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ABSTRACT.—Accurate time- and cost-efficient mapping is central to successful rangeland invasive plant management. In this study sampling together with Inverse Distance Weighted (IDW) interpolation modeling was tested as a mapping alternative to expensive full-coverage delineation survey mapping methods. Our objective was to examine accuracies of presence/absence maps generated from 18 sampling strategies (3 sampling methods × 6 sample densities) using IDW. Invasive plant field survey maps with known accuracies were used to generate samples and to test interpolation results at 2 sites. Site 1 was approximately 6.0 km^2, dominated by Russian knapweed (*Acroptilon repens* L.). Site 2, an upland area of approximately 13.5 km^2, was dominated by spotted knapweed (*Centaurea maculosa* Lam). Sampling method × sample density combinations were gathered from field survey infestation maps using repeated computer-based sampling methods. IDW modeling was applied to each of the sample data sets. Accuracies of the IDW interpolation results were calculated by re-referencing field survey maps. We determined that sampling at density of 0.25% (about 1 point per ha) using a systematic sampling method was the preferred sampling strategy for both sites. This combination of sampling density and method yielded 85% accurate presence/absence maps. We conclude that sampling combined with IDW interpolation modeling can generate accurate invasive plant maps and is a potential alternative to current delineation survey methods.

Key words: invasive plant mapping, sampling, interpolation modeling, inverse distance weighting, IDW, Russian knapweed, spotted knapweed.

Invasive plant distribution maps are a critical component of invasive plant management, and periodic repeated mapping is essential for evaluation and adaptive management. Time and cost constraints currently limit extent, accuracy, and repeatability of invasive plant mapping. Efficient methods of accurately mapping invasive plants are needed. Inverse Distance Weighted (IDW) interpolation modeling is a potential timesaving alternative to current survey methods for generating rangeland invasive plant distribution maps.

Interpolation modeling uses sample data sets and spatial relationships among samples to predict values at unknown locations. It is commonly used to predict continuous variables such as density, but it can also be used for predicting categorical data. In this study we used IDW to predict presence/absence of invasive plants by classifying ranges of values into separate groups. Of the various interpolation methods, IDW is a technique easy to use and highly accessible. Like other methods IDW uses linear combinations of weights at known points to estimate unknown location values. In inter-polation models, $Z(s_o)$ equals the values at unknown locations and is determined by the weighting value (λ_i) and values at known locations $Z(s_i)$.

$$Z(s_o) = \sum_{i=1}^{n} \lambda_i Z(s_i)$$

In the IDW equation, $d(s_i, s_o)$ is the Euclidean distance between s_i and s_o. P is a power

$$\lambda_i = [d(s_i, s_o)]^P / \sum_{i=1}^{n} [d(s_i, s_o)]^P$$

value that controls how fast the weights tend to zero as the distance from the location increases. The higher the exponent, the more influence nearby data will have on the predicted values (Boman et al. 1995).

Interpolation modeling techniques such as kriging have proven to be effective for mapping invasive plants in agricultural systems (Donald 1994, Heisel et al. 1996). Due to the

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use of a spatial variability model for the sample data set and an ability to estimate a semivariogram (a measure of variability of interpolated values), spatial statisticians often consider kriging a more robust and desirable interpolation method (Rouhani 1996, Zimmerman et al. 1999). The question of interpolation method superiority, however, is often debated (Gotway et al. 1996, Rouhani 1996, Zimmerman et al. 1999). Under conditions of high spatial autocorrelation, comparison studies have found IDW equal to, and at times more successful than, kriging (Bowman et al. 1995, Gotway et al. 1996, Dirks et al. 1998). Due to the simplicity of the IDW technique (there is no semivariogram model-fitting component), we considered it more accessible for practical use in invasive plant management and selected it instead of kriging for our analysis.

Since interpolation modeling is dependent on strong spatial relationships for prediction success, the success of IDW for predicting invasive plant distributions will be partially dependent on levels of spatial autocorrelation in plant locations at each study site. Both *Acroptilon repens* L. (Russian knapweed) and *Centaurea maculosa* Lam. (spotted knapweed), when fully established, tend to out-compete other plant species, form varying densities of monocultural stands (Watson 1980, Sheley et al. 1999), and thus have tendencies toward strong spatial autocorrelation. The success of IDW will also be dependent on how well the sample data set represents the distribution of plant species and reflects actual levels of autocorrelation.

To use IDW to predict invasive plant distributions, we needed a starting data set of presence/absence values at sampled locations to interpolate values at nonsampled locations. Since our objective was to obtain the best map for the lowest cost, choosing a sampling method that results in the best representation of the invasive plants' distribution across the landscape was essential. The 3 sampling methods evaluated in this study were systematic, random, and systematic-random. Systematic sampling results in values located in equal intervals along the x- and y-axes. Random sampling creates an unbiased data set pattern where every location in the survey area has an equal probability of being sampled (Thompson 1992). Systematic-random sampling is a hybrid technique, selected for this study, where points are

sampled in equal intervals along 1 axis but along random starting locations on the contrasting axis.

We tested 3 methods in an effort to determine whether, despite the limitations of each, a single sampling method would consistently outperform the others. Systematic sampling methods are limited by the sampling interval relative to response distribution. Research has shown that a representative sample is difficult to obtain if the sampling interval is out of phase with the plant's distribution and response patch sizes are not twice the size of the sampling interval (Theobald 1989). In random sampling, gathering a representative sample is often difficult due to the requirement of large sample sizes (Goedickemeier et al. 1997). Therefore, in cases where a large sample size is gathered but patch sizes are small, random sampling can be superior to systematic. Systematic sampling might be more successful where strong autocorrelation exists, a spatial phenomenon often existing in plant distribution patterns (Moore and Chapman 1986). Less analysis of systematic-random sampling techniques exists in the literature. In this study it was used as an attempt to test whether a combination of systematic and random sampling could result in a successful sampling method.

For IDW to be a useful tool for invasive plant managers, the plant distribution maps must take less time and result in higher accuracy levels than currently used mapping methods. Currently used methods include full delineation surveys, often using GPS units which require circumscribing infestations to denote boundaries, collecting points for small infestations, and using lines to identify linear infestations (Cooksey et al. 1999). When these full-area surveys are conducted, high accuracies are recommended for managers to quantitatively assess their management strategies and improve their management efforts (Cooksey et al. 1999). For sampling and IDW to be a satisfactory replacement to full-area survey methods, the time to collect the sample points must be less than delineating the area's infestations and their boundaries. In this study we wished to determine if an optimum sampling density existed for each sample method and to answer the following question: Can we create accurate enough maps from sample sizes small enough to save time and money?

We evaluated the success of 3 sampling methods and 6 sampling densities using IDW to predict *A. repens* (Russian knapweed) and *C. maculosa* (spotted knapweed) distribution patterns. We hypothesized that both sampling method and density would influence the success of IDW in predicting invasive plant distributions. In addition, we predicted that accurate presence/absence maps could be produced using sample sizes that are a reasonable size for use by land managers.

METHODS

We used Environmental System Research Institute's (ESRI) ArcView GIS 3.2 and the Spatial Analyst extension to create presence/absence invasive plant distribution maps using Inverse Distance Weighted (IDW) interpolation modeling techniques. Eighteen sampling strategies (3 sampling methods × 6 sampling density combinations) were tested to predict *A. repens* and *C. maculosa* distribution patterns in 2 Montana rangeland environments. Using full-coverage field survey mapping methods and GPS, we collected data for invasive plant distribution maps. An accuracy assessment of the field survey maps was conducted prior to testing the sampling and IDW interpolation techniques. We created invasive plant distribution maps from computer-generated samples extracted from the field survey infestation maps. Accuracy of predicted maps was determined by re-referencing field survey maps.

Study Sites

Prediction success was evaluated for invasive plant distributions at 2 locations. The *A. repens* site is a 6.0-km² riparian zone along the Missouri River within the Charles M. Russell Wildlife Refuge in north central Montana (extents: 47°41′30″N, 108°47′30″W and 47°38′N, 108°42′30″W—NAD27). Elevation at the site ranges from 600 m to 900 m, and average annual precipitation is 25–31 cm. The study area is infested primarily with *Acroptilon repens*, a nonindigenous, invasive perennial. *Acroptilon repens* produces seeds but spreads primarily by rhizomatous adventitious roots and is able to suppress growth of nearby plants due to its rhizomatous root system, allelopathic properties, and primarily local spread. This invasive plant tends to form dense stands in areas with shallow water tables or extra water from irrigation (Watson 1980). Native vegetation at the *A. repens* site includes *Salix* spp. (willow), *Populus deltoides* Bartr. ex Marsh. (cottonwood), *Symphoricarpos albus* (L.) Blake (snowberry), *Sarcobatus vermiculatus* (Hook.) Torrey (greasewood), and *Chrysothamnus viscidiflorus* (Hook.) Nutt. (rabbitbrush). Other nonnatives are *Cirsium arvense* L. Scop. (Canada thistle), *Euphorbia esula* L. (leafy spurge), *Centaurea maculosa* Lam. (spotted knapweed), *Cardaria pubescens* (C.A. Mey.) Jarmolenko (whitetop), *Agropyron cristatum* (L.) Gaertn. (crested wheatgrass), and *Bromus inermis* Leyss. (smooth brome).

The *C. maculosa* site encompasses 13.5 km² of upland mixed forest–rangeland on the Northern Cheyenne Indian Reservation in southeastern Montana (extents: 45°45′N, 107°00′W and 45°37′30″N, 106°52′30″W—NAD27). Intermittent streams occur throughout this area and elevation ranges from 900 m to 1500 m. Average annual precipitation is 36–41 cm. This area is primarily infested with *C. maculosa*, a nonindigenous, invasive plant rapidly spreading throughout much of the northwestern United States (Sheley et al. 1999). This taprooted perennial produces large numbers of seeds that are dispersed both locally and over long distances, with local extension of peripheral stands playing a large role in its spread (Watson et al. 1974). Local dispersal of 1–2 m from the parent plant occurs when animals shift the plants and loosen seeds from the seed heads. Long-distance dispersal occurs when seeds become attached to passing people, animals, or vehicles. Seeds can be carried along watercourses and transported with crop seeds and hay. Native vegetation on the site includes *Pinus ponderosa* Dougl. ex Laws. & Laws. (ponderosa pine), *Juniperus scopulorum* Sarg. (juniper), *Pseudoroegneria spicatum* (L.) Gaertn. (bluebunch wheatgrass), and *Agropyron smithii* (Rydb.) Gould (western wheatgrass). An additional nonnative at this site is *Bromus japonicus* Thunb. ex Murr. (Japanese brome).

Field Survey
Infestation Maps

For this study we could have used either simulated hypothetical invasive plant maps or actual field survey maps. Instead of using computer-generated map data, we wished to

use existing invasive plant distribution information that reflected actual invasive plant distributions. Maps existed for the *A. repens* site that were created by the United States Fish and Wildlife Service using intensive ground and helicopter GPS mapping methods in 1997 and 1998. At the *C. maculosa* site, data were collected in 1999 using helicopter GPS mapping methods only. Data at both sites were collected according to the Montana Noxious Weed Survey and Mapping System level 1 standards (Cooksey et al. 1999). Original data were collected as points, lines, and areas and assigned to either a low, moderate, or high cover classification. After the infestation maps were collected, the point and line data were converted to areas equal to infestation size identified by the data collector. Data were reclassified for analysis in this study as present or absent. Present locations were given a value of 1 and absent areas were assigned a value of 0.

Accuracy Assessment of Field Survey Infestation Maps

To determine how well the field survey maps reflected reality of the distributions of the invasive plant species, we conducted accuracy assessments of infestation data at each site in fall 1999. Fifty random present locations and 11 random absent locations were assessed at the *A. repens* site. Forty-five and 10 present and absent locations, respectively, were assessed at the *C. maculosa* site. Using Rockwell GPS Pluggers with 5–15 m navigational accuracy, we located points and determined their correctness. User and producer accuracies for the presence and absence categories and for overall accuracy were calculated.

Accuracy Assessment Estimators

User and producer accuracies and overall accuracy are 3 estimators that together provided a full perspective on the quality of the field survey and IDW predicted map data. These estimators were used for both the field survey data (as discussed above) and the IDW prediction maps. User accuracy is the number of correct locations in a category divided by the total number of locations in the category. It estimates how well the data, for each category mapped, can be trusted by land managers in the field (i.e., if a manager were to travel to a location where a plant was indicated on the map, how likely would it be that a plant would indeed be there). Producer accuracy is the number of correct locations in the category divided by the number of reference locations in the category. It indicates how successful the field surveyor and, in the case of simulations, the IDW model are at determining plant locations (i.e., of all locations where a plant was present, what amount was correct). Overall accuracy is the number of locations correct for all categories divided by the total number of reference locations for all categories. It provides a generalized accuracy estimate, as it combines results from both categories (presence and absence).

Study Site Sampling Area

The field survey infestation maps for each study site were converted from points, lines, and areas to grid format in the GIS. The cell size was determined by the need to match experimental scale with management scale (Firbank 1993) and was set to a resolution of 5 m (25 m²). For the *A. repens* site, the sample area included 240,140 cells. For the *C. maculosa* site, the sample area included 543,703 cells.

Sampling Strategies

We evaluated 18 sampling strategies that were based on the 3 sampling methods and 6 sampling densities. The 6 sampling densities were 0.04%, 0.06%, 0.08%, 0.11%, 0.16%, 0.25% (number of cells sampled/total number of cells within study area), approximately 0.2, 0.3, 0.35, 0.45, 0.7, and 1.0 points · ha⁻¹, respectively.

Samples were gathered by applying each sample strategy (sample method × sample density) to the field survey infestation maps. To test for differences among sampling strategies, we replicated each strategy 3 times for the 18 method × density combinations for a total of 54 sample data sets at each site. Sampling the GPS data sets was completed in ArcView GIS software. GIS-based computer code was written to automate the sampling process. For systematic sampling, we randomly shifted the 1st sample point in the systematic sampling strategies ±50 m along the x-axis. Systematic-random samples were generated by randomizing sampling locations on the y-axis and setting an even sampling interval along the x-axis.

IDW Analysis

At each site we analyzed the 54 data set combinations using the IDW interpolation function in the ArcView Spatial Analyst extension. User inputs to the IDW function were the distance power value (p) and n (the number of nearest sample points used in the interpolation of each cell). A distance power value of 2 is most commonly used in IDW applications (Gotway et al. 1996) and was the value selected for our analysis. N can be set as a fixed number of sample points or radius distance value. Researchers using interpolation methods have used n sample sizes ranging from $6 \leq n \leq 24$ (Zimmerman et al. 1999). Twelve sample points were chosen within the range of recommended values for abruptly changing surfaces (Declercq 1996). The IDW function was applied to each sample data set and produced a grid map with continuous predicted values ranging from 0 to 1. The resulting prediction grid was reclassified to values <0.5 when identified as absent and values ≥0.5 when identified as present.

Assessing IDW Predicted Map Accuracies

We used field survey infestation maps to generate data for sampling strategies and then referenced them to determine the accuracy of the interpolation maps. Analysis of variance was used to determine significant effects of sampling method or sampling density on user and producer accuracy for presence and overall accuracy. Three replications of the sample method × sample density combinations enabled a calculation of experiment-wide error protected means separations at each study site; this was done using multiple comparison analysis (MCA) with Tukey's test when a priori statistical P-values were ≤0.05.

RESULTS

Field Survey Infestation Map Accuracies

Ten absence locations were evaluated at the C. maculosa site and 11 at the A. repens site. Four times as many locations were evaluated for presence as absence at both sites. This resulted in a high level of confidence (>90%) of presence accuracies and a lower confidence (≤85%) of accuracies for absent locations (Tortora 1978).

At the *A. repens* site, user and producer accuracies for presence and overall accuracy were 95.0%, 97.4%, and 94.0%, respectively. At the *C. maculosa* site, user and producer accuracies and overall accuracy were 85.2%, 82.1%, and 80.0%. User and producer accuracies for absence at the *A. repens* and *C. maculosa* sites were 90.0% and 81.8%, and 72.2% and 76.5%, respectively.

Accuracy assessment of the field survey maps was conducted to ensure that the data represented true invasive plant distributions. With presence and overall accuracies ≥80.0% at both sites, we determined the maps to be accurate representations of reality for invasive plant presence and overall. Accuracies for absence were not as high, and we were less confident in results for this category. Therefore, we chose to evaluate statistical differences for user and producer presence accuracies and overall accuracy only. Based on the field survey maps, the percent of study sites infested, hereafter referred to as infestation level, was 43.0% at the *A. repens* site and 12.5% at the *C. maculosa* site.

IDW Predicted Map Accuracy Differences

USER ACCURACY.—Effect of sample method and sample density on user accuracy depended on the study site (Table 1).

Acroptilon repens site: Interactions existed between sample method and sample density (Table 1), indicating that the effect of sample method on user accuracy was dependent on the sample density. Multiple comparison analysis indicated that the only differences among sample densities were where the systematic sample method produced higher accuracies than systematic-random at 0.04% and 0.08% densities (Fig. 1).

Centaurea maculosa site: There were no interactions between sample method and sample density (Table 1). Sample method and sample density main effects influenced user accuracy. Systematic sampling produced higher user accuracies (2.7%) than the systematic-random sample method, but not significantly higher than random sampling (Fig. 2a). Random and systematic-random sample methods produced similar user accuracies. *Centaurea maculosa* user accuracies for the systematic, random, and systematic-random sample methods were 81.0%, 79.1%, and 78.3%, respectively.

TABLE 1. ANOVA *P*-values for sampling method and sampling density using user and producer presence accuracies and overall prediction accuracies for *A. repens* and *C. maculosa* sites.

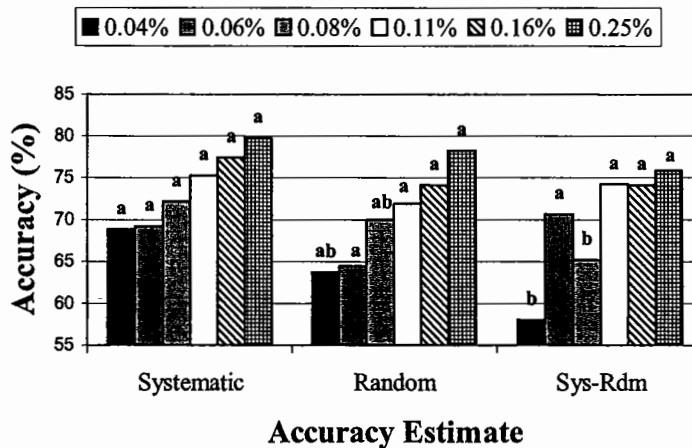| | | Accuracy types | | |
| | | User's | Producer's | Overall |
	df	*P*-values		
A. repens site				
Sample method	2	0.0001	0.0020	0.5131
Sample density	5	<0.0001	<0.0001	<0.0001
Sample method × sample density	10	0.0108	0.9712	0.9189
C. maculosa site				
Sample method	2	0.0106	<0.0001	0.7605
Sample density	5	<0.0001	<0.0001	<0.0001
Sample method × sample density	10	0.0694	0.3689	0.9113

Fig. 1. MCA of sample method × sample density presence prediction accuracies for systematic, random, and systematic-random sampling methods at *A. repens* site. Significant differences among sample method × density combinations are identified by *a*'s and *b*'s.

The highest sample density (0.25%) produced the highest user accuracies (Fig. 2b). Increases occurred between 0.04% and 0.08% and 0.06% and 0.11%. User accuracy for the *C. maculosa* site was the only instance in which the highest 2 sample densities (0.16% and 0.25%) were different from each other (Fig. 2b). Sample density user accuracies ranged from 72.3% to 85.8% at the *C. maculosa* site.

PRODUCER ACCURACY.—The main effects of sample method and sample density influenced producer presence accuracy at both sites (Table 1). No interaction between sample method and sample density was detected at either site.

Acroptilon repens site: Systematic sampling produced a higher average accuracy (7.9%) than the systematic-random method (Fig. 3a).

There was no difference between the random and systematic-random sample methods. Producer accuracies for the systematic, random, and systematic-random sample methods were 73.1%, 68.4%, and 65.2%, respectively. Increasing sample density produced higher producer accuracies (Fig. 3b). The 0.25% sample density resulted in higher producer accuracies than all other densities except for the 0.16% sample density. Producer accuracy at the lowest sample density was 58.0% and 79.3% at the highest.

Centaurea maculosa site: There were no interactions between sample method and sample density (Table 1). Sample method and sample density main effects influenced user accuracy. Systematic sampling produced higher user accuracies than the random sample method

a | ■ Systematic ▓ Random □ Systematic-Random |

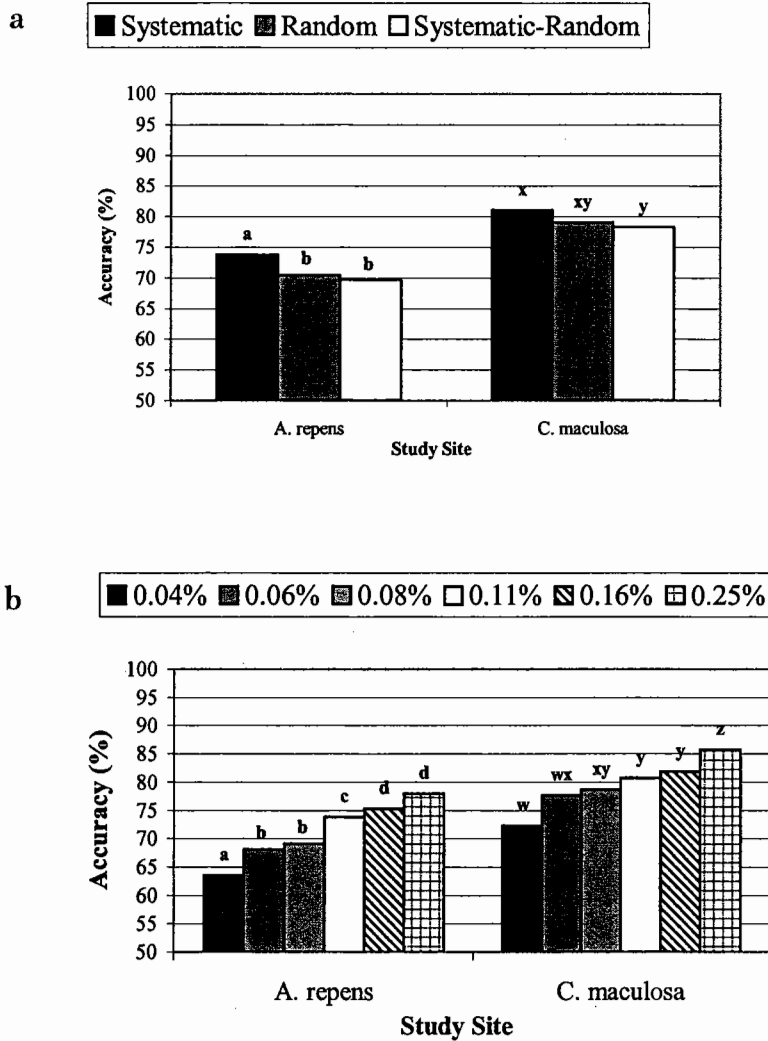b | ■0.04% ▓0.06% ▒0.08% □0.11% ▨0.16% ⊞0.25% |

Fig. 2. MCA differences between sample methods of user's accuracy for prediction presence at the *A. repens* site and *C. maculosa* site: (a) sample method, (b) sample density. Significant differences are identified by *a*'s and *b*'s and *x*'s and *y*'s for each site.

(7.0%) and the systematic-random sampling (7.3%; Fig. 3a). Systematic-random and random sample methods produced similar accuracies. *Centaurea maculosa* presence producer accuracies for the systematic, random, and systematic-random sample methods were 74.5%, 67.5%, and 67.2%, respectively. Higher producer accuracies occurred when sample density was increased from 0.04% and 0.06% (Fig. 3b). The 0.16% sample density produced higher producer accuracies than the 0.08% sample density. The 0.25% sample density produced higher accura-

cies than the 0.11% sample density. There was no difference in producer accuracy at the 2 highest densities. Producer accuracy was 57.7% at the lowest sample density and 78.7% at the highest sample density.

OVERALL ACCURACY.—Sample method did not affect overall accuracy at either site (Table 1). Sample density influenced overall accuracy at both sites.

Acroptilon repens site: Mean overall accuracy across all sample methods was 82.0%. Differences between 0.04% and 0.06%, 0.06% and
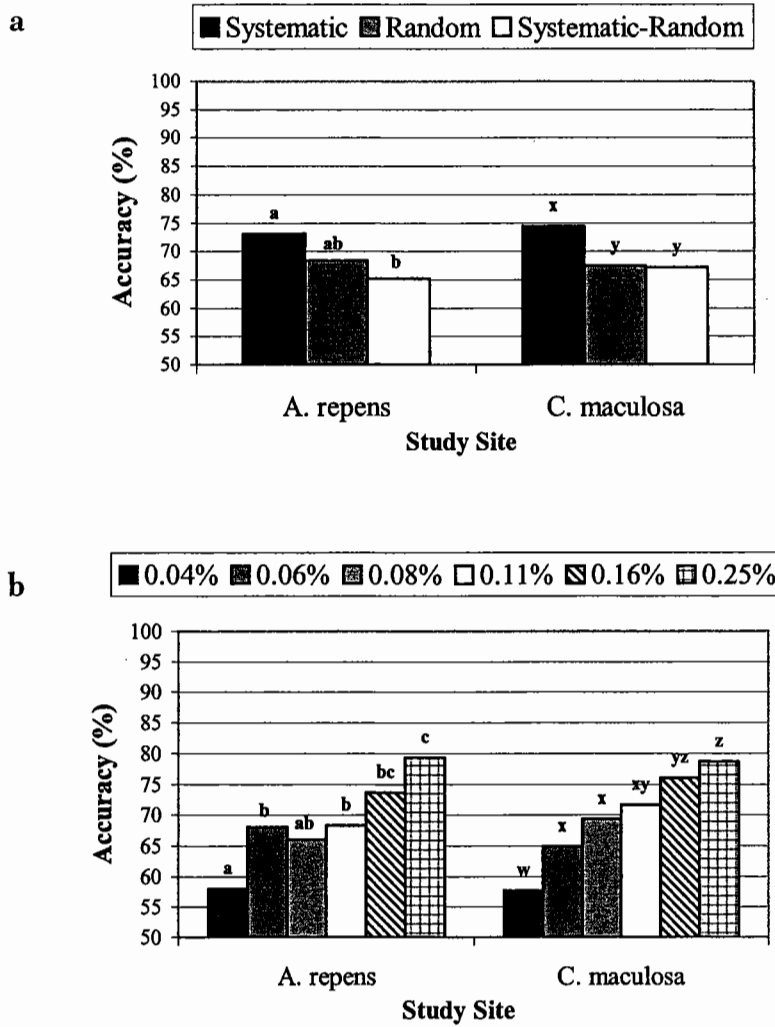
a

b

Fig. 3. MCA differences of producer's accuracy for prediction presence at the *A. repens* site and *C. maculosa* sites: (a) sample method, (b) sample density.

0.16%, and 0.11% and 0.25% sample densities were detected (Fig. 4b). The average accuracy values ranged between 76.9% at the lowest sample density and 86.8% at the highest sample density.

Centaurea maculosa site: Mean overall accuracy across sample methods was 94.2%. Increases in some sample densities produced higher accuracies (Fig. 4b). Accuracy differences occurred between 0.04% and 0.08%, 0.06% and 0.11%, and 0.11% and 0.25% sample densities. The overall accuracy ranged between 92.3% at the lowest sample density and 95.8% at the highest sample density.

Map Comparisons of Sample Methods

At the 0.25% sample density, comparison of 1 replication of the 3 sampling methods showed systematic sampling missed the fewest infestations at the *A. repens* site (Fig 5a). However, systematic sampling resulted in a larger amount of over-prediction (i.e., predicted incorrect) of presence than random sampling. Most incorrectly classified locations using systematic sampling appear on the edges of large patches. Random sampling resulted in incorrect predictions in the central portion of the study area. Systematic-random sampling predicted
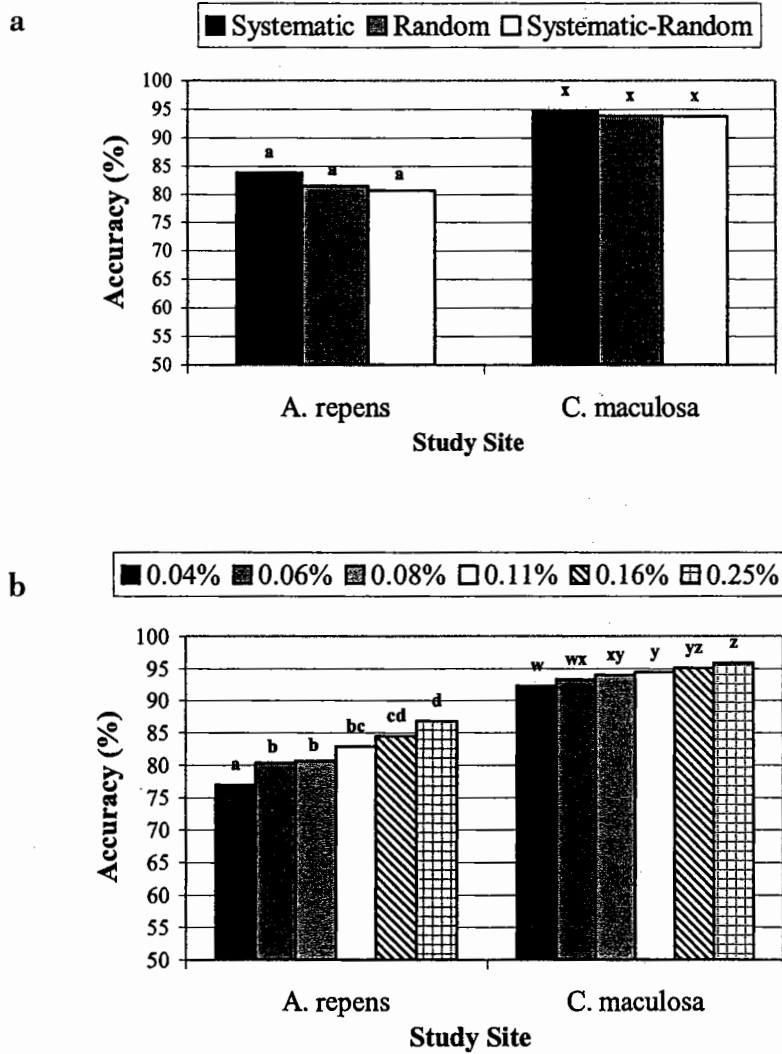
a

b

Fig. 4. MCA differences of overall accuracy for prediction presence at the *A. repens* site and *C. maculosa* site: (a) sample method, (b) sample density.

incorrectly more areas present than random and missed more infestations than systematic. The maps also indicated systematic sampling was able to capture a larger number of the smaller infestations (<2.02 ha) more successfully than either random or systematic-random sampling. Similar results occurred at the *C. maculosa* site (Fig. 5b).

DISCUSSION

Sampling density had the greatest and most consistent effect on prediction accuracies. At the 0.25% sample density, overall accuracies ranged from 78.0% to 86.8% at the *A. repens* site and from 92.3% to 95.8% at the *C. maculosa* site. The highest values meet the United States Geological Survey 85% classification accuracy standard for vegetation mapping (Anderson et al. 1976) and are suitable accuracy levels for invasive plant management. Based on experience from invasive plant managers, traditional survey maps (except at the most intensive level) rarely exceed these accuracy levels (Cooksey personal communication). Since sampling (even at the 0.25% density) would
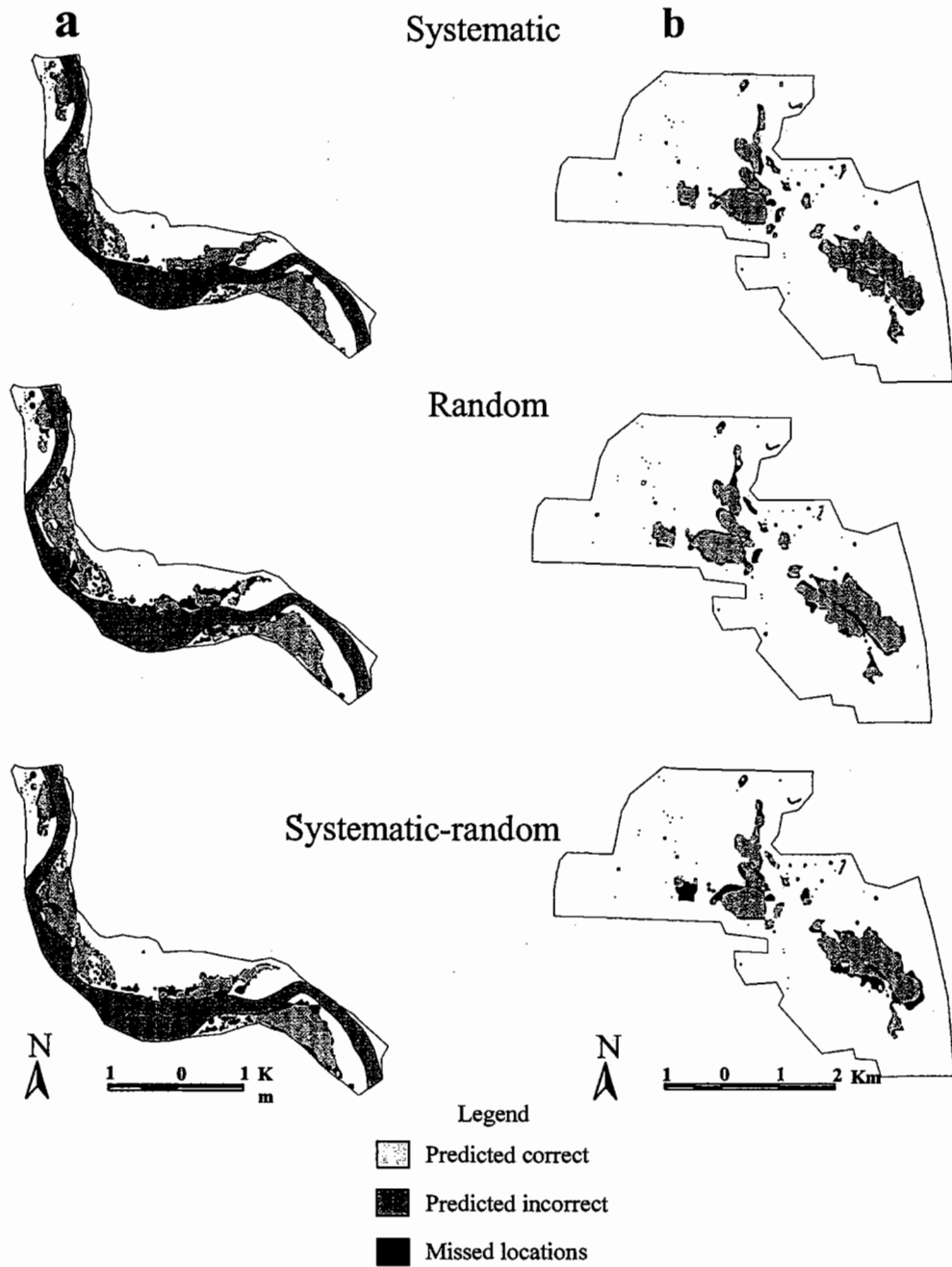
Fig. 5. Comparison of predicted infestation maps at 0.25% sampling density: predicted correct vs. predicted incorrect vs. missed locations at (a) A. *repens* site, (b) C. *maculosa* site.

take less time than traditional surveys, IDW can be considered a potential alternative to traditional survey mapping.

Sample method did not have as strong an influence on accuracy values as sample density. At both our study sites, however, systematic sampling performed significantly better than the other sampling methods for some of the accuracy estimates. In contrast, at no time did either the random or the systematic-random sample methods perform better than systematic sampling for any of the accuracy estimates at either site.

While systematic sampling was the most appropriate sample method in this study for IDW prediction mapping, there are some potential limitations to using this method that land managers should be aware of. Variations in systematic sample locations can, at times, result in nonrepresentative samples (Podani 1984), and if the sampling interval is not synchronized with the plant distribution, interpolation success may decrease (Fortin et al. 1989). Our analyses, however, did not support these concerns. Despite the fact that grid origins were randomly shifted ±50 m in all systematic sampling replications, only small variations in accuracy results at each density were evident. We found the average variation in accuracy was only 3.1% at the *A. repens* site and 2.2% at the *C. maculosa* site. One possible explanation for the success of the systematic sampling method in obtaining a consistently representative sample is the relatively high infestation levels at the 2 sites. Therefore, at 12.1% infestation levels and higher, ~1 point · ha^{-1} might be a high enough sampling interval to eliminate out-of-phase effects between a systematic sampling grid and invasive plant distribution.

Based on the sample densities tested, we were unable to determine an optimum sample density (in all cases accuracies continued to increase and did not level off). Even at the highest sample densities (0.16%, 0.25%), accuracies were continuing to increase. At 0.25% (~1 point · ha^{-1}), however, relatively high accuracies for all estimates were reached, indicating that ~1 point · ha^{-1} can be a sample size that would achieve time- and money-saving management goals. We caution, however, that appropriate sample densities might fluctuate, depending on species and site location. The most appropriate sample density for a management project may be unique to the management

conditions. For each management situation infestation type, infestation levels, accuracy needs, and time constraints should be considered.

Before making a final recommendation, additional issues regarding the abilities and limitations of sampling and IDW should be discussed. The 1st is the inability of all sample methods to predict presence/absence along the infestation patch edges. Some spatial uncertainty is inevitable with any modeling effort. Uncertainty is commonly estimated for digitizer error but has been applied to map classifications (Aspinall and Pearson 1995) and can be used with the sampling/interpolation results in this study. Using our data, when systematically sampling at 100-m intervals (0.25% density), the mean distance of each unsampled location in each of the study areas was 38.2 m. This distance value is an estimate of the positional uncertainty to expect from the predicted infestation boundaries for the systematic/0.25% sample strategy. Use of IDW to identify reduction or spread at the patch boundary when changes are less than ~40 m is therefore inappropriate. Until spread has occurred at levels greater than the spatial uncertainty, our results indicate that land managers could calculate changes only in total infestation levels and not rely on data to identify changes within patches.

A 2nd limitation is the missed infestation patches <2.02 ha in size by all sample methods. According to sampling theory, when systematic sampling is used, the minimum detectable patch size is twice the area determined by the sampling interval (Theobald 1989). At the 0.25% sample density, the intersample distance was 100 m, thus making 2 ha the minimum detectable patch size. Most of the small infestations less than 2.02 ha were not identified using the systematic sampling method. More sample points would be necessary to produce high-accuracy maps if a greater number of small patches exist or if infestation levels are low. When choosing between systematic, random, and systematic-random sampling methods, despite this limitation, the systematic sampling method was more successful in capturing the small patches than the other methods at both study sites.

Inverse distance weighting is based on the principle of spatial autocorrelation, meaning that nearer locations have more similar conditions than further away locations. While spatial autocorrelation was not explicitly tested in

this study, since IDW was successful at both sites, spatial autocorrelation among the sample locations necessarily exists. If sampling and IDW are to be used at other sites, the sampling interval must be high enough to capture the spatial autocorrelation between points. This might be more difficult in cases where infestation levels are lower than in this study. In addition, higher sample sizes might be required when more than a single species is being predicted. Our study also did not test the sensitivity of prediction under varying IDW power values (p) and variations in recategorization thresholds (using values other than 0.5 for reclassification). Additional testing of variations in these values would be useful.

This study has shown that sampling and IDW can produce high accuracy presence/absence distribution maps for 2 invasive plant species at 2 study sites. Based on this research, we recommend using sampling in conjunction with IDW to create invasive plant distribution maps. In our study systematic sampling at a 0.25% (~ 1 point $\cdot$ ha^{-1}) sample density resulted in overall map accuracies of $\geq 85\%$. For each management case land managers should conduct a premapping test in order to determine an appropriate sample strategy which will result in suitable accuracies for their management purposes. Additional research should focus on determining minimum infestation level requirements for predicting distributions for *A. repens*, *C. maculosa*, and other invasive species.

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