invasive *Phragmites australis* in the coastal Great Lakes with ALOS PALSAR satellite imagery for decision support

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ABSTRACT

The invasive variety of *Phragmites australis* (common reed) forms dense stands that can cause negative impacts on coastal Great Lakes wetlands including habitat degradation and reduced biological diversity. Early treatment is key to controlling *Phragmites*, therefore a map of the current distribution is needed. ALOS PALSAR imagery was used to produce the first basin-wide distribution map showing the extent of large, dense invasive *Phragmites*-dominated habitats in wetlands and other coastal ecosystems along the U.S. shore of the Great Lakes. PALSAR is a satellite imaging radar sensor that is sensitive to differences in plant biomass and inundation patterns, allowing for the detection and delineation of these tall (up to 5 m), high density, high biomass invasive *Phragmites* stands. Classification was based on multi-season ALOS PALSAR L-band (23 cm wavelength) HH and HV polarization data. Seasonal (spring, summer, and fall) datasets were used to improve discrimination of *Phragmites* by taking advantage of phenological changes in vegetation and inundation patterns over the seasons. Extensive field collections of training and randomly selected validation data were conducted in 2010–2011 to aid in mapping and for accuracy assessments. Overall basin-wide map accuracy was 87%, with 86% producer's accuracy and 43% user's accuracy for invasive *Phragmites*. The invasive *Phragmites* maps are being used to identify major environmental drivers of this invader's distribution, to assess areas vulnerable to new invasion, and to provide information to regional stakeholders through a decision support tool.

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Introduction

Understanding the current extent of problematic invasive species is critical for management and control, for determining areas at risk from invasion, and for assessing potential impacts on ecosystem services. One particular invasive wetland plant species, *Phragmites australis* (Cav.) Trin. ex Steud. (common reed), has been an acute detriment to coastal Great Lakes wetlands. Although a native form of *Phragmites* exists throughout the Great Lakes region, it does not exhibit the aggressive, native marsh-displacing growth habits of the invasive form. The fast-growing invasive form of *Phragmites* (Fig. 1) is an extreme threat to native ecosystems due to the plant's ability to

outcompete native wetland plants for resources and dominate the ecosystem. Invasive *Phragmites* can become established quickly because it propagates using aerial seed dispersal and an extensive network of above- and below-ground rhizomes. Once established, invasive *Phragmites* is capable of forming dense, tall (up to 5 m) monocultures that are difficult to control without continuous and long-term management. Methods of control include a combination of cutting, burning and repeated herbicide (Derr, 2008a,b; MDEQ, 2011). In the Great Lakes region, invasion by *Phragmites* has had several negative impacts on ecosystem services including displacement of native wetland vegetation, reduction of habitat quality and biological diversity (flora and fauna), alteration of nutrient cycles including impacts on nitrogen and phosphorous availability, modifications in hydrological regimes, increased air temperature within the wetlands, altered rates of plant decomposition, drying of wetland soils, and sediment trapping (Findlay et al., 2002; Meyerson et al., 2000; Plant Community Alliance, 2005; Tulbure et al., 2007; Wilcox et al., 2003). One of the main aesthetic impacts of this invader is the reduction of shoreline views, which may negatively affect property values.

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Fig. 1. Photo of large, dense monoculture of invasive *Phragmites australis* near Muskegon, MI along coastal Lake Michigan. Reference person in photo is 5 ft. tall.

Management and control of such a basin-wide invader requires knowledge of the species distribution. Numerous environmental organizations have been working to locate and record the extent of *Phragmites* on local plots of land, but a basin-wide dataset has not yet been available. In order to fill this data gap and support basin-wide habitat restoration efforts, a project was initiated to map the distribution of large, mature stands of invasive *Phragmites* along the shores of the five Great Lakes. Satellite imaging radar methods, previously developed for distinguishing invasive *Phragmites*-dominated wetlands from other emergent wetland types (Bourgeau-Chavez and Powell, 2009; Bourgeau-Chavez et al., 2008), were employed to develop distribution maps for a 10 km wide coastal zone spanning the entire length of the U.S. Great Lakes shoreline. This mapping extent captures the areas at greatest risk of being invaded by dense stands of invasive *Phragmites*; areas that are home to many endangered and threatened species (FWS, 2011).

The overall goal of the mapping project was to use a combination of extensive field measurements and remote sensing analyses to detect and map the presence of large, mature stands of invasive *Phragmites* along the entire U.S. coastal region of the Great Lakes. This effort has generated the baseline data needed for subsequent modeling efforts and decision support tools that are being developed by USGS Great

Lakes Science Center (GLSC), as well as other management and restoration efforts. The specific project objectives were to: 1) further refine the imaging radar mapping algorithms previously developed in pilot study areas to be applicable along the entire Great Lakes basin; 2) develop and implement field data collection protocol that support the imaging radar algorithm development; 3) collect sufficient field data basin-wide to be used in training and validation of the radar mapping; and 4) implement radar-mapping protocols to produce a basin-wide map of large, mature stands of invasive *Phragmites*.

Radar remote sensing background

Although the National Oceanic and Atmospheric Administration's Coastal Change Analysis Program (NOAA C-CAP) uses the Landsat satellite sensor (30 m resolution) to provide a timely and cost-effective national system of coastal wetland maps on a five-year interval, neither NOAA C-CAP nor the United States Fish and Wildlife Service's (USFWS) National Wetland Inventory (NWI) provides detailed information at the species-level.

In an effort to develop improved, timely, and cost-effective methods for mapping and monitoring coastal Great Lakes wetland types and extent on a regional scale, a hybrid radar-electro-optical

approach using archival 30 m satellite data was investigated in the mid-2000s for the Great Lakes Coastal Wetlands Consortium (GLCWC; Bourgeau-Chavez et al., 2004, 2008). In the GLCWC research analysis, it was demonstrated that multi-date Synthetic Aperture Radar (SAR) satellite imagery combined with traditional multispectral data (e.g., Landsat) could be an effective method to map the distribution of wetland types, including distinction of monocultures of *Typha* spp. and invasive *Phragmites* (Bourgeau-Chavez et al., 2004, 2008). In a subsequent USFWS NWI-funded study, Bourgeau-Chavez et al. (2009) demonstrated how the L-band (23 cm wavelength) SAR sensor of the Japanese satellite ALOS PALSAR (Phased Array type L-band Synthetic Aperture Radar on board the Advanced Land Observing Satellite) could be used singularly to map stands of invasive *Phragmites*, with better accuracy than airborne hyperspectral (17 m NASA AVIRIS) data collected over the same test area (Bourgeau-Chavez et al., 2009).

Imaging radar data provide a promising method for detection of invasive *Phragmites* because radar technology allows analysts to map differences in structure and biomass among plant species. A high biomass species, such as invasive *Phragmites*, that is structurally much larger and denser than other herbaceous wetland plant types is readily detected (Bourgeau-Chavez et al., 2009). SARs are active sensors, emitting their own energy and measuring the energy backscattered from the elements being imaged (e.g. wetland plants). The long wavelength (cm scale) microwave energy backscattered and received by the SAR sensor from a wetland is dependent upon vegetative structure and biomass, dielectric properties (i.e., moisture content) of vegetation and soils, surface roughness, and presence or absence of flooded surfaces (Bourgeau-Chavez et al., 2009). This is complementary to passive optical and infrared (IR) sensors, which operate at wavelengths on the micrometer scale and measure solar energy naturally reflected from earth surfaces. Optical and IR short-wave radiant energy reflectance from vegetation varies depending on features at the cellular level (e.g., chlorophyll and leaf moisture), as well as variations in surface or background reflectance (e.g., soil type and water). Additionally, the long wavelengths of SAR penetrate vegetation cover to sense the presence of wet soil or flooded conditions beneath the canopy. An enhanced signature is often received from a canopy underlain by water due to a double-bounce effect from the water surface and stems of the canopy. The signature will change depending on the water level, plant height, and density, thus, SAR can be used to distinguish between *Phragmites* and other wetland types by using multi-seasonal data to sense phenological differences in plant and flood conditions (Bourgeau-Chavez et al., 2009).

In the spring, dead *Phragmites* stems remain standing, while most other herbaceous species have fallen over or decayed. This characteristic, along with growth and inundation patterns, is used to assist in distinguishing between dominant plant cover types. To demonstrate this, an analysis of backscatter from a variety of wetland types from the various seasons of PALSAR data collection is shown in Fig. 2. Invasive *Phragmites* typically has a higher backscatter than all other herbaceous dominated wetlands but is lower than shrub and forest. Table 1 shows the difference in backscatter (data are from over 1000 pixels averaged for each wetland class) in decibels ⁴(dB) between invasive *Phragmites* and the two wetland classes closest to *Phragmites* from Fig. 2 (with 3 dB representing a change in intensity ratio of a factor of 2, a significant difference for distinguishing two cover types). This table shows the importance of summer L-HV (L-band horizontal (H) send and vertical (V) receive polarizations) data for differentiation of the two classes most similar to *Phragmites*, shrub and *Typha* spp. (Fig. 2). Spring L-HH data also show good separation between all the classes, however the dB difference between *Phragmites* and other classes is not as great as in summer L-HV data.

⁴ The decibel (dB) is a logarithmic unit that is calculated as $10 \cdot \log_{10}(\text{backscatter intensity})$.

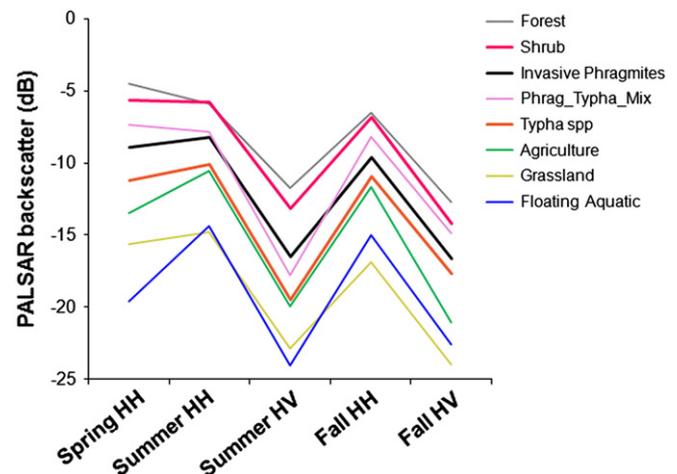


Fig. 2. Plot of PALSAR backscatter from various wetland classes in western coastal Lake Erie by season and L-band polarization. The PALSAR sensor collects in various modes, one of which is fine beam dual (FBD) polarization corresponding to a horizontal send, horizontal receive (HH) and a horizontal send, vertical receive (HV). This sensor also collects fine beam singular (FBS) polarization, in which the sensor collects only HH polarized data. A minimum of 1000 pixels were averaged for each polarization/season backscatter measurement from each wetland class. Note that spring L-HV is missing since it was from a FBS image.

The PALSAR imagery has a noise equivalence of -31.1 dB for HH and -32.3 dB for HV. The radiometric accuracy is 0.64 dB (Shimada et al., 2005, 2007). Note that there are other non-wetland classes that may get confused with *Phragmites* (e.g., low intensity urban or residential) that are not plotted here. To further illustrate how the different wetland types can be distinguished from multi-season SAR, an example of a three season false-color composite of a diked wetland system at Pointe Mouillee on Lake Erie is presented in Fig. 3. In this figure, *Phragmites* appears orange in a very wet state and a brighter yellow when the site is not as inundated. This contrasts with other wetland types that appear green (*Typha* spp.) or purple (sedge meadow) in this multi-season L-HH composite.

Material and methods

Study area

The mapping and field data collections were focused on the emergent wetlands within 10 km of the U.S. coastline of Lakes Huron, Erie, Ontario, Michigan and Superior. A 10 km buffer allowed for assessment of inland wetland complexes that could provide a seed source for coastal wetlands and represented a manageable area to map and conduct field data collection within the time and cost limitations of the project. There are over 120,000 ha of freshwater emergent wetlands (NWI) in this 10 km buffer of the U.S. Great Lakes coastline. Fig. 4 shows the extent of the area (white delineated area) evaluated for detection of monotypic stands of *Phragmites australis*. Efforts to include all islands and large lakes, such as Lake St. Clair and adjoining waterways were made.

Table 1

Comparison of backscatter differences (dB) between invasive *Phragmites* and the two wetland classes that were most similar in our analysis of Fig. 2, shrub wetland and *Typha* spp. HH represents horizontal send and receive polarization and HV represents horizontal send and vertical receive polarization.

	Spring HH	Summer HH	Summer HV	Fall HH	Fall HV
	dB diff	dB diff	dB diff	dB diff	dB diff
Shrub-Phrag	3.2	2.4	3.4	2.8	2.5
Phrag-Typha	2.4	1.9	3	1.4	1
Noise Equivalent	-31.1	-31.1	-32.3	-31.1	-32.2
Radiometric Accuracy	0.64	0.64	0.64	0.64	0.64

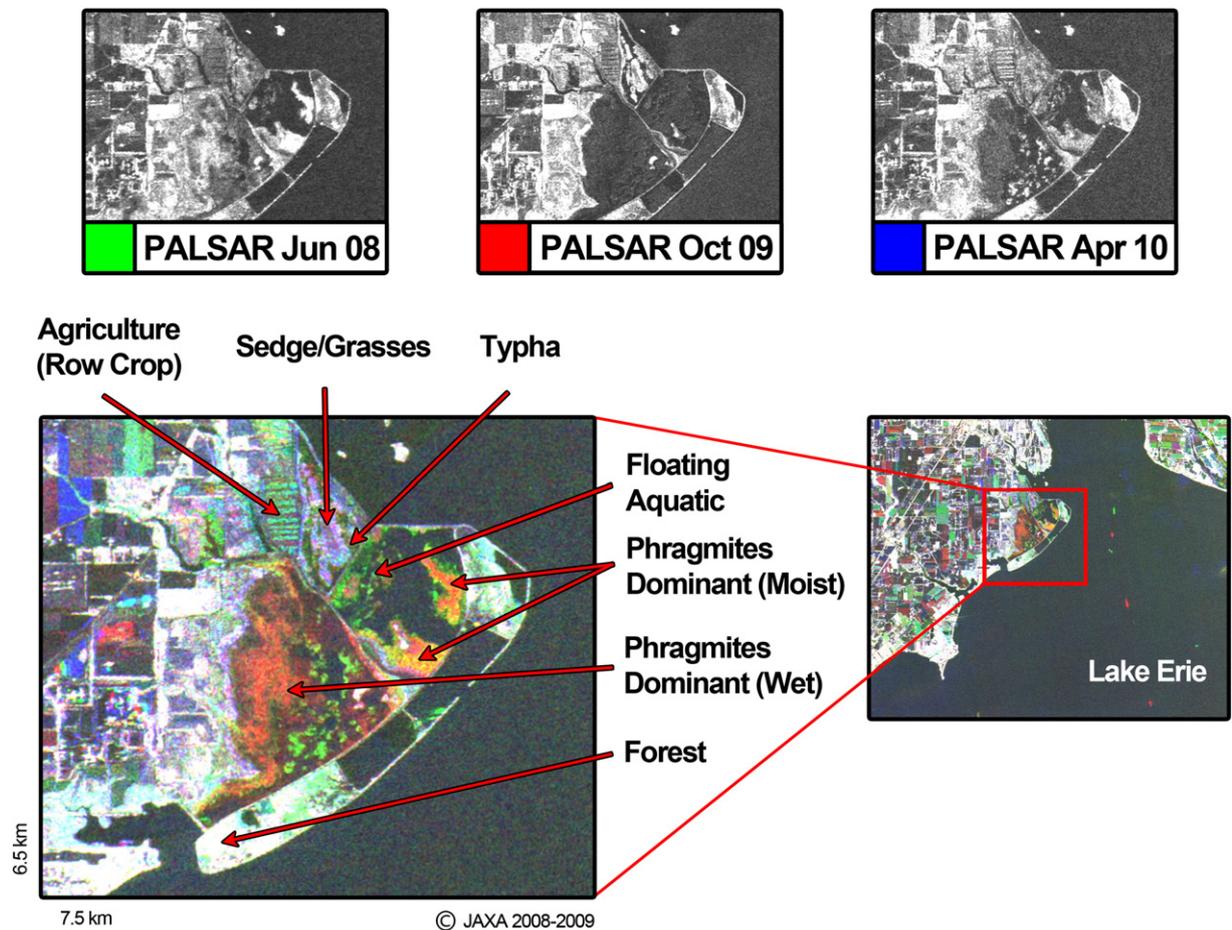


Fig. 3. Three seasonal images of PALSAR L-HH data (top black and white images) over a diked wetland at Pointe Mouillee State Game Area on Lake Erie were used to create a red, green, blue false color composite (bottom images). The bottom left image is a zoom of the full PALSAR scene (shown in bottom right). This false color image highlights the differences in water levels and phenologic condition of the vegetation over the seasons allowing the image analyst to distinguish vegetation types (e.g. *Phragmites* is orange in this composite).

Due to funding limitations, the mapping project was focused only on the U.S. side of the Great Lakes. A mapping effort for portions of the Canadian side of the Great Lakes coast is underway by the Ministry of Natural Resources using Landsat NDVI (Young et al., 2011). Similarly, a basin-wide mapping effort has been initiated by MTRI through an EPA-funded initiative that will use SAR-electro optical methods (Bourgeau-Chavez et al., 2004, 2008) for mapping wetland type and adjacent land use. This mapping effort will build from the *Phragmites* project database and include classification of invasive *Phragmites* on the Canadian side of the Great Lakes using circa 2008–2010 data.

Imagery

The images used for mapping were from PALSAR on board the ALOS platform. ALOS was launched in 2006 and continued to collect data until it failed in April 2011 (see Rosenqvist et al., 2007 for a detailed review of the PALSAR sensor). During this time, particularly in 2010, excellent coverage of the Great Lakes region was acquired by the sensor and downloaded to the Alaska Satellite Facility (ASF) for processing, calibration and archive. The Fine Beam Dual (FBD) polarization mode data were the focus for the mapping due to the moderate resolution (20 m) and two polarimetric channels, horizontal send and receive (L-HH) and horizontal send and vertical receive (L-HV). The L-HH polarized data have been found to be most useful for detection of flooding beneath a canopy (Hess et al., 1995) while L-HV is more sensitive to differences in biomass (Bourgeau-Chavez et al.,

2009). The like-polarized data (L-HH) allow for detection of variations in water levels over the season.

Based on previous wetland work with SAR (Bourgeau-Chavez et al., 2001, 2004, 2005, 2008, 2009), a three-date seasonal dataset (spring, summer, and fall) of PALSAR (FBD) images was selected as optimal for mapping *Phragmites* and to differentiate *Phragmites* from other wetland types. In the absence of the FBD data, FBS (Fine Beam Single Polarization) data were selected (23 scenes). FBS data have a single polarization, L-HH, and 10 m resolution but the same 70 × 70 km footprint as FBD data. While the ideal dataset would include three seasons of data with both polarizations, a minimum of two seasons of data with two polarizations were found to be sufficient for the detection and mapping of invasive *Phragmites*.

The minimum mapping unit (mmu) of 0.2 ha was defined by project needs and limitations of the resolution and nature of the SAR imagery. Although the SAR imagery has 10–20 m resolution, due to inherent speckle noise, the effective mapping unit must be a multiple of the resolution cell. Speckle noise is a ‘salt and pepper’ effect resulting from the coherent radiation used by SAR systems. Based on field data comparison to PALSAR map products, in the case of 20 m resolution radar, 0.2 ha or 2 × 2.5 resolution cells is the minimum size which can be confidently mapped (Bourgeau-Chavez et al., 2009).

All PALSAR images were collected in descending orbits with an incidence angle of 34.3°, except for three FBS images which were of 41.5° incidence angle. The difference in the incidence angle should not have much effect on the ability to detect flooding beneath the

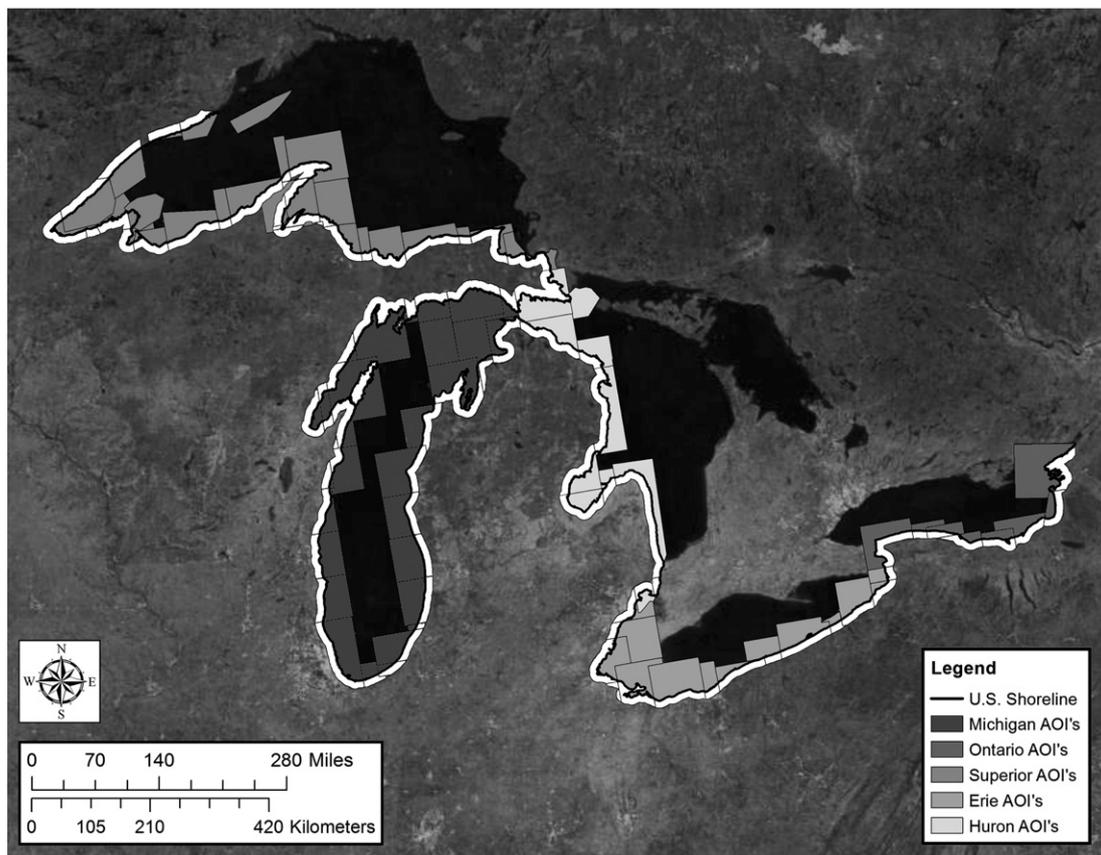


Fig. 4. Map showing studied coastlines which extended from the coastal waterline inland 10 km (white area). Also shown are the PALSAR-derived Areas of Interest (AOIs) used for mapping.

canopy (Lang et al., 2008), and the shallower angle (41.5°) should have a stronger influence of plant biomass on the return signal since the radar energy has a longer path length through the canopy.

All PALSAR imagery was obtained through the ASF-US Government-sponsored Research Consortium Datapool (University of Alaska Fairbanks, <http://www.asf.alaska.edu/>). Approximately 247 FBD and 23 FBS, 70×70 km PALSAR images from 2008 to 2010 of the U.S. Great Lakes coastal region were downloaded from the ALOS satellite, processed, terrain corrected, and georeferenced to within 1.5 PALSAR pixels (12.5 m) by ASF. Upon receipt of the PALSAR data from ASF, additional verification and adjustment of positional accuracy were conducted when necessary using the multipoint geometric correction tool and Autosync application within ERDAS IMAGINE™.

In addition to the PALSAR imagery, Landsat data from three seasons and high resolution aerial photography (2005, 2009, 2010 USDA National Agriculture Imagery Program (NAIP) and 2009 Department of Homeland Security (DHS) Border Flight data) were used for checks on georectification, field planning and data collection, as well as identification of *Phragmites* and interpretation of wetlands.

Field data collection

In spring of 2010, a large field campaign was initiated to collect information on wetland type and dominant cover at randomly selected locations within coastal emergent wetlands in the U.S. coastal Great Lakes basin (as determined by the emergent classes of the USFWS NWI). To match the mmu of the map product (0.2 ha; 0.5 acre), all sites were sampled in 0.2 ha increments. Both training data and validation data were collected from May to October of 2010 and 2011. The training data were used to inform the remote sensing algorithm, and

the validation data were reserved for accuracy assessments of the map products.

An equation from Ross (1987) was used to determine the number of field validation data locations needed for assessment of the maps to be produced. Based on Ross (1987), a 95% confidence level could be achieved using 377 samples per lake basin. However, this would be logistically impossible to achieve with the field crews and time period available. Therefore, a total of 400 locations were physically visited in the first year of field work (2010) across all five basins, and additional sites were targeted in Year 2 (2011). According to calculations based on Ross (1987), a target of 110 validation locations per lake basin would provide a 70% confidence level (132–75%, 163–80%, 206–85%, and 267–90% confidence level per lake basin).

ESRI ArcGIS was used to randomly select validation locations for field data collection using a spatial query for each basin. The emergent class from the NWI GIS layer was merged with wetlands from the Great Lakes Coastal Wetlands Consortium map (<http://www.glc.org/wetlands/inventory.html>) to generate a spatial layer of all known emergent wetlands. This layer was clipped using a 10 km shoreline buffer. Next, the NOAA Sampling Design Tool (<http://ccma.nos.noaa.gov/products/biogeography/sampling/>) was used in ArcGIS to randomly generate sampling points within each lake basin. The points were randomly selected to remove bias in the accuracy assessments performed at the end of the mapping project. 377 locations were selected for each basin, with 110 randomly selected from those. Additional points were randomly selected from the 267 remaining points for sampling in Year 2.

The randomly selected points were overlaid on air photos, and the geographic positions were uploaded to Geographic Positioning System (GPS) units to aid the field crews in navigating to sampling locations. These locations often were challenging to navigate to,

sometimes requiring a boat or traversing through difficult terrain. In contrast to the validation data protocol, random sampling was not the most efficient way to collect the training data needed from a variety of wetlands types within each 70×70 km PALSAR scene to characterize the radar signature of each wetland type. Therefore, training sites were chosen via identification on air photos or in the field via observation. Data collection protocol at the training sites was identical to that of the validation sites, characterizing a 0.2 ha (40×50 m) area in the field.

Equipment for field data collection included laptop computers, air photo maps, GPS units, and digital cameras with built-in GPS and compass for geo-tagging the field photos, which were taken in four cardinal directions. Parameters collected at each site included general ecosystem type (e.g., shrub wetland, emergent wetland, wet prairie, open water, floating aquatic, mudflat, and upland), percent cover by dominant cover type, dominant vegetation height and density (density was only recorded for *Phragmites* and *Typha*), water level, time of day, location (GPS coordinates collected in WGS 84 latitude and longitude coordinates), and field-drawn maps for estimating extent of adjacent land cover features.

A web-based interface was developed for immediate entry of field data into the computer database for geographic analysis and interpretation. This database was then checked for quality control against the field datasheets to reduce data entry or transcription errors at the end of the 2011 season. Once a list of errors was generated, a systematic approach of correcting these errors was accomplished including retrieval of data sheets completed in the field, analysis of field collected photos for potential verification of species present, and reassessment of field collected GPS coordinates. Once quality control was completed, the database was then linked to the uploaded GPS points collected at the center of each training and validation location sampled in the field. An ESRI shapefile was generated using all the attributes collected in the field. This process allowed the image analysts to have all the field data and field photos within the GIS available to them when creating the map products.

Mapping

A total of 87 PALSAR frames were needed to cover the U.S. coastal Great Lakes (an example of the frames is shown for Lake Michigan in Fig. 5.) Depending on the orbit path for each particular image date, however, all of the frames for a given area did not perfectly overlay. After verifying positional accuracy, the six images (three dates with two polarization modes for each date) for each area of interest (AOI) were stacked into a single image file. The overlapping coverage extent of each seasonal set of stacked PALSAR frames determined the AOIs for mapping (Fig. 4). Some frames required mosaicking to fill in missing data from one or more seasons with adjacent scene data due to the orbital shift between seasonal scene collections (Fig. 4). This mosaicking was conducted in ERDAS IMAGINE using the Mosaic Pro tool. For the PALSAR image stacks, speckle was reduced to decrease the inherent noise in the imagery and make the data more suitable for classification within relatively homogeneous mapping areas by using a 3×3 median filter in the ERDAS Radar module.

Each AOI was mapped separately using field data and air photo comparison for training. For each image set, a manual analysis of the unsupervised classifications was performed for the field-truthed areas throughout the coastal Great Lakes region. Around each field location, the unsupervised class was recorded for association with the ecosystem type observed in the field. In most cases water and urban areas were sufficiently clear for identification without field data.

The isodata unsupervised classification algorithm was used to group pixels together that have statistically similar cell values (Lillesand et al., 2007). Image triplicates were processed through the isodata unsupervised classification routine (ERDAS Field Guide®, 2010) with a range of classes (32 to 64), iterations (20 maximum),

and a convergence threshold of 0.95. This effort was followed by the application of a series of clusterbusting masks (group partitioning of similar pixel clusters) in ERDAS IMAGINE. Classes that contain potential *Phragmites* were extracted and run through the unsupervised classifier again. This iterative process continued until one or multiple classes contained only *Phragmites*. The selected process was based on Bourgeau-Chavez et al. (2009) PALSAR work over Lake St. Clair.

In mixed vegetation areas where *Phragmites* was heavily confused with other vegetation types, spectral signatures of identified classes from the isodata unsupervised classification algorithm were extracted and used for supervised, maximum likelihood classification. This process could only be used in areas that contained field verification to ensure spectral signals used in the maximum likelihood classifier were monotypic stands of vegetation.

In an effort to minimize exclusion of invasive *Phragmites* areas near upland areas, classes were grouped to err on the side of commission rather than omission, meaning an inclusion of *Phragmites* rather than missing it through exclusion, while filtering out obvious upland areas in post processing. Areas smaller than our mmu produced by the supervised classification were grouped with their surrounding cells (12 minimum) and assigned the same class.

Once the classification was complete, agricultural confusion pixels were filtered out using selected cover types from 2006 NOAA C-CAP and 2009 Cropland Data Layer (CDL) products in ArcGIS. The agricultural confusion classes often occur due to the effect of row structure on SAR backscatter. C-CAP and CDL data were used in their native form with 30 m resolution. The 2006 NOAA C-CAP land cover classification layers that were kept included grassland herbaceous, palustrine forested wetland, palustrine scrub-shrub wetland, open water, palustrine aquatic bed, and unconsolidated shore. The cover types kept from the 2009 CDL included open water, shrub land, grassland herbaceous, and herbaceous wetlands.

Next, the invasive *Phragmites* classification maps were run through the clump and eliminate model in ERDAS IMAGINE to group like-pixels and eliminate small groupings. Both of these steps helped to eliminate small areas of confusion throughout the upland areas in the maps and removed isolated pixels (those less than the mmu). As a final clean up, areas of misclassification were hand edited out of the final map by overlaying the detected *Phragmites* map on the air photos. These misclassified areas were locations of obvious upland types that were mapped as potential invasive *Phragmites* by the SAR but were not filtered out with the C-CAP or CDL products. Most of these were residential areas with a scattering of large trees underlaid by grass, which likely caused the high biomass and double bounce scattering similar to monotypic stands of *Phragmites*.

Accuracy ASSESSMENT

Only two classes were evaluated in the accuracy assessments, “*Phragmites*” and “Other” land cover types (primarily wetlands). Accuracy was determined using the randomly selected validation sites, withheld from the original mapping process, in comparison with the final mapped invasive *Phragmites* products. Assessments were conducted basin-wide as well as on a per lake basin basis. Three estimates of accuracy were calculated, user's, producer's and overall accuracy. User's accuracy is a measure of how accurately a classification performed in the field (errors of commission) while producer's accuracy is a measure of how accurately the analyst classified the image data (errors of omission) (Congalton and Green, 1999). The overall accuracy provides the summary of correctly classified validation locations.

Focal majority statistics in ArcGIS were applied to the map products to account for the error in the GPS units that had a minimum horizontal positional accuracy of +/- 25 m and to ensure that the 0.2 ha field sampled area (rather than the single GPS point) was matched to the 0.2 ha mmu of the mapped product (which has 12.5 m pixel

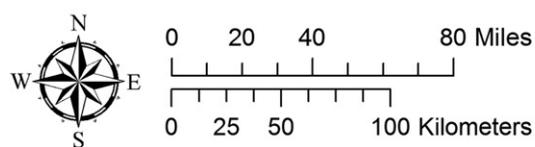
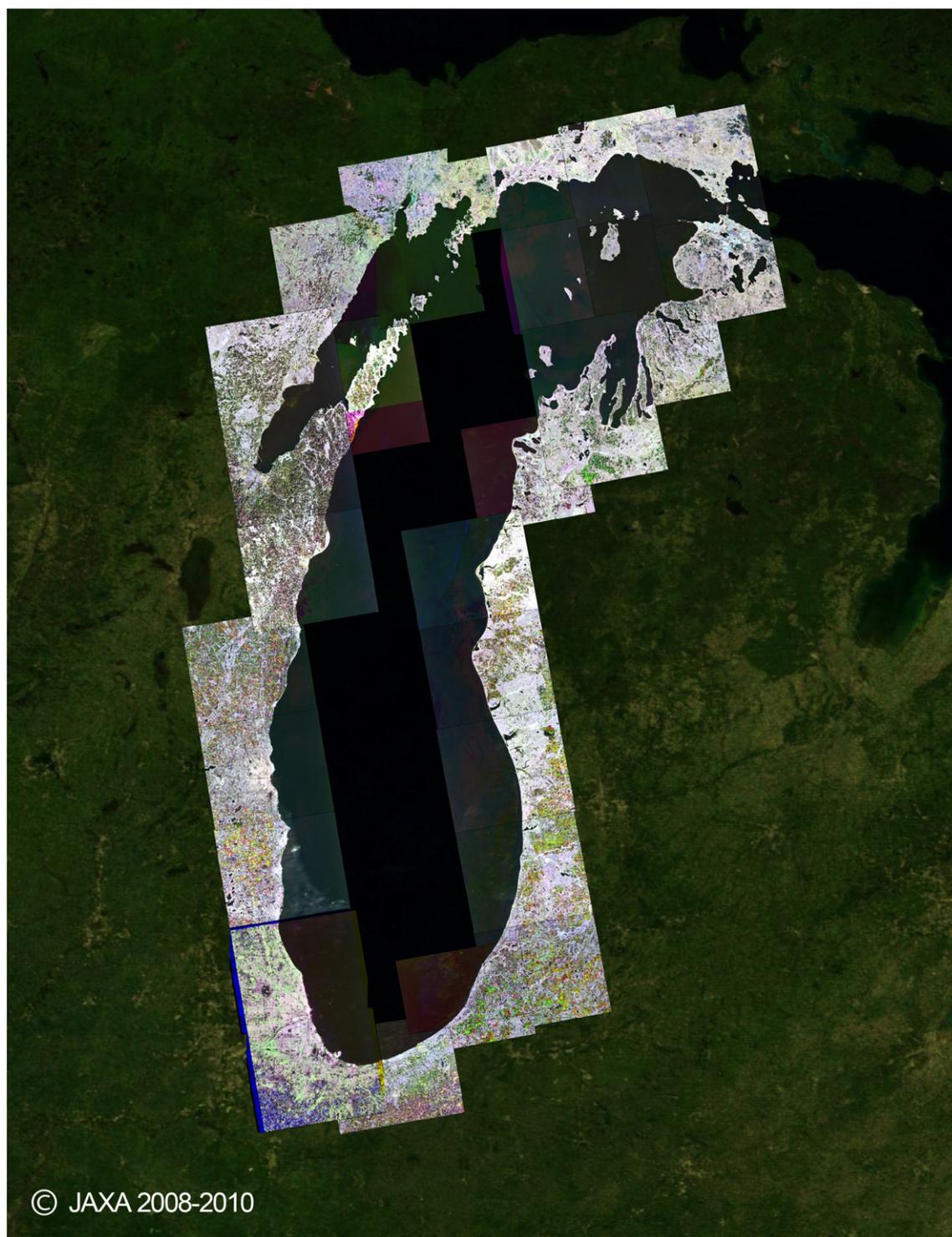


Fig. 5. The PALSAR three-date image composites required to cover the entire coastline of Lake Michigan.

spacing, 20 m resolution). The Focal majority tool was used to describe each cell in the final mapped product with the value that occurs most often within a 3×4 cell neighborhood (an approximately 0.2 ha area). Linear features were lost after the 3×4 Focal majority was run

on the map products, so the output product was merged with the original map product to preserve linear features.

Focal majority values were joined with validation GPS points using the Extract Values to Points tool from the Spatial Analyst module

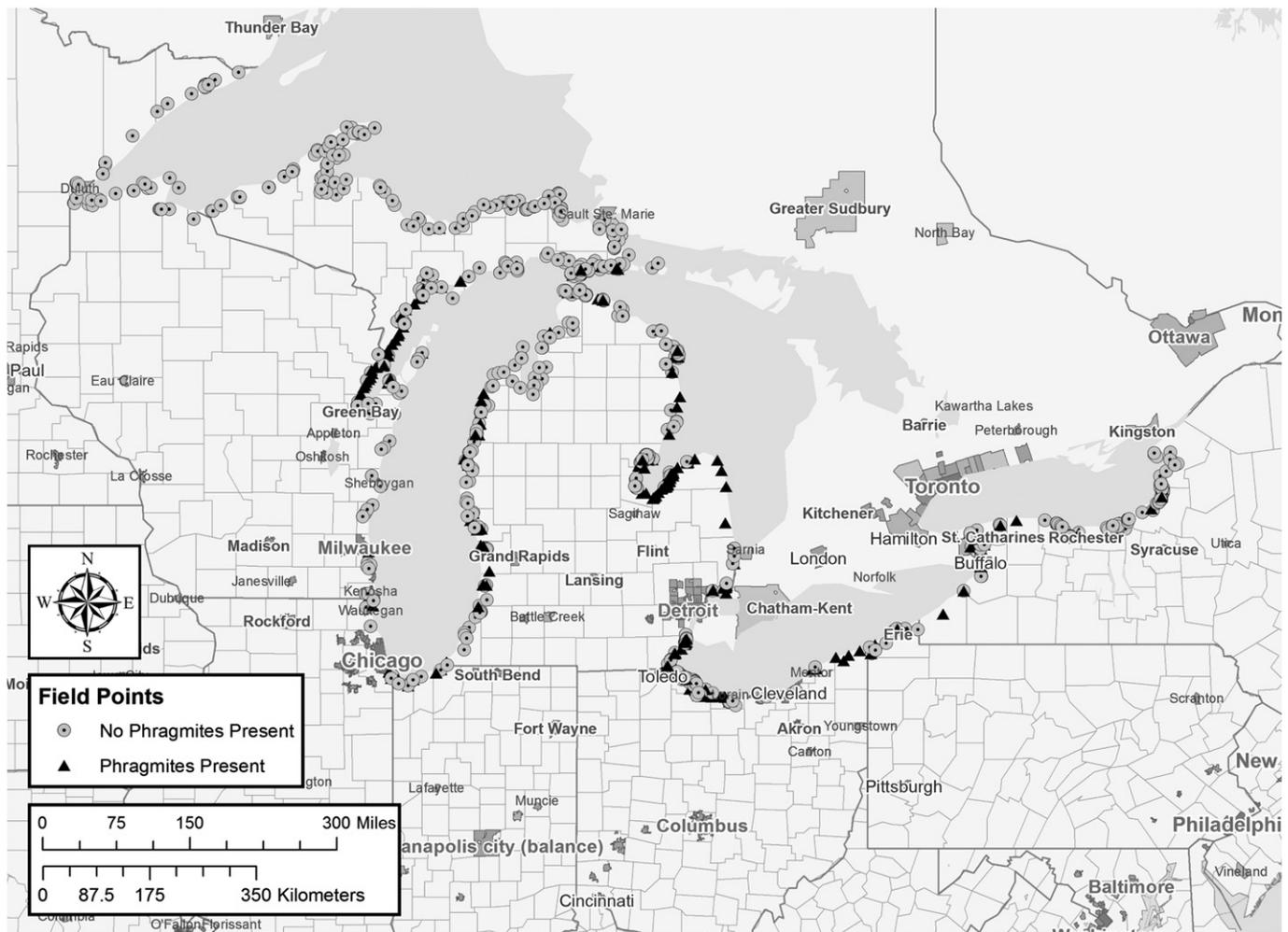


Fig. 6. Locations of sites in the study area where invasive *Phragmites* was observed (triangles) and locations where *Phragmites* was not observed (circles).

within ArcGIS. Sites classified in the field with greater than 90% invasive *Phragmites* cover (as determined by ground truthing protocol) were the target of the mapping project and considered the most identifiable using radar. These field-identified validation sites were compared to the final SAR-mapped product. To test the limits of the radar mapping, lower density stands of *Phragmites* sampled in the field that had greater than or equal to 50% dominant cover were also assessed in a second accuracy assessment for each lake basin.

Results

Field results

At the conclusion of the 2011 field season, a total of 1145 training and validation field sites had been visited. *Phragmites* was documented at 348

of these sites (30%, Fig. 6). 761 sites were visited in 2010 and 384 in 2011. 782 sites represent the randomly selected validation points, and 363 represent the training sites. The number of sites visited per lake basin varied; 333 sites were collected on Lake Michigan, 274 on Lake Huron, 204 on Lake Erie, 194 on Lake Superior, and 140 on Lake Ontario.

Of the field locations sampled, 55% (628 points) were categorized as emergent wetlands in the field observations, and 17% (194 points) as wet meadow. Other site categorizations were less than 10% of the total and included floating aquatic, forest, mudflat, open water, shrubby, and other.

Table 2 summarizes the number of 0.2 ha (0.5 ac) validation and training sites visited in 2010–2011 by lake basin and the number of those that had invasive *Phragmites* present. Also included is the number of validation sites with greater than 50% *Phragmites* dominance and those with greater than 90% *Phragmites* dominance (monotypic

Table 2
Summary of validation sites, training sites (opportunistically selected in the field or by aerial imagery) and *Phragmites* presence for each lake basin.

coastal lake basin	Validation 0.2 ha sites	Validation sites with <i>Phragmites</i> present		Validation Sites with <i>Phragmites</i> >50% dominance		Validation Sites with <i>Phragmites</i> >90% dominance		Training 0.2 ha sites	Training sites with <i>Phragmites</i> present	
Erie	120	55	46%	33	28%	22	18%	84	51	61%
Ontario	109	11	10%	1	1%	0	0%	31	6	19%
Huron	184	77	42%	43	23%	24	13%	90	48	53%
Michigan	255	74	29%	32	13%	20	8%	78	23	29%
Superior	114	0	0%	0	0%	0	0%	80	3	4%
Total	782	217	28%	109	14%	66	8%	363	131	36%



Fig. 7. Overview of U.S. coastlines of Great Lakes' distribution of invasive *Phragmites*, with a minimum mapping unit (mmu) of 0.2 ha, as mapped with PALSAR L-band data from 2008 to 2010 (red). The area is labeled as "potential *Phragmites*" recognizing that although this map represents the range of PALSAR spectral signatures observed in monocultures of invasive *Phragmites* with a 0.2 ha mmmu, there may be some confusion with other types (e.g. high biomass *Typha spp.*) or omission due to ongoing control efforts and rapid spread beyond the temporal resolution of this work.

stands). Note that the presence of *Phragmites* in the validation points is of greater statistical significance than the training sites, since the former were randomly selected, while the latter were targeted.

Table 3

Summary of total area within the 10 km buffer, sum of wetland and other (e.g. unconsolidated shore, grasslands) areas within the 10 km buffer, and hectares of *Phragmites* mapped with PALSAR within these areas per lake basin.

Coastal lake basin	Coastal area in 10 km buffer (ha)	Area of wetland and select ecosystem types in the filter (ha)	<i>Phragmites</i> mapped in the filtered areas (ha)
Erie	778,447	96,862	8233
Michigan	1,724,800	578,320	6002
Ontario	442,113	102,056	13
Superior	1,270,484	N/A	N/A
Huron	650,715	75,402	10,395
Total	4,866,559	852,640	24,643

Table 4

Accuracy assessment for the entire U.S. Great Lakes Basin for invasive *Phragmites* stands with greater than 90% cover and greater than 50% cover (in parentheses). User's accuracy is a measure of how accurately a classification performed in the field (errors of commission) while producer's accuracy is a measure of how accurately the analyst classified the image data (errors of omission) (Congalton and Green, 1999).

Field observation		PALSAR Class			Producer's accuracy (omission error)
		<i>Phragmites</i>	Other	Total	
Invasive <i>Phragmites</i> over 90% (and 50%) Entire U.S. Great Lakes Basin					
	<i>Phragmites</i>	57 (73)	9 (33)	66 (109)	86 (70)
	Other	75 (56)	527 (503)	602 (559)	88 (90)
	Total	132 (132)	536 (536)	668 (668)	
	User's accuracy (commission error)	43 (58)	98 (94)		87 (87)

Mapping results

The map of *Phragmites* distribution was completed by lake basin (Fig. 7) using a mmmu of 0.2 ha and representing stands of invasive *Phragmites* that have 50 to 100% cover. The target was *Phragmites*-dominant stands with greater than 90% cover, but it was determined during the mapping process and accuracy assessment that many stands of at least 50% cover were detectable as *Phragmites* dominant.

The total area assessed within the wetlands and other filtered ecosystem types (e.g. grasslands and unconsolidated shore) as well as the sum of the entire area of the 10 km buffer by lake basin is shown in Table 3, along with the corresponding areas of *Phragmites* mapped within those filtered areas. The area of *Phragmites* mapped is greatest on Lake Huron (10,395 ha), with Erie (8233 ha) and Michigan (6002 ha) following closely behind (Table 3). Very little invasive *Phragmites* was detected on the shores of Lake Ontario (13 ha) and no large monotypic stands of invasive *Phragmites* were detected

Table 5
Accuracy assessment for Lake Huron for invasive *Phragmites* stands with greater than 90% cover and greater than 50% cover (in parentheses). Note this includes Lake St. Clair. User's accuracy is a measure of how accurately a classification performed in the field (errors of commission) while producer's accuracy is a measure of how accurately the analyst classified the image data (errors of omission) (Congalton and Green, 1999).

Invasive <i>Phragmites</i> over 90% (and 50%) Lake Huron Basin				
Field observations	PALSAR Class		Total	Producer's accuracy (omission error)
	<i>Phragmites</i>	Other		
<i>Phragmites</i>	21 (31)	3 (12)	24 (43)	88 (70)
Other	34 (24)	126 (117)	160 (141)	79 (83)
Total	55 (55)	129 (129)	184 (184)	
User's accuracy (commission error)	38 (56)	98 (91)		80 (80)

Table 6
Accuracy assessment for Lake Erie for invasive *Phragmites* stands with greater than 90% cover and greater than 50% cover (in parentheses). User's accuracy is a measure of how accurately a classification performed in the field (errors of commission) while producer's accuracy is a measure of how accurately the analyst classified the image data (errors of omission) (Congalton and Green, 1999).

Invasive <i>Phragmites</i> over 90% (and 50%) Lake Erie Basin				
Field observations	PALSAR Class		Total	Producer's accuracy (omission error)
	<i>Phragmites</i>	Other		
<i>Phragmites</i>	22 (29)	0 (4)	22 (33)	100 (88)
Other	21 (14)	77 (73)	98 (87)	82 (84)
Total	43 (43)	77 (77)	120 (120)	
User's accuracy (commission error)	51 (67)	100 (95)		83 (85)

during field activities (Table 2) or image analysis (Table 3) in coastal Lake Superior. Since no *Phragmites* was mapped on coastal Lake Superior, no areas were filtered by the C-CAP or CDL (Table 3).

For the entire Great Lakes basin, the overall accuracy was 87%, with 86% producer's accuracy (i.e., errors of omission) for *Phragmites* with greater than 90% cover, and 43% user's accuracy (i.e., errors of commission), thus a high commission error (Table 4). For *Phragmites* > 50% cover the producer's accuracy drops to 70%, and the user's accuracy increases to 58% (Table 4).

For the assessment of *Phragmites* stands with greater than 90% cover: Lake Huron had an overall accuracy of 80%, with 88% producer's accuracy and 38% user's accuracy (Table 5); Lake Erie

had an overall accuracy of 83%, with 100% producer's accuracy for *Phragmites* and 51% user's accuracy (Table 6); Lake Michigan had 91% overall accuracy with 70% producer's and 44% user's accuracy (Table 7); and Lake Ontario had 98% overall accuracy. For Lake Ontario there were only 2 *Phragmites* dominant areas of 109 sites visited, and these had less than 90% dominance; Lake Ontario had 0% user's and producer's accuracy (Table 8).

For *Phragmites* sites with greater than 50% dominant cover for Lake Huron, overall accuracy was 80%, with 70% producer's and 56% user's (Table 5); for Lake Erie the overall accuracy was 85%, with 88% producer's and 67% user's accuracies (Table 6); Lake Michigan had 87% overall accuracy with 47% producer's and 47% user's accuracy

Table 7
Accuracy assessment for Lake Michigan for invasive *Phragmites* stands with greater than 90% cover and greater than 50% cover (in parentheses). User's accuracy is a measure of how accurately a classification performed in the field (errors of commission) while producer's accuracy is a measure of how accurately the analyst classified the image data (errors of omission) (Congalton and Green, 1999).

Invasive <i>Phragmites</i> over 90% (and 50%) Lake Michigan Basin				
Field observations	PALSAR Class		Total	Producer's accuracy (omission error)
	<i>Phragmites</i>	Other		
<i>Phragmites</i>	14 (15)	6 (17)	20 (32)	70 (47)
Other	18 (17)	217 (206)	235 (223)	92 (92)
Total	32 (32)	223 (223)	255 (255)	

Table 8
Accuracy assessment for Lake Ontario for invasive *Phragmites* stands with greater than 90% cover and greater than 50% cover (in parentheses). User's accuracy is a measure of how accurately a classification performed in the field (errors of commission) while producer's accuracy is a measure of how accurately the analyst classified the image data (errors of omission) (Congalton and Green, 1999).

Invasive <i>Phragmites</i> over 90% (and 50%) Lake Ontario Basin				
Field observations	PALSAR Class		Total	Producer's accuracy (omission error)
	<i>Phragmites</i>	Other		
<i>Phragmites</i>	0 (1)	0 (0)	0 (1)	0 (100)
Other	2 (1)	107 (107)	109 (108)	98 (99)
Total	2 (2)	107 (107)	109 (109)	
User's accuracy (commission error)	0 (50)	100 (100)		98 (99)

(Table 7); and Lake Ontario had 99% overall accuracy with 100% producer's and 50% user's accuracy (Table 8). In all cases (Tables 4–8), the user's accuracy improves, commission error drops, when all invasive *Phragmites* validation stands with greater than 50% dominance are assessed, although in most cases the producer's accuracy for *Phragmites* drops slightly (except for Lake Ontario where it could only improve when the sole *Phragmites* field validation site with greater than 50% cover was correctly mapped).

Discussion

The image classification methods refined in this project using the medium resolution (10–20 m) PALSAR imagery allowed for the mapping of large mature stands of invasive *Phragmites* at a basin-wide extent. The classification methodology was based solely on seasonal PALSAR imagery using field data and air photos to aid in training. Post-classification filtering was then used to remove confusion classes. This methodology was found to be applicable for large mature stands of 0.2 ha across the basin, as is seen in the high overall accuracy assessment (87%, Table 4). However the accuracy for the individual lakes is variable, depending on the nature of the invasive *Phragmites* stands (rare or common, contiguous or patchy). The lakes with large contiguous stands of invasive *Phragmites* were the least problematic to map with the 20 m resolution PALSAR, and also the easiest to collect a significant number of *Phragmites* field validation points for accuracy assessment using random point generation. For example, the maps for Lakes Huron and Erie, which had the greatest producer's accuracy (88 and 100%, respectively, Tables 5 and 6), also showed a high amount of *Phragmites* (42% and 46%) in the validation sites (Table 2).

Conversely, the *Phragmites* stands in Lake Ontario were more sporadic, and large stands were rare, making mapping more difficult and reducing map accuracy. With so little potential invasive *Phragmites* mapped and observed in field validation on Lake Ontario, it was challenging to develop a representative accuracy assessment. Further, an aerial photo (2009 DHS) review of the eleven *Phragmites* field validation sites with *Phragmites* present (Table 2) revealed that only one had *Phragmites* cover extending over the 0.2 ha minimum. A few others, although they were dense monotypic stands, encompassed very little spatial area (<0.1 ha) and therefore were not detectable with our radar mapping techniques. With so few areas mapped as *Phragmites* on Lake Ontario, it may be better to verify the existence of *Phragmites* at those sites through targeted field visits or air photo delineation.

Mapping on Lake Michigan was complicated because there were many stands of *Phragmites* that were patchy, and the overall map required much more post-classification editing to remove pixels of confusion classes than was needed for Lakes Erie or Huron. However, with 91% overall accuracy and 70% producer's accuracy for invasive *Phragmites* on Lake Michigan (Table 7), the map results are respectable. There is a high commission error for Lake Michigan (44% user's accuracy) which is likely a result of our efforts to err on the side of inclusion rather than exclusion in areas confused with invasive *Phragmites*. Since *Phragmites* is a highly invasive plant that can establish quickly in new areas, knowing where the leading edges of invasion (often the isolated or small patches of mapped *Phragmites*) are can be extremely useful to land managers seeking to detect and manage newly colonized areas before *Phragmites* becomes established. Inclusion of the patchier *Phragmites* stands in our classification map likely resulted in more commission errors but ultimately an end product showing more ecologically significant stands of *Phragmites*.

The timeline (April 2010 to December 2011) and success of the *Phragmites* mapping project demonstrate the suitability of medium resolution (10 m to 20 m) L-band SAR imagery for mapping and monitoring a region the size of the Great Lakes basin. Others have evaluated optical-infrared satellite imagery such as Landsat (30 m), SPOT (15 m), and Hyperion (30 m) for mapping invasive plant species, including *Phragmites* in local parts of the Great Lakes

(Arzandeh and Wang, 2003; Pengra et al., 2007; Young et al., 2011), but each image source has limitations. Although hyperspectral imagery is a popular choice for species differentiation, the satellite-based hyperspectral sensor Hyperion was operationally limited and therefore cannot be used to develop a basin-wide map (Bourgeau-Chavez et al., 2008). There is an alternative satellite-based hyperspectral sensor, HICO (Hyperspectral Imager for the Coastal Ocean), currently onboard the International Space Station (hico.coas.oregonstate.edu). However, HICO (90 m) has a coarser resolution than PALSAR which would not allow for map creation at the 0.2 ha mmu and access to HICO data is difficult. Further, in comparison to PALSAR, hyperspectral (17 m resolution airborne AVIRIS) data were found to be less accurate in mapping large dense stands of invasive *Phragmites* than PALSAR when compared to field data observation on coastal Lake St. Clair (Bourgeau-Chavez et al., 2009). In that study, hyperspectral data were not assessed for immature low density *Phragmites* stands and they may prove useful for that purpose.

Landsat data are available basin-wide, and methods developed by Young et al. (2011) involving the normalized difference vegetation index (NDVI) from peak summer data masked with known wetlands are promising, although they have not yet conducted an independent accuracy assessment and plans to create a basin-wide map are pending. A visual comparison of the NDVI-derived map over Lake St. Clair to the same area on the Canadian side mapped with PALSAR indicates similarities on the coastal water edges, but the PALSAR product indicates a greater amount of *Phragmites* within the wetland complexes than does the NDVI product. Further comparisons are needed with digital data and field validation data before any conclusions may be drawn, but NDVI appears to be another viable source of information on the high biomass invasive *Phragmites* stands.

The field methods developed for the PALSAR mapping project allowed for assessment of the variables that influence SAR backscatter (e.g. plant height and density, percent cover, species dominance, herbicide or cutting treatments) on the ground at the mmu. The size of the areas observed in the field and the variables collected were crucial for both training and validation of the map products. Although numerous individuals and agencies have collected GPS field points on *Phragmites* presence across the Great Lakes, they were not used in the map training or validation. Collection of a single GPS point in the field without an areal representation is not useful when mapping to a mmu of 0.2 ha. In the *Phragmites* mapping project in coastal provincial Ontario, Young et al. (2011) also found survey point data collected by outside sources to lack utility since the points were not always within but near possible *Phragmites* stands and there was no indication of the extent of the stands. The field component of our *Phragmites* mapping project was key to the success of the algorithm development and accuracy assessment. Without the detailed information on the site characteristics, including information on sites that had been treated, had low density but *Phragmites* dominance, or were otherwise non-detectable by our methods, all sites with *Phragmites* presence would have been inadvertently used in the training of the algorithms and the validation assessments. Further, having the GPS tagged field photos in four cardinal directions and scanned field sheets allowed for a quick review of any field site in question from the database.

Although, the optimal number of field validation locations needed for a 95% confidence level in the accuracy assessments of the map products could not be attained due to time and budget constraints, sufficient data were collected for a minimum confidence level of 70%. Further, the field validation data provide for a statistical evaluation of the presence of invasive *Phragmites* in each of the lake basins that can be compared to the mapped statistics.

For Lakes Michigan, Huron and Erie, both the map products and random field validation statistics showed substantial *Phragmites* presence, with 29–46% of the field sites having *Phragmites* (Table 2) and 6000 to more than 10,000 ha (Table 3) of potential invasive *Phragmites* mapped

on these lakes. The results from the PALSAR mapping and the field validation data statistics showed that invasive *Phragmites* is less extensive and problematic in the 2008–2010 timeframe on Lakes Ontario and Superior than the other Lake basins, with 10% *Phragmites* presence at the randomly selected (validation) wetlands of Lake Ontario and 0% on Lake Superior, and only 13 ha of potential invasive *Phragmites* mapped on Lake Ontario and 0 ha mapped on Superior. Three training locations were observed on Lake Superior with invasive *Phragmites* presence (Table 2), and a few areas were indicated by outside sources, however analysis of the imagery over these sites, as well as air photo interpretation, indicated the stands were smaller than our mmu of 0.2 ha. The differences observed by lake basin in *Phragmites* distribution may be due to environmental drivers (e.g., nutrients or land use) or due to biological mechanisms of invasion (e.g., propagule or seed dispersal). This is the subject of ongoing studies that may elucidate areas vulnerable to future invasion.

While our methods provided a basin-wide assessment of mature monotypic stands of invasive *Phragmites* of 0.2 ha and larger, they cannot be used accurately to evaluate smaller patches (<50% cover or <0.2 ha area) or immature *Phragmites* stands. These need to be assessed using methods such as those focused on small catchments with high-resolution aerial photographs, hyperspectral images, or LiDAR data (e.g. Lopez et al., 2006; Wilcox et al., 2003). Such high-resolution (e.g., 1 m) mapping of the entire 17,549 km Great Lakes coastline would be prohibitive in terms of timeliness and cost. Therefore, proximity to locations near large dense stands and field observation can be used to indicate those critical areas that need higher resolution focused mapping. Likewise, the maps of invasive *Phragmites* do not include the native variety, which lacks the biomass and structure of invasive *Phragmites* stands. While invasive *Phragmites* usually creates dense monotypic stands of nearly 100% cover, native *Phragmites* is much sparser and is generally intermixed with other wetland vegetation. Therefore, no confusion has been observed nor is expected in the mapping due to the nature of the scattering of SAR energy from high versus low biomass stands. With further algorithm development, mapping of sparse invasive stands or native *Phragmites* may be possible with SAR. Nonetheless, the current map product, with its capacity to detect large contiguous patches of *Phragmites*, provides an invaluable source for the decision support tools being developed by USGS, habitat suitability modeling, and other basin-wide analysis efforts.

Decisions to accept higher levels of commission error help to ensure that the mapped extent of potential *Phragmites* is inclusive of areas of highest concern to managers. Knowing the distribution of the mature stands allows resource managers to prioritize control efforts and scientists to better understand *Phragmites* distribution in the Great Lakes basin. Given the negative impacts *Phragmites* can have on coastal ecosystems, distribution maps may be especially valuable to those charged with conducting and managing the many coastal habitat restoration projects supported by the congressionally-funded Great Lakes Restoration Initiative.

Conclusions

Multi-season and multi-year ALOS PALSAR data, circa 2008–2010, were used to build a high accuracy dataset representing the distribution of large, mature, monotypic *Phragmites* stands along the U.S. coast of the Great Lakes. As the first of its kind, this highly accurate data set provides a benchmark that will allow national, regional, and local managers to visualize the extent of *Phragmites* invasion in the Great Lakes and strategically plan efforts to manage existing populations and minimize new colonization. These data also provide the foundation for ongoing efforts to conduct habitat suitability modeling for *Phragmites* and assess levels of vulnerability to new invasions. Landowners, managers, and decision makers will be able to

access distribution maps and vulnerability assessments through web-based decision support tools developed by USGS.

Phragmites treatment and control operations are underway across the Great Lakes region. These efforts, however, are most often small operations limited in geographic extent. The Michigan Departments of Environmental Quality and Natural Resources, in cooperation with the Great Lakes Commission, have been hosting stakeholder meetings to develop a Strategic Framework for the Management and Control of Invasive *Phragmites* in Michigan (<http://glc.org/ans/initiatives.html#phrag>). It is only through coordinated regional and basin-wide efforts that the ecological, recreational, and economical effects of widely distributed invasive species such as *Phragmites* will be assessed, the areas vulnerable to future invasion predicted, and control efforts implemented.

The potential invasive *Phragmites* distribution maps produced by this project could be used to inform management and policy efforts as well as provide a baseline characterization for monitoring *Phragmites* distribution over time. Unfortunately, the ALOS PALSAR failed in spring of 2011, but PALSAR-2 is planned for launch in the next couple of years and may be used to track future vegetation changes. The circa 2008–2010 *Phragmites* distribution maps will be made publically available for the U.S. portion of the Great Lakes coastline (<http://www.glsc.usgs.gov>) along with the spatially explicit field data (1145 sites) and associated attributes collected as part of this mapping effort (<http://mtri.org/Phragmites.html>). An online map-based decision support tool will enable the visualization of current *Phragmites* distribution at user-defined scales and display a variety of approaches for assessing vulnerability to future invasions (<http://cida.usgs.gov/glri/phragmites/>).

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