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ABSTRACT.—Throughout Midwestern forests, invasion by the exotic plant garlic mustard [*Alliaria petiolata* M. Bieb. (Cavara & Grande)] has become increasingly problematic. A multi-criteria risk model was developed to predict invasion in the Upper Peninsula of Michigan where garlic mustard is present but not yet widely distributed. The model uses geographic information system (GIS) data to predict the risk of invasion at three phases: introduction, establishment and spread. Known occurrence data for garlic mustard were used to validate the model predictions, with 89% of points correctly identified at moderate to high risk for invasion. The risk model predicted 13% of the Upper Peninsula to be at high risk and 33% at moderate risk for establishment of garlic mustard. Field sampling of randomly generated points across the Upper Peninsula provided only two additional observations of garlic mustard presence. The low encounter rate during field sampling may indicate that garlic mustard has not yet reached its full invasion potential in the Upper Peninsula. This presents an opportunity to use the model predictions and associated risk maps for monitoring and management in a relatively uninvaded region.

INTRODUCTION

Garlic mustard [*Alliaria petiolata* M. Bieb. (Cavara & Grande)] is one of the most pervasive exotic plants in Midwestern forests (Blossey *et al.*, 2002). It is an obligate biennial herb in the mustard family (Brassicaceae), and can be identified by its heart-shaped, coarsely toothed leaves, white flowers and seeds in slender pods. It is native to northern Europe and was first documented in North America on the east coast in 1868 (Nuzzo, 1993). Since then it has become widely established across eastern and central North America. Unlike many invasive plants, garlic mustard can invade and dominate the understory of forests, displacing native herbaceous plants, influencing ecosystem function and decreasing plant diversity (Blossey *et al.*, 2002).

Garlic mustard prefers sites dominated by mature deciduous forests (Meekins and McCarthy, 1999; Myers and Anderson, 2003), but it is also found in urban areas, disturbed areas, and along roads, railroads and rivers (Nuzzo, 1993). It is more likely to invade species-rich sites rather than species-poor sites (Blossey *et al.*, 2002) and commonly inhabits mesic shaded areas but can survive in well-drained sunny sites as well (Meekins and McCarthy, 2002). In its native range it grows best on base-rich soils (Cavers *et al.*, 1979), and this association is also observed within its invaded range but with a more noticeable absence from acidic soils (Nuzzo, 1991). Garlic mustard can also survive in wetland habitats, moist woods and swamp forests, despite being less competitive (Voss, 1985). In Michigan, garlic mustard invades mainly deciduous woodlands, roadsides and urban areas (Voss, 1985). Invasion is promoted by disturbances, both human and natural (Anderson *et al.*, 1996; Welk *et al.*, 2002). Although most populations appear to be associated with some degree of disturbance (Byers and Quinn, 1998), garlic mustard can invade relatively undisturbed forests with ease (Anderson *et al.*, 1996).

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The successful spread of garlic mustard is due to its ability to reproduce effectively (Cruden *et al.*, 1996). Garlic mustard has a biennial life cycle; seeds germinate in the spring, forming rosettes that over-winter and emerge as flowering adults the following spring (Nuzzo, 1993). The adults grow rapidly in early spring when most native plants are still dormant (Anderson *et al.*, 1996). The flowers are pollinated by a variety of insects but also have the ability to self-pollinate in their absence (Cruden *et al.*, 1996). The seeds are held in siliques, and a single robust plant can have as many as 7900 seeds (Nuzzo, 1993) that are expelled up to 2 m from the parent plant (Nuzzo, 1999). Most seeds land and germinate within 1 m of the parent plant creating thick patches of garlic mustard that crowd out native plants (Drayton and Primack, 1999). Long-distance dispersal of garlic mustard seedlings occurs by humans, animals and floodwaters (Cavers *et al.*, 1979) as well as via deer, mice and other small mammals (Blossey *et al.*, 2001). Roadways, trails, waterways, irrigation systems and lakeshores offer pathways for human and natural dispersal. The use of heavy equipment in the construction of roads, dams and bridges aids in the spread of seedlings between construction sites. The spread rate of garlic mustard is rapid into suitable microsites while slower into less suitable sites, but it can be dramatically increased by a single disturbance event or enhanced even further by repeated disturbance (Nuzzo, 1999).

Predictive modeling of the potential distribution of garlic mustard has been attempted, producing alarming results. Using a bioclimatic model, Welk *et al.* (2002) found that garlic mustard could invade a large portion of North America, ranging from the Rocky Mountains to the eastern coast and including the whole state of Michigan. Peterson *et al.* (2003) used ecological niche modeling to predict similar results, indicating that a majority of North America could potentially be invaded. Both methods were based on climate-related variables and predicted distribution on a national scale while not identifying limitations in terms of suitable habitat to the distribution of the plant at more local scales. A finer scale model would improve predictions of potential habitat and probable invasion patterns within states. This approach would also permit the use of additional parameters and available Geographic Information System (GIS) data. More recently, multi-criteria models have played a role in invasive species management, proving to be a useful tool for making complex management decisions (Born *et al.*, 2005; Cook and Proctor, 2007; Krist *et al.*, 2007). As defined by Krist *et al.* (2007) multi-criteria modeling is ''a modeling process run in a GIS that allows for the combination and weighting of multiple factors, providing a common framework for combining dissimilar information while resulting in a single index of evaluation.'' These methods allow for the combination of habitat preferences and landscape characteristics. For example, Mortensen *et al.* (2009) found that roads were significantly related to the presence of invasive plants and were able to develop population growth and spread models using this and other landscape features. Values derived from multi-criteria modeling have the potential to be used in the creation of risk maps to guide invasive plant monitoring (Eastman, 1999). When species occurrence data is limited, as in the case of newly invading species, expert knowledge can be used in place of traditional statistical evaluation in the creation of spatial predictive models (Store and Kangas, 2001). A detailed method for creating multi-criteria risk models and maps using only knowledge of factors affecting susceptibility was explained for forest insects and diseases by Krist *et al.* (2007). By altering these methods slightly, multi-criteria risk models and risk maps can be developed for invasive plants such as garlic mustard.

Garlic mustard is not yet widely distributed in the Upper Peninsula, a region of the Midwest with relatively high ecological integrity; however it has the potential to be a serious, wide-ranging problem. Voss (1985) indicated that garlic mustard was present in only two of the 15 Upper Peninsula counties. This is consistent with the distribution data found on the USDA PLANTS Database (accessed Apr. 2009). As expected, further garlic mustard invasions have been identified in additional counties throughout the Upper Peninsula. Invasion data provided by the U.S. Forest Service, U.S. Fish and Wildlife Service and the Michigan Department of Natural Resources indicate garlic mustard invasions in five of the 15 Upper Peninsula counties. Counties with spatial data for invasions were Alger, Gogebic, Mackinac, Marquette and Ontonagon. In addition, anecdotal reports of garlic mustard exist for Houghton and Keweenaw Counties. Within counties the occurrence of garlic mustard is usually limited to only a few sites. The full consequences of garlic mustard in Upper Peninsula forests are not yet understood, but it is evident that the invasion of garlic mustard poses a threat to forested ecosystems, with deciduous forests being most vulnerable.

Survey and monitoring for invasive plants has proven to be an important but time-consuming and costly management strategy (Rejmanek, 2000). The use of predictive modeling to guide monitoring of invasions may make this approach more practical. The work reported here involved the development of a multi-criteria risk model for garlic mustard in the Upper Peninsula to be used for monitoring and management. Our specific objectives were to: (1) develop a multi-criteria risk model for garlic mustard invasion risk, (2) test the model by comparing known occurrence data and field sampling and (3) utilize the model to create risk maps for the Upper Peninsula and for smaller selected natural areas throughout the Upper Peninsula.

METHODS

STUDY AREA

The Upper Peninsula of Michigan contains 4,261,048 ha, approximately one-third of the land area of the state. Despite this, the Upper Peninsula has only 3% of the human population of Michigan. The landscape is comprised mainly of deciduous, coniferous and mixed forests and wetlands. Much of the forested land is found within the Ottawa and Hiawatha National Forests and State Forests. Other federally-managed natural areas include Pictured Rocks National Lakeshore, Isle Royale National Park and Seney National Wildlife Refuge. Many smaller natural areas are distributed among these contiguous forested areas. The natural areas selected to be modeled at a finer scale in this study were the western and eastern portions of the Hiawatha National Forest (WHNF and EHNF), Pictured Rocks National Lakeshore (PIRO), Ottawa National Forest (ONF) and Seney National Wildlife Refuge (SNWR).

MODEL DEVELOPMENT

A multi-criteria risk model for garlic mustard invasion in the Upper Peninsula was developed within ArcGIS 9.2 using ModelBuilder (ESRI, 2006). To develop the model the invasion process was broken into three phases: introduction, establishment and spread. Definitions of each phase were adapted from several previous definitions (*see* Williamson, 1996; Richardson *et al.*, 2000; Kolar and Lodge, 2001; Sakai *et al.*, 2001). Introduction was defined as the arrival and successful germination of garlic mustard seeds in an area where it was not previously present. Establishment was defined as the development of a free-living, reproducing population of garlic mustard, requiring the survival of plants past germination along with successful reproduction. Spread was defined as an increase in area and number of individuals of an established population, including the survival and growth of the established population and the potential for short- and long-distance dispersal. A review of the literature on garlic mustard was made to determine the factors affecting each phase of invasion. Factors found to be important were vegetation type, species composition, soil moisture, soil pH, and natural and human disturbance. An important aspect of human disturbance was the presence of roads, railroads, trails and waterways, which have been associated with disturbed habitat, long-distance dispersal and pathways for further spread of garlic mustard, as with other invasive plants (Cavers *et al.*, 1979; Forman and Alexander, 1998; Dark, 2004; Mortensen *et al.*, 2009).

Spatial GIS data were obtained or created for each model parameter. The parameters included were distance to roads, railroads, and trails, distance to water, land cover class, soil moisture, soil pH, ''other features'' and known garlic mustard invasions. Transportation and hydrology layers were obtained from Michigan Geographic Framework data, available from the Michigan Geographic Data Library (State of Michigan, 2007). The 2001 National Land Cover Dataset (NLCD, USGS, 2001) was used for vegetation. NLCD was available in raster format with a spatial resolution of 30 m. There were 15 unique land cover classes present across the Upper Peninsula. More detailed vegetation data was available as shapefiles for PIRO (18 land cover classes) and SNWR (41 land cover classes). These datasets were provided by the natural areas. State Soil Geographic (STATSGO) data were obtained from the Natural Resource Conservation Service and used to create the parameters of soil drainage and soil pH. When available, Soil Survey Geographic (SSURGO) data were used for modeling the natural areas, taking advantage of the finer scale of 1:24,000, as compared to STATSGO data which had a scale of 1:250,000. The parameter ''other features'' was included in the model to represent points of anthropogenic disturbance that may affect invasion. This included, when available, campgrounds, lighthouses and visitor centers. Campground data was not currently available as a GIS layer; however, a point shapefile was created for all State Forest campgrounds using a Michigan atlas and location details from a state forest campground brochure (MI DNR, 2007). Campground locations and other points of disturbance (lighthouses and visitor centers) were provided by the National Park Service and the U.S. Forest Service. There are no campgrounds within the boundaries of SNWR. A point shapefile was created for the distribution of known garlic mustard in the Upper Peninsula by combining data provided by the U.S. Forest Service, U.S. Fish and Wildlife Service and the Michigan Department of Natural Resources.

Two versions of the model were created. The first version was developed for the entire Upper Peninsula, using a 30 m spatial resolution. The second model was developed to predict risk within smaller selected areas. This model used a 10 m spatial resolution to account for higher-quality, finer-scale data available within natural areas. Non-raster GIS layers were converted to grids using the feature to raster tool or during the process of calculating Euclidean distance, both tools in ArcGIS 9.2. The assignment of parameter risks was based on the literature review and the efforts of a related project developing multi-criteria risk models for a suite of invasive plants (including garlic mustard) in the Great Lakes Network of the National Park Service (*see* Shartell, 2007). Risks for the Upper Peninsula garlic mustard model described here were adapted from those assigned to the garlic mustard model developed for the National Park Service, which was based on a literature review and known garlic mustard occurrence data from Indiana Dunes National Lakeshore, Indiana; Mississippi National River and Recreation Area, Minnesota; and Sleeping Bear Dunes National Lakeshore, Lower Peninsula of Michigan.

Risk ratings from one to five were assigned to each level of a parameter based on its relationship to the invasion and survival of garlic mustard. A rating of five represented high risk and was assigned to conditions that were very suitable and frequently associated with the

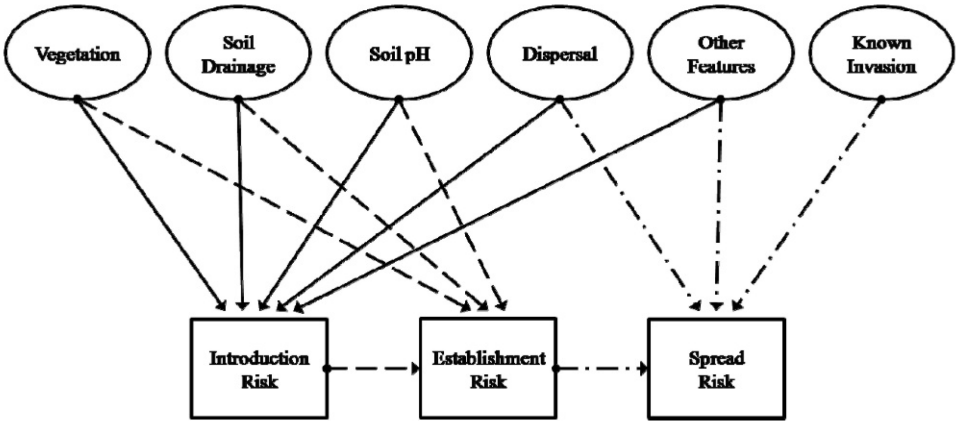

FIG. 1.—Stylized layout of the multi-criteria risk model developed for garlic mustard

presence of garlic mustard (*e.g.,* a deciduous forest). A risk of four indicated moderately suitable conditions, three indicated somewhat suitable conditions, two indicated rarely suitable conditions and one indicated unsuitable conditions (*e.g.,* an emergent wetland). For dispersal, the distance from each pixel to a road, trail, railroad or waterway was calculated to a maximum of 300 m using the Euclidean distance tool. The distances were grouped into five equal interval categories and assigned a risk from five (high risk, 0 to 60 m) to one (low risk, 240 to 300 m). For vegetation type each land cover class was assigned a risk from one to five based on suitability for garlic mustard seedling invasion and survival based on literature sources (Voss, 1985; Nuzzo, 1993; Meekins and McCarthy, 1999; Myers and Anderson, 2003). Drainage, extracted from STATSGO or SSURGO soil data, was a categorical rating with eight categories from excessively drained to very poorly drained and water. As garlic mustard prefers mesic to well drained sites (Meekins and McCarthy, 2002), moderately well drained and somewhat poorly drained were assigned a five. As ratings decreased in suitability they were assigned lower risks. In this way well drained and poorly drained received a risk of four, very poorly drained and somewhat excessively drained received a risk of three, and excessively drained and water received a risk of one. Average pH, also from the soil data, was rounded to the closest whole number which resulted in pH values ranging from four to seven. Since garlic mustard prefers neutral to basic soils (Nuzzo, 1991) risk of five was assigned to pH six or seven, risk of three to pH of five and risk of one for pH of four. Point data for other features were combined and a 100 m buffer was applied. This area was assigned a risk of five indicating high risk while all other areas received a risk of two. The distances to known garlic mustard locations were calculated to a maximum of 600 m using the Euclidean distance tool and grouped into three 200 m categories that were assigned risks from five to three, with any distances greater receiving a value of two. The calculated risks for the previous phase of invasion fed into the next (*i.e.*, introduction risk from the model was a parameter for establishment, as was establishment for spread).

Introduction, establishment, and spread of garlic mustard were each based on a different set of parameters and influences (Fig. 1, Table 1). Introduction was based on a weighted overlay of dispersal, vegetation, soil drainage, soil pH, and other features, establishment on introduction risk, vegetation, soil moisture, and soil pH, and spread on establishment risk,

TABLE 1.—The parameters and percent influences (weights) used to determine risk for each phase of invasion in the multi-criteria risk model

Introduction		Establishment		Spread	
Dispersal	0.43	Vegetation	0.45	Establishment Risk	0.53
Vegetation	0.22	Soil Drainage	0.22	Dispersal	0.26
Soil Drainage	0.14	Soil pH	0.22	Other Features	0.13
Soil pH	0.14	Introduction Risk	0.11	Known Invasion	0.08
Other Features	0.07				

dispersal, other features and known garlic mustard invasion. Each parameter in the model was assigned a rank based on its importance to the particular phase of invasion. Percent influence was calculated as the parameter rank divided by the sum of all parameter ranks involved in the phase of invasion. The percent influence was used as the weight for the weighted overlay tool used to combine parameters.

The models were run for the entire Upper Peninsula and individually for each of the selected natural areas (EHNF, WHNF, PIRO, ONF and SNWR). The appropriate GIS data were selected for each parameter on the model dialog screen. The GIS data were processed through the steps of the model creating the three output files, one for each phase of invasion. Each pixel in the output received a risk from one to five. The output files were used to create maps highlighting the areas at risk for invasion. The areas at highest risk, a rating of five, were shown in red. Areas of moderate risk, a rating of four, were shown in orange. Low risk areas, a rating of three, were shown in yellow. Areas with little to no risk for invasion (ratings of two or one) were not shown but were represented by white areas on the maps.

ACCURACY ASSESSMENT

The accuracy of the model was assessed using two methods. First, known garlic mustard invasion data from the Upper Peninsula were compared to the model output. The percentage of pixels with known garlic mustard that received a high risk of invasion was calculated for each phase. This was done for the Upper Peninsula as well as the selected natural areas. While the model accuracy was high following initial development and validation of the model, the percent area of the Upper Peninsula at risk was also high. The models were slightly adjusted by altering risk levels and ranks (and thereby influence) for some parameters to maintain initial accuracy while avoiding over-fitting. This was done subjectively, adjusting the rank of each parameter individually and recalculating a percent influence, while monitoring the percent of the area at risk. The resultant weights are those presented in the model development methods (Table 1).

To further validate the model a ground survey was conducted to look for the presence of garlic mustard. This method of evaluation was anticipated to test the performance of the adjusted model and also the model's utility in the field. Two of the natural areas, ONF and SNWR, were selected for testing the model. At each area, 25 random points were generated using the program Random Point Generator (Sawada, 2002). An additional 40 points were generated along selected Upper Peninsula roads and at campgrounds occurring along these roads. The GPS coordinates of each point were downloaded onto a Garmin GPS Map 76 unit. Using maps of the random points, a field crew navigated to within 15 m of each point. The exact coordinates were recorded at each point, as well as the accuracy of the GPS unit.

The points were later adjusted to the exact coordinates recorded in the field. At each random point the presence and abundance of garlic mustard was recorded within a 30 m × 30 m plot. The random point served as the center of the plot, and a compass was used to align the plot with the cardinal directions. Abundance was based on a visual assessment of percent cover. The presence data were used to calculate the percent of pixels with garlic mustard and a high risk of invasion using the predicted risks for each phase. The absence data were also assessed but with the understanding that garlic mustard has not yet reached its full invasion potential. The abundance data were used to qualitatively assess the differences in risk among the three phases of invasion.

RESULTS

Assessment of model accuracy using known garlic mustard invasion data resulted in an average across all three phases of 89% (±4.2%) of pixels with garlic mustard correctly predicted at moderate to high risk (rating of four or five). This was an average for the three phases of invasion based on 494 pixels with confirmed presence of garlic mustard. Broken down by phase the locations of known invasions predicted at moderate to high risk were 87% for introduction, 94% for establishment and 86% for spread. Three of the selected natural areas, WHNF, ONF and PIRO, had known garlic mustard invasions within their boundaries, thus the outputs from the finer scale model were assessed for these areas. The majority of known garlic mustard locations (65%) fell within the WHNF, representing 320 pixels. Of these 95%, 98% and 95% were assigned a moderate or high risk of invasion for introduction, establishment and spread respectively. At ONF only 18 pixels had presence of garlic mustard of which 67%, 44% and 61% were assigned a moderate or high risk for introduction, establishment and spread. At both sites all garlic mustard points that were not ranked as moderate or high, a rating of four or five, were however predicted to be at risk for garlic mustard with a rating of three. At PIRO only one known point representing a small population of garlic mustard was available which was in an area rated as high risk for introduction and establishment and moderate risk for spread.

During the field sampling period, garlic mustard was only found at two of 90 sampling points. The first location was at South Manistique Lake State Forest Campground in Mackinac County, and the second was near a known invasion site at Forest Lake State Campground in Alger County. The risks predicted by the model at these points were high risk for introduction and establishment and moderate risk for spread at South Manistique Lake and moderate risk for introduction, establishment and spread at Forest Lake. No garlic mustard was found at sampling points within ONF or SNWR during the field sampling.

The model predicted a range of risks across the Upper Peninsula, which varied slightly by phase of invasion (Fig. 2). The model predicted 10% of the Upper Peninsula to be at high risk (risk of five) for introduction, 13% for establishment, and <1% for spread. An additional 37% was at moderate risk (risk of four) for introduction, 33% for establishment and 23% for spread. Risk varied among the selected natural areas modeled with some showing large amounts of the area at risk (Table 2). The most extensive risk for garlic mustard across all three phases was found at ONF, with 53% of the area at moderate or high risk for introduction, 66% for establishment and 27% for spread. Similarly, PIRO had 67% of its area at moderate to high risk for establishment, though only 30% for introduction and 17% for spread. SNWR had the lowest risk with only 8% of the area at moderate to high risk for introduction, 4% for establishment and 2% for spread.

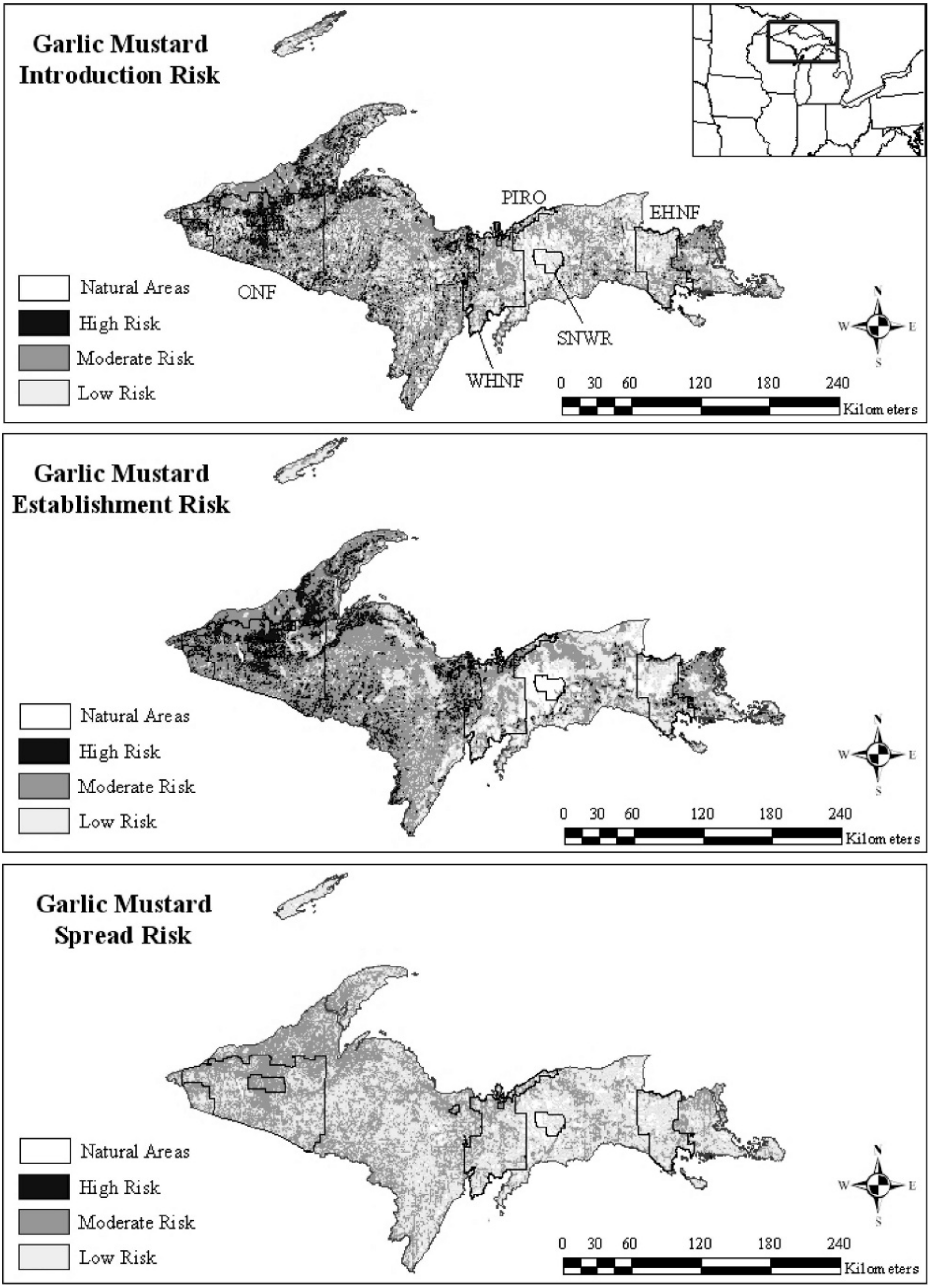

FIG. 2.—Garlic mustard invasion risk at three phases of invasion for the Upper Peninsula of Michigan and selected natural areas

TABLE 2.—Percent area at moderate to high risk for garlic mustard within the Upper Peninsula and selected natural areas

	Introduction	Establishment	Spread
Upper Peninsula	0.47	0.46	0.23
Ottawa NF	0.53	0.66	0.27
W. Hiawatha NF	0.43	0.38	0.21
E. Hiawatha NF	0.38	0.24	0.16
Pictured Rocks	0.30	0.67	0.17
Seney NWR	0.08	0.04	0.02

DISCUSSION

The multi-criteria risk model created for garlic mustard correctly identified invaded areas to be at moderate to high risk 89% of the time. The risk maps created from the model output provide a unique view of the model results. Garlic mustard invasion risk at all three phases covered many areas of the Upper Peninsula. These results were consistent with the findings of Welk *et al.* (2002) and Peterson *et al.* (2003), who both used models to predict that the Upper Peninsula would be suitable habitat for invasion. The risk map for the spread phase showed few areas at high risk. It was expected that the risk of spread in uninvaded areas would be low since there are no established populations to facilitate spread from. Known invasions at the time of modeling covered only 0.001% of the Upper Peninsula. The spread risk and known invasion parameter will become more important in the future as garlic mustard fills its invasion potential. At this time the model can be used to guide surveys for the occurrence of garlic mustard populations and to assist with the planning of control efforts, including biological control releases that are anticipated in the future (Evans and Landis, 2007), favoring areas at greatest risk for spread.

Those natural areas with known garlic mustard occurrence, ONF and WHNF, had the greatest area at risk for garlic mustard. Similarly, SNWR showed the lowest area at risk for garlic mustard, due to its primary habitat of wetlands and xeric, pine-dominated forests and consequently had no garlic mustard occurrence data or any garlic mustard observed during field sampling. PIRO showed some areas of risk, particularly for establishment, and had one invaded site. Despite large areas of risk at ONF and known occurrence data, no garlic mustard was observed during field sampling. Garlic mustard seems to be more prevalent in the Eastern Upper Peninsula which may be a result of its proximity to source populations of garlic mustard in the Lower Peninsula. Another factor to consider is that the recent control efforts to remove and treat garlic mustard within ONF may have affected occurrence of garlic mustard at sampling points.

Relationships between garlic mustard abundance and disturbance have been recently described for deer herbivory, exotic earthworm invasion and fire. These disturbances are thought to provide garlic mustard with a competitive edge over native plants. The presence of deer played a role in the abundance of garlic mustard versus native plants, with garlic mustard benefiting from deer herbivory of native plants (Knight *et al.*, 2009). Likewise exotic earthworm presence has been linked to increased garlic mustard abundance as a consequence of decreased mycorrhizal fungi following earthworm invasion (Hale, 2004). However it has also been suggested that garlic mustard itself contributes to the disruption of mycorrhizal fungi by the release of antifungal phytochemicals (Stinson *et al.*, 2006). Fire, despite its use as a control method for garlic mustard, may further facilitate its invasion. High-intensity fires kill rosettes and adult plants but leave the seeds viable and the disturbance leads to a release from competition allowing further spread of garlic mustard (Luken and Shea, 2000). Burning is also thought to enhance the growth of garlic mustard seedlings by removing the litter layer creating a more suitable seedbed (Blossey *et al.*, 2001). Incorporation of data regarding deer and earthworm densities and recent fire history could aid the prediction of garlic mustard presence as well as indicate areas where garlic mustard abundance is expected to be highest if invaded.

The multi-criteria risk model developed here determines the level of risk for invasion based on biological, environmental and human-induced factors that are significant in the Upper Peninsula. The model in its current form is not applicable to sites outside this region. However, for similar areas, models could be produced and further developed to include additional parameters such as land use, elevation and climate. Accuracy of the results is dependent on the quality of the spatial data and source data used in risk assignment (Store and Kangas, 2001). Many factors affecting the invasion of garlic mustard cannot be mapped spatially or applied in models. Stochastic events may play a large role in the location of initial introductions. As a result, monitoring for garlic mustard should not be based solely on the results of predictive models, but rather, guided by them.

The lack of presence data made the analysis of the field sampling data difficult. Sampling effort was limited due to time and resources, and consequently, the low encounter rate may be due to low sampling intensity. For this reason the assessment of the model accuracy was based primarily on the comparison of predicted risks to known garlic mustard invasions. Continued validation of the model as new garlic mustard occurrence data becomes available is needed to assess the efficiency and utility of the model. Future sampling efforts should take into account methods for detecting rare species occurrence (*see* Dixon *et al.*, 2005; Rew *et al.*, 2006), as garlic mustard is still not abundant in the Upper Peninsula.

The low encounter rate of garlic mustard during field sampling and distribution data collection may indicate that garlic mustard has not reached its full invasion potential in the Upper Peninsula. This presents an ideal setting for the application, as well as evaluation, of the predictive model and risk maps as resources for monitoring introduction, establishment and spread of garlic mustard, as well as prioritizing management. Integrating landscape characteristics that affect distribution into sampling efforts should improve their success (Rew *et al.*, 2006, 2007). By using the risk maps as a guide, the time and resources required for monitoring and management of garlic mustard can be greatly reduced. Monitoring efforts can focus on areas at high risk for introduction and establishment, and control efforts can be prioritized to areas with a high risk of establishment and spread. Maxwell *et al.* (2009) compared strategies for invasive plant management suggesting that monitoring should be combined with control efforts to optimize success. The insight gained from the model and risk maps should increase the success of monitoring and control efforts for garlic mustard. In the future, incorporation of parameters with improved accuracy and associated disturbances could ultimately lead to a model capable of predicting not only garlic mustard presence, but also abundance.

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