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Prioritizing Invasive Plant Management with Multi-Criteria Decision Analysis

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Prioritizing management of invasive plants is important for large land management entities, such as federal and state public land stewards, because management resources are limited and multiple land uses and management objectives are differentially impacted. Management decisions also have important consequences for the likelihood of success and ultimate cost of control efforts. We applied multi-criteria decision analysis methods in a geographic information system using natural resource and land use data from Fort Bragg, North Carolina. Landscape-scale prioritization was based on a hierarchical model designed to increase invasive plant management efficiencies and reduce the risk of impacts to key installation management goals, such as training-land management and protected species conservation. We also applied spatial sensitivity analyses to evaluate the robustness of the prioritization to perturbations of the model weights, which were used to describe the relative importance of different elements of the hierarchical model. Based on stakeholders' need for confidence in making management investments, we incorporated the results of the sensitivity analysis into the decision-making process. We identified high-priority sites that were minimally affected by the weight perturbations as being suitable for up-front management and evaluated how adopting this strategy affected management area, locations, and costs. We found that incorporating the results of the sensitivity analysis led to a reduced management area, different target locations, and lower costs for an equal area managed. Finally, we confirmed the distinctiveness of the approach by comparing this same subset of prioritized sites with locations representing species-centric strategies for three invasive plants and their aggregate distribution. By supplying pragmatic information about the localized effects of weighting uncertainty, spatial sensitivity analyses enhanced the invasive plant management decision-making process and increased stakeholder confidence.

Key words: Analytic Hierarchy Process (AHP), management prioritization, multi-species management strategies, spatially explicit.

Limitations on the availability of funds or labor resources prevent most land managers from adequately controlling all known invasive plant infestations across focal properties or landscapes. Consequently, prioritization of effort is critically important in order to generate the greatest progress towards satisfying management goals. Unfortunately, management decisions are typically informal or largely based on regional species-level rankings (Fox and Gordon 2009), with limited evaluation of factors relevant for attaining explicit or implicit natural resource management goals. This approach to decision-making potentially squanders limited resources and fails to adequately address the range and spatial variability of invasive plant impacts. Infestations of multiple species at different stages of invasion within a managed landscape can pose complex direct and indirect impacts that are likely to be overlooked by informal decision-making methods. Informal decisions are also particularly vulnerable to failure when applied to lands under multipurpose management, as the complex interaction of various management activities on control efforts is left underappreciated. Failure to successfully control invasive plants can result in multiple well-documented ecological and economic impacts (Pimental et al. 2005; Vilà et al. 2011). By utilizing a formal decision-making approach to prioritize where management should occur, managers can ensure limited management resources are applied effectively and impacts are prevented or limited.

Multi-criteria decision analysis (MCDA) is a well-established and increasingly utilized group of decision-making methods (Greene et al. 2010; Hajkowicz 2008; Malczewski

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Management Implications

Limited resources force land managers to make choices about where and when to implement invasive plant management actions. Ideally these choices will satisfy the multiple land management objectives, legal requirements, and stakeholders pertinent to most invasive plant management campaigns. Multi-criteria decision analysis (MCDA) provides a proven approach for solving complex decision problems, but has not been widely used for invasive plant management. We applied one MCDA method, the Analytic Hierarchy Process (AHP), to a landscape-scale prioritization of invasive plant management at Fort Bragg, North Carolina. Cognizant of the potential impact of weight uncertainty on AHP outputs, we additionally used spatial sensitivity analyses to reveal high-priority locations where investments in invasive plant management could be made with a degree of confidence deemed acceptable by installation stakeholders.

Our results showed that AHP can be easily implemented in a geographic information system to match local invasive plant management concerns and that incorporating spatial sensitivity analysis into the decision-making process affected the area, locations, and costs associated with management implementation. Results of the integrated prioritization also differed from ad hoc species-centric strategies in terms of the locations identified for management and the priority values associated with these locations.

The AHP can be applied to diverse invasive plant management prioritization problems using available data, expert opinion, and science-based heuristics, but can also be expanded to include new insights provided by additional data, stakeholder input, or models of relevant system processes as they become available. Additionally, spatial sensitivity analyses of AHP weights, decision criteria, or both are recommended in order to gain insights about model robustness and enhance land managers' acceptance of the outputs.

2006) potentially ideal for integrating the many considerations important for effective invasive plant management. MCDA is defined as an evaluation based on multiple criteria, wherein the criteria are quantifiable indicators of the degree to which the decision problem may be influenced (Malczewski 1999). MCDA provides a hierarchical, scaling framework to integrate multiple objectives with multiple datasets to help decision makers solve complex decision problems (Malczewski 2006). Although MCDA has a history of use in environmental planning and natural resource management (e.g., Geneletti 2004; Guikema and Milke 1999; Mendoza and Martins 2006; Prato 1999; Regan et al. 2007), it is not commonly applied to landscape-scale spatial prioritization of invasive plant management (e.g., Roura-Pascual et al. 2009; Skurka Darin et al. 2011).

Although MCDA has great potential to assist invasive plant management decision making, it is important to consider the robustness of the outcome of any decision analysis. Sensitivity analysis (SA) should be used to examine the stability of the MCDA outcome to uncertainty in the decision framework, which can be introduced to weights, data representing criteria, or the number and identity of criteria. Yet, in a recent review of SA in multi-criteria spatial decision making, Delgado and Sendra (2004) showed that SA was conducted in only 61% of published studies. SA methods used to evaluate MCDA vary, but fairly well-established and consistently applied methods exist for the most common decision analysis scenario, which is aspatial and considers a discrete number of decision alternatives (e.g., Triantaphyllou and Sánchez 1997). Although SA in MCDA is an active topic of research (e.g., Chen and Kocaoglu 2008; Hyde et al. 2005), methods for use in a spatial context are less well developed (Feick and Hall 2004; Ligmann-Zielinska and Jankowski 2008). This is especially true for raster-based analyses, which typically lack a discrete set of decision alternatives. Roura-Pascual et al. (2010) introduced the use of the earth mover's distance and Shannon diversity index (H) for spatially explicit SA of a MCDA-based prioritization that evaluated multiple invasive plant management strategies. These metrics, which are summarized as single values for an entire focal area, seem well suited to landscape-wide characterizations of sensitivity; however, most management actions are implemented locally. Consequently, it is also important to know which locations on a landscape are more or less robust to uncertainty. Those locations identified as having high management priority and being insensitive to uncertainty can be confidently targeted for control with limited funding or resources.

The objective of this study was to evaluate the utility of MCDA for spatially explicit prioritization of invasive plant management across a multipurpose landscape represented by Fort Bragg, NC. Specifically, we (1) illustrate how an MCDA framework can integrate the complexities of invasive plant management to assist managers in deciding where to prioritize control efforts, (2) evaluate the local stability of the MCDA output using a spatial SA, (3) examine how incorporating the insights provided by spatial SA can affect implementation of the prioritization output, and (4) compare the output of the structured prioritization with commonly adopted, species-centric approaches.

Materials and Methods

Study Area and Invasive Plant Management Requirements. Fort Bragg spans approximately 65,000 ha (160,618 ac) in the Sandhills ecoregion of south-central North Carolina. The installation harbors the largest tract of longleaf pine–wiregrass (*Pinus palustris* Mill.–*Aristida stricta* Michx.) ecosystem in the state and dozens of nationally and state significant natural heritage areas (NCNHP 2009). Fort Bragg's conservation efforts play a crucial role in preserving rare species diversity of the longleaf pine–wiregrass ecosystem, which has been reduced to 5% of its historic range (Noel et al. 1998; Ware et al. 1993). Success of these efforts is demonstrated by the occurrence of 61 federal- or state-listed threatened, endangered, and at-risk plant species (Gray et al. 2003; Sorrie et al. 2006), as well as populations of the federally endangered red-cockaded woodpecker (RCW) (USFWS 2003) and St. Francis' satyr butterfly on the installation (Kuefler et al. 2008; Parshall and Kral 1989). Although conservation of threatened and endangered species (TES) is an important driver for many land management activities on Fort Bragg, the installation must balance these actions with its primary mission to support troop training, as well as logistical and mobilization/deployment support.

Like other federal land managers, the Department of Defense (DoD) is required to manage the natural resources on its lands for sustained multipurpose use. Integrated management to support sustainable use for military training requires significant coordination among the stakeholders that represent various installation land uses and their associated management programs. This coordination is documented within an installation's Integrated Natural Resource Management Plan (INRMP), which brings together the goals, objectives, and actions of diverse and potentially conflicting land use and management programs (e.g., military training land rehabilitation, recreation, forestry, TES, agricultural out-leasing, etc.). Army policy guidance in response to the 1999 Executive Order 13112 on Invasive Species also requires installations to (1) give priority to invasive species management actions that restore native species habitat in ecosystems that have been invaded, support the installation's primary military mission and contribute to the protection of federally listed threatened and endangered species and critical habitat and (2) ensure that invasive species do not detract from the usefulness of training and testing lands.

Forty-one different invasive plant species are documented from 6,400 infestations on Fort Bragg. Distribution and percent-cover data were available for most species from a recent (2004 to 2005) installation-wide, plot-based, random stratified survey. We used GS+™ (Gamma Design Software, Plainwell, MI) to interpolate species' percentage of cover as raster data layers using data collected within the more than 5,000 survey plots (25 m [82 ft] by 50 m [164 ft]). Interpolations were performed via ordinary kriging for species with $\geq$ 100 plot observations, whereas inverse distance weighting was applied to those with $<$ 100 plot observations. Various species-specific constraint layers were used to mask the output of both procedures (e.g., aquatic species were limited to wetland habitats).

Analytic Hierarchy Process. We employed the Analytic Hierarchy Process (AHP) MCDA technique to develop our invasive plant management prioritization framework (Saaty 1977, 1980). The AHP frames a decision problem within a hierarchy of objectives, evaluation criteria, and subcriteria relevant to the problem. Our decision problem was to "prioritize invasive plant management," and we defined two distinct objectives: (1) "reduce invasive plant impacts" on the natural resource management goals of Fort Bragg, and (2) "increase invasive plant management efficiency" (Table 1). Management efficiencies can be realized by implementing certain management strategies (e.g., early detection and rapid response, prevention, containment, etc.) as general heuristics in light of land use and management activities (e.g., Cacho et al. 2008; Christen and Matlack 2009; Coutts et al. 2011; Davies and Sheley 2007; Finnoff et al. 2007; Panetta and Cacho 2012; Sharov 2004; Theoharides and Dukes 2007).

We identified evaluation criteria and subcriteria to serve as metrics for the two objectives, based on existing land management goals identified in the installation's INRMP (Table 1). We used ArcGIS® (Esri, Redlands, CA) and available spatial datasets describing the location and pertinent characteristics of rare plant populations, RCW nesting clusters, invasive plant infestations, military training areas, and road and stream networks to derive raster data layers for subcriteria. We calculated correlations among subcriteria to confirm they were sufficiently independent from one another and to prevent "double counting" them in the prioritization. We standardized the subcriteria to a common scale by using a score range procedure (Malczewski 2000):

$$x_i = (R_i - R_{\min})/(R_{\max} - R_{\min}) \quad [1]$$

where R_i represents the observed values, $R_{\min}$ and $R_{\max}$ are the range of observed subcriterion values, and x_i are the standardized values on a scale of 0 to1, with higher values representing higher management priority.

Criteria Weighting. A defining feature of AHP is a pair-wise weighting process that compares elements within levels and branches of the decision hierarchy two at a time, in order to capture experts' or stakeholders' judgments about relative importance (Saaty 1977, 1980). We elicited installation stakeholder input about the relative importance of the two objectives, the three criteria, and the subcriteria where more than one occurred below a criterion. A nine-point ordinal scale was applied to compare relative importance (Saaty 1977). For each set of comparisons, consensus judgments were organized into pair-wise comparison matrices to convey the input about relative importance provided by five stakeholders representing the diverse training and natural resource management programs on the installation. We used the IDRISI® module "WEIGHT" (Clark Labs, Worcester, MA) to calculate sets of weights from the pair-wise comparison matrices, based on the normalized values of the eigenvector associated with the maximum eigenvalue (Saaty 1977, 1980).

Variation in pair-wise judgments was examined to identify how consistent stakeholders were when comparing the relative importance of elements. We used a measure of

Table 1. Objectives, criteria, subcriteria, weights, and associated data values used to spatially prioritize invasive plant management on Fort Bragg, North Carolina.

Objectives [weight]	Criteria [weight]	Subcriteria [weight]	Data values
Reduce invasive plant impacts [0.56]	Impacts to rare plants [0.65]	Proximity of rare plant sites (n = 1,125; area = 5,275 ha) to known invasive plant locations [0.60]	0–150 m[a]
		Protection status of rare plants [0.40]	Federally endangered = 5, federally threatened = 4, federally significantly rare = 3, state endangered = 2, state threatened = 1
	Impacts to RCW[b] [0.28]	Proximity of RCW clusters (n = 525, area = 7,514 ha) to known invasive plant locations	0–150 m[a]
	Impacts to military training [0.07]	Proximity of drop zones and landing zones (n = 41; area = 3,254 ha) to known infestations[c]	0–150 m[a]
Increase invasive plant management efficiencies [0.44]	Management cost [0.16]	Site-specific management cost based on species growth form and estimated percentage of cover	\$543–3,721 ha^{-1}[a]
	Suitability for early detection/ rapid response [0.54]	Species invasiveness ranking[d] [0.75]	High = 3, moderate = 2, low = 1
		Number of infestations [0.25]	1–1,365[a]
	Risk of spread along dispersal corridors [0.30]	Presence within 20 m of roadsides, firebreaks, and streams (area = 14,647 ha)	Presence = 1, absence = 0

[a] Values were inverted to generate intended effect on prioritization.

[b] Abbreviation: RCW, red-cockaded woodpecker.

[c] Only tree and shrub species were used for this subcriterion.

[d] Invasiveness rankings were from Heffernan et al. (2001).

consistency called the consistency ratio (CR), which describes the probability that a stakeholder provided judgment matrix differs from a randomly generated judgment matrix (Saaty 1977). The consistency ratio is given by

$$CR = (CI/RI(n)) \quad [2]$$

where RI(n) is the random consistency index for matrices of order n, and (CI) is the consistency index. CI is calculated as:

$$CI = (\lambda_{max} - 1)/(n - 1) \quad [3]$$

where λ_{max} is the principal eigenvalue of the judgment matrix. Saaty (1980) provides a table of RI(n) values. In all cases the CR values were < 0.10, indicating an appropriate amount of agreement in the consensus judgments provided by stakeholders (Saaty 1980) and used to develop weights across the hierarchy.

Combination. Certain areas of Fort Bragg have access restrictions due to live artillery firing and unexploded ordinance. To ensure only logical or feasible management locations were included in the final priority map (Malczewski 2000), we masked illogical locations from our analysis. We then applied weights at each level of the hierarchy. Starting with the subcriteria level, and working up the hierarchy to the objectives level, we multiplied weight values with the respective standardized spatial data layers. After weights were applied to a level, elements on that level and the same branch of the hierarchy were summed. This process was performed with a series of ArcGIS map algebra procedures to generate a map depicting overall invasive plant management priorities.

Sensitivity Analysis. Uncertainty is an inherent part of any decision-making process and can arise from multiple sources, including spatial and data errors, as well as ambiguity about the relationships between or among objectives, criteria, and subcriteria. We used SA to assess the general stability of the weights derived from stakeholders' expert opinion, identify weights that are especially responsive to change, and evaluate the spatial variability of weight sensitivity. We introduced a known amount of change to the weights, and then examined the impact on the AHP outcome. Weights were randomly perturbed within a range representing the stakeholders' consensus-derived values $\pm$ 20%. We introduced this perturbation in three different ways to explore the weight sensitivity within different levels and branches of the decision hierarchy. Specifically, we perturbed the weights at the objectives level, and separately along the two branches of the criteria level. This was repeated 500 times for each set of criteria weights, but only 177 times for the objective weights. For the latter, novel combinations of perturbed values were limited by the range of values representing the maximum perturbations ($\pm$ 20%) of the smallest weight and our choice to only examine values to three decimal places. In each case, the AHP requirement to have the weights sum to one was satisfied.

To quantify the aggregate or global response in the AHP outputs to weight perturbations we calculated the mean and standard deviation of the relative change between the base prioritization map generated from the original weights and prioritization maps generated using the perturbed sets of weights. To evaluate the spatial effects of weight sensitivity, we generated raster layers of the local variation arising from weight perturbations. Specifically, we calculated the cell-by-cell coefficient of variation (CV) for the sets of prioritization maps generated using the weight perturbation scenarios described above. We then evaluated these maps jointly with the original management prioritization map to identify sites having high priority values and low CV. Specifically, we used the upper quartile of the priority values and a stakeholder-specified cutoff of $<$ 5% CV to identify locations where investing in invasive plant management could be made with an acceptable degree of confidence. To reveal how incorporating the output of the spatial SAs would affect management implementation costs we estimated the cumulative cost in rank order (highest to lowest) for the upper quartile of prioritized locations and the $<$ 5% CV constrained subset. The site-specific management costs for this assessment were the same as those used in the prioritization and represented the average cost of six different bids obtained from three vendors over a 5 yr period.

Comparison of Integrated and Species-Centric Management. Using the subset of locations identified by the SA (top quartile of priority values with $<$ 5% CV), we compared the output of the AHP prioritization with species-centric strategies for three invasive plants: silktree (*Albizia julibrissin* Durazz.), Chinese privet (*Ligustrum sinense* Lour.), and kudzu [*Pueraria montana* (Lour.) Merr.]. These species were perceived to be of primary management importance on Fort Bragg prior to conducting the formal prioritization and identified for management in the installation's INRMP. We assessed differences in the two strategies in two ways: (1) we calculated the percentages of the areas identified by the species-centric strategy that were also included in the $<$ 5% CV constrained subset of the top quartile of priority values and (2) we evaluated whether the priority values differed between the areas targeted for management by the different strategies. For both of these assessments we examined species separately and as an aggregate. To determine whether priority values differed, we bootstrapped the priority values representing the two strategies with replacement 1,000 times. For each iteration, we calculated the mean difference by subtracting the priority values of locations (cells) representing the species' distributions from the values of the $<$ 5% CV subset of the top quartile. We estimated 95% confidence intervals (CIs) for differences and assessed statistical significance by examining whether the CIs overlapped zero (Manly 2007).

Results

MCDA-Based Spatial Prioritization of Invasive Plant Management. We integrated invasive plant management planning across a complex landscape, producing a spatially explicit prioritization of management actions in light of multiple land management objectives. By implementing the AHP in a geographic information system (GIS), output was generated as a raster layer with a value in each cell representing management priority. High-priority management sites (represented by the upper quartile of priority values) were spatially clustered primarily along roadsides, at rare plant sites, and in the cantonment (Figure 1). A high density of roads and numerous different invasive plant species in the cantonment likely caused the observed concentration of high-priority sites in this portion of the installation (roughly the southern half of the eastern third). Lower-priority management sites were broadly distributed throughout the installation and were spatially clustered into large patches within military training areas, which cover the western two-thirds of the installation, as well as the northern half of the eastern third (Figure 1). Drop zones, which are covered by expansive areas of sericea lespedeza [*Lespedeza cuneata* (Dum. Cours.) G. Don] and weeping lovegrass [*Eragrostis curvula* (Schrad.) Nees], were evident as large low-priority blocks.

Sensitivity Analysis. Spatial and aspatial SA showed uncertainty in the various weights differentially affected AHP outputs. Results of the global SA showed that mean

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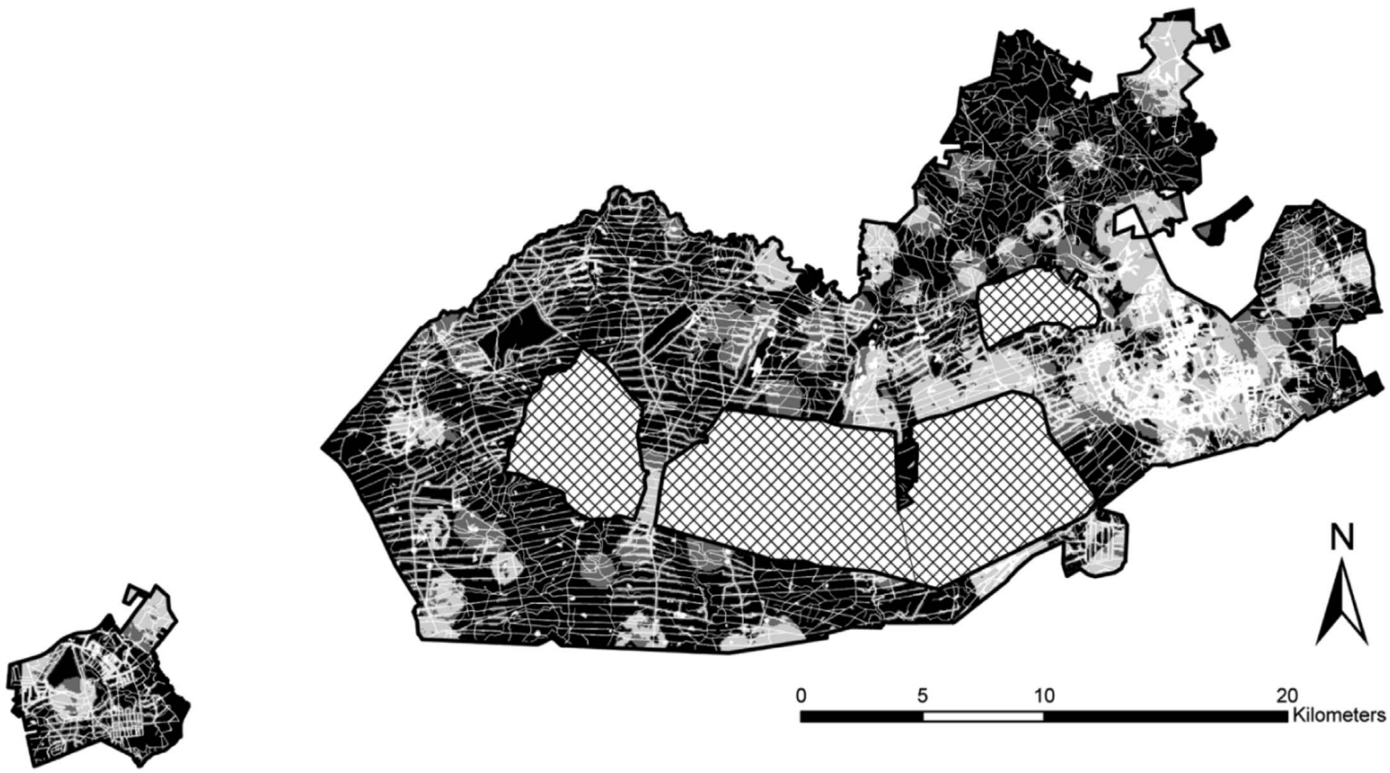

Figure 1. Distribution of invasive plant management priority values across Fort Bragg (right) and Camp MacKall (left). Priority values are displayed as quartiles, ranging from high (white) to low (black). Crosshatched areas are inaccessible for management due to safety restrictions associated with live artillery firing and unexploded ordinance.

relative change and standard deviation between prioritization maps generated from the original and perturbed weights varied depending on which sets of weights in the hierarchy were perturbed (Figure 2). The range of relative change values was larger for weight perturbations applied at the objectives level than perturbations at the criteria level. The greater influence of the weights at the objectives level on the AHP outputs was not unanticipated given their position in the hierarchy of calculations.

The spatial variation in weight sensitivity across the study landscape was visualized and evaluated by alternately applying weight perturbations at objective and criteria levels of the decision hierarchy and calculating the cell-by-cell CVs. Whether the sets of perturbations were applied to objective or criteria weights, cell-by-cell CV values were moderate, ranging from approximately 0 to 12%. At the objectives level, large areas in the cantonment and northeastern portion of the installation exhibited high CVs, whereas roads and fire breaks in the western training areas exhibited lower CVs (not shown). Comparing the spatial distribution of CV values derived from the two sets of criteria weight perturbations, we found that the prioritization output was less sensitive to weights under the "reduce invasive plant impacts" than the "increase management efficiencies" criteria (Figures 3a and 3b). This result mirrored the pattern observed in the global (i.e., aspatial) SAs (Figure 2).

Joint evaluation of the original priority and CV maps revealed a substantial portion of the upper quartile of priority values (75%) did not meet the stakeholder specified $< 5\%$ CV cutoff, reducing the area deemed to be suitable for investing limited management resources. Locations where both conditions were met were distributed throughout the installation, but noticeably corresponded with roads, firebreaks, and TES sites in the noncantonment portions of the installation (Figure 4). These results show how management implementation can be fundamentally affected if insights provided by spatial SA are embraced as part of the decision making process.

Incorporating the results of the spatial SA into the decision-making process not only affected management locations, but also had consequences for management costs. Estimated cumulative costs of implementing management at the top quartile of prioritized locations and the $< 5\%$ CV constrained subset (Figure 5) were similar up to approximately 750 ha. However, costs diverged for management of larger areas, with the strategy that incorporated the results of the spatial SA being less costly (i.e., a larger area could be managed for the same number of dollars) than one based solely on the original AHP outputs. This difference in

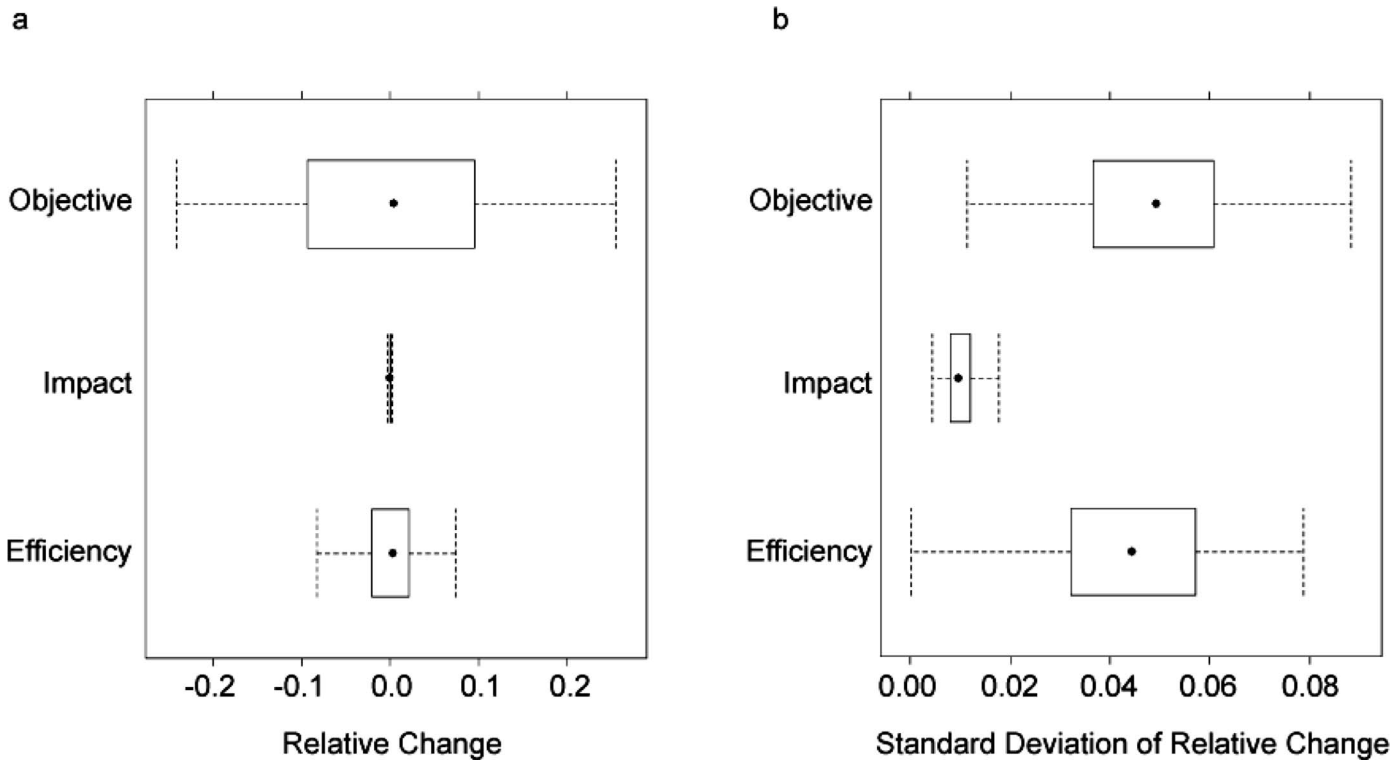

Figure 2. Box plots showing (a) mean relative change and (b) standard deviation between prioritization maps generated from the original and perturbed sets of weights, which were separately applied to objectives and criteria (i.e., "reduce invasive plant impacts" and "increase invasive plant management efficiencies") levels of the hierarchy. Dots in the boxes are the medians, the boxes include 50% of the data, whiskers are the minimum and maximum (excepting any outliers), and open circles are outliers.

cumulative costs approached 10% for areas larger than approximately 2,500 ha. The lack of divergence in cumulative cost for areas less than 750 ha suggests that the highest-priority sites under both strategies had roughly similar management costs.

Comparison of Integrated and Species-centric Management. Management priorities identified by the AHP differed from ad hoc, species-centric approaches. For the three species, less than 8% of the aggregate area that would be targeted in a species-centric strategy was identified for management by the integrated AHP prioritization. Locations identified as being a high management priority and robust to weight uncertainty via AHP also had higher priority values than locations representing species-centric approaches (Figure 6). Distributions of the priority values representing the two strategies exhibited some overlap, but 95% CIs of the mean differences between priority values were larger than zero (Table 2).

Discussion

Invasive plants are a significant management challenge for land managers and limited budgets force decisions about implementation of management actions. The advantages of using a formalized prioritization framework for management planning, such as the AHP approach we have applied here, are that the process is defensible, transparent, systematic, reproducible, collaborative, and spatially explicit. These traits are particularly desirable when multiple land management objectives add to the complexity of management planning.

Few studies have explicitly examined how spatial characteristics of a heterogeneous management landscape can affect invasive plant control strategies or inform where control efforts should be preferentially applied (e.g., Giljohann et al. 2011; Higgins et al. 2000; Roura-Pascual et al. 2009; Yager and Smith 2009). Applying the AHP within a GIS allowed us to generate a spatial prioritization of management across our study landscape. We incorporated important spatial relevancies into the prioritization by expressing certain decision criteria and subcriteria as grids of distances separating known infestations and land management units likely to be impacted. As these spatial relevancies are propagated through the decision analysis, areas of high management priority can be detected that are unlikely to be identified in less structured decision-making approaches. Unsurprisingly, our integrated spatial prioritization identified different locations for management than ad hoc, species-centric approaches, and these locations

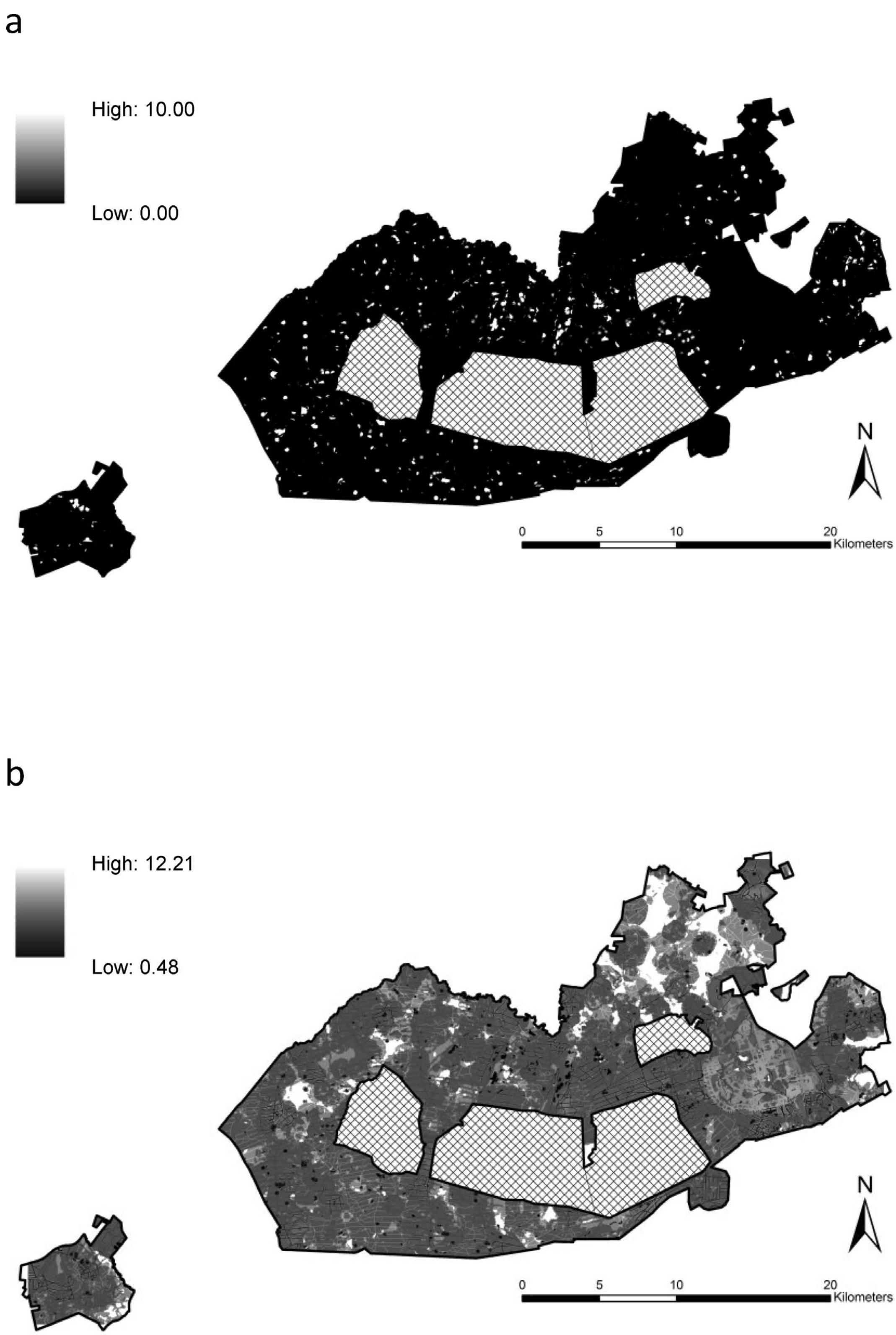

Figure 3. Spatial sensitivity analysis output showing cell-by-cell coefficient of variation (%) for perturbations separately applied to weights under (a) "reduce invasive plant impacts" and (b) "increase invasive plant management efficiencies."

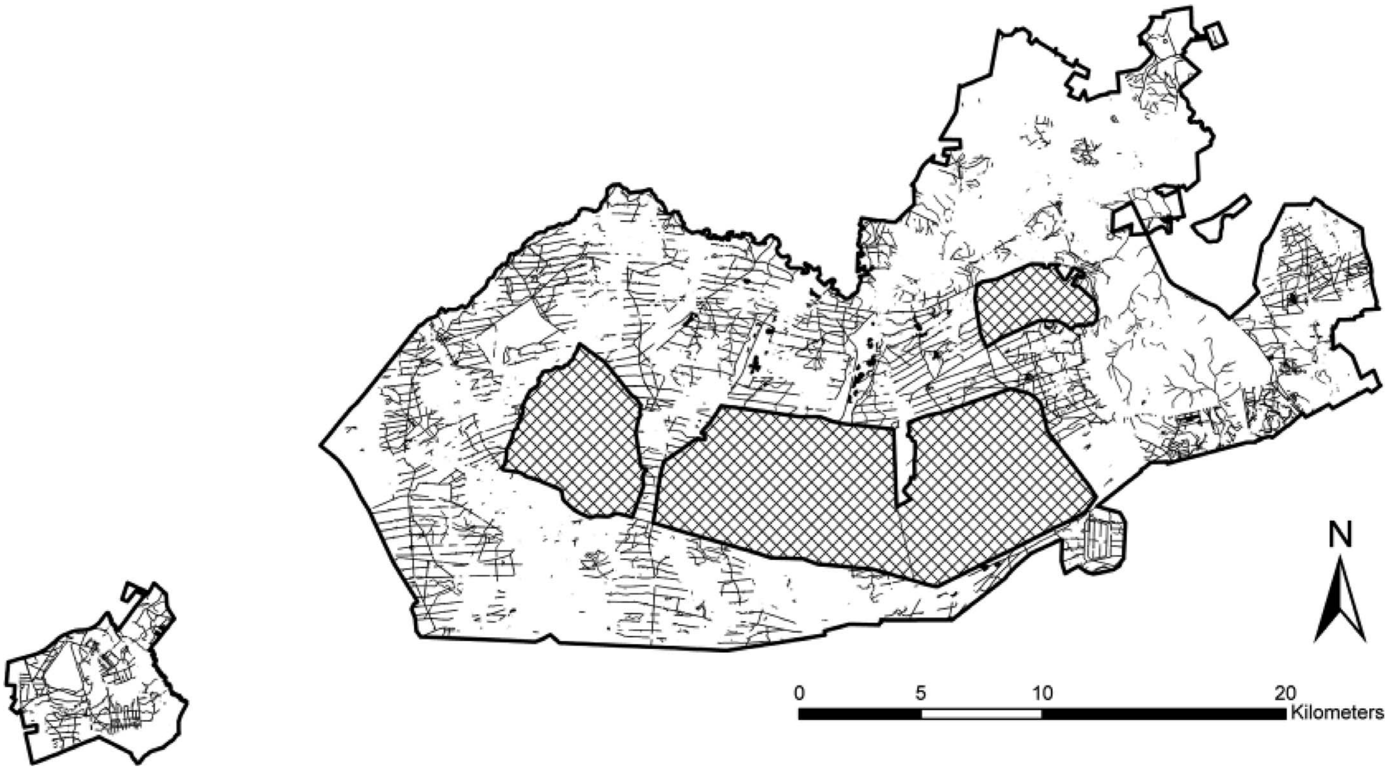

Figure 4. Locations where invasive plant management priority was high and coefficient of variation was low (< 5%) when random perturbations of ± 20% were applied to Analytic Hierarchy Process weights. The installation boundary is shown as a heavy black line and restricted access areas are hatched.

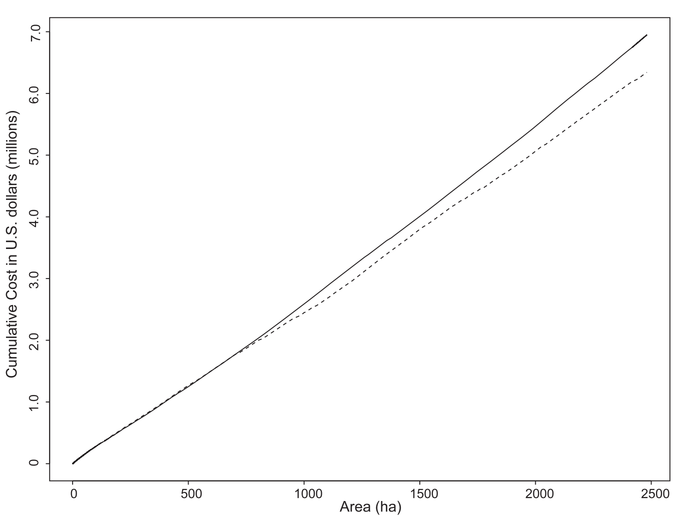

Figure 5. Estimated cumulative costs and area treated for the top quartile of prioritized management locations (solid line) and the subset of locations where investing in management could be made with a degree of confidence deemed acceptable by managers (i.e., having coefficients of variation < 5%) (dashed line).

better represented the installation's multi-objective land management goals (as indicated by higher priority values).

Prioritization output can be evaluated in multiple ways depending on the specific need or summary desired. For example, one could extract the highest-priority locations that meet a specified area goal for annual management. Alternately, prioritization values could be evaluated in light of a management cost layer to identify the highest-priority sites that can be managed given a predefined annual budget. Over a longer time horizon, the histogram of prioritization values for a managed landscape can be used to justify funding requests. For example, a negatively skewed and leptokurtic histogram of prioritization values suggests a need for large, up-front budgets.

The specific criteria one might use in a local application of AHP to prioritize invasive plant management is only limited by the creativity of the individuals developing the prioritization and the availability of data. Additional criteria potentially relevant for management prioritization on other public lands or in different regional settings might include concerns about impacts on aesthetics, recreational use, water resources management, public/neighbor relations, erosion potential, biodiversity conservation, and wildfire risk. Additional criteria describing management efficiencies specifically relevant for prioritizing management might include logistical limitations on the implementation

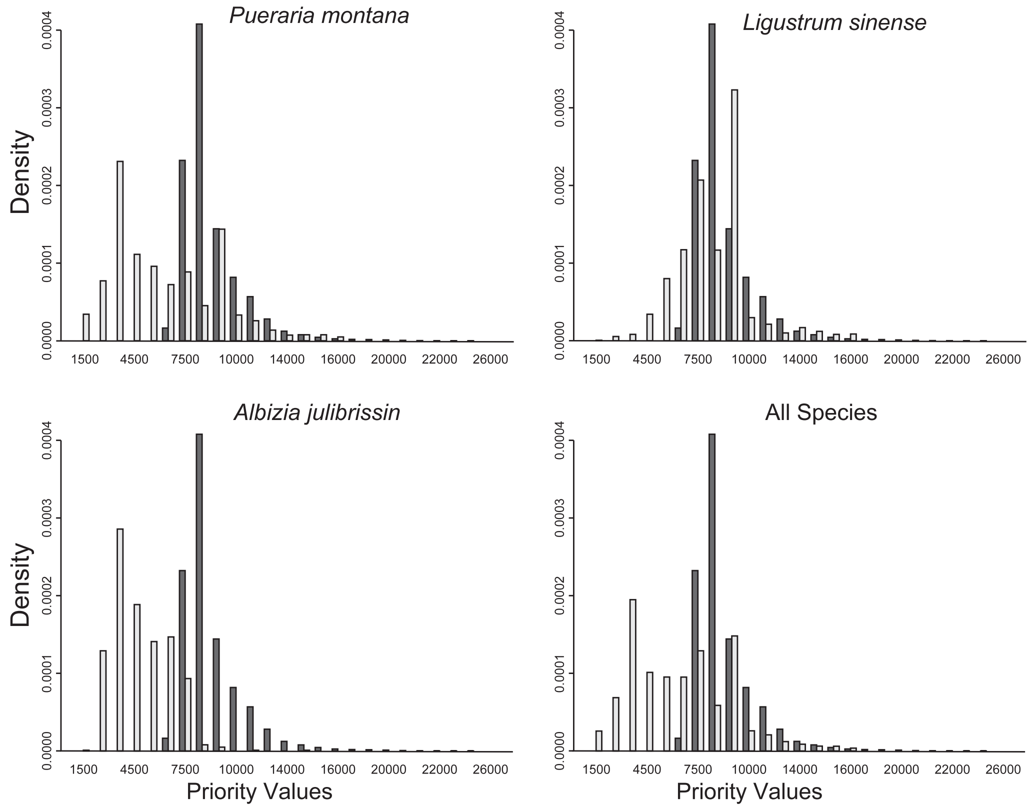

Figure 6. Density of high-priority values insensitive to uncertainty in Analytic Hierarchy Process weights (i.e., upper quartile having < 5% coefficient of variation) (black bars) and priority values for locations representing single species distributions and their aggregate distribution (white bars).

of management actions in remote locations (Yager and Smith 2009) or complex topography, the role land management or recreational activities may play in facilitating dispersal, as well as site-, species-, or size-specific efficacy of treatments (Roura-Pascual et al. 2009). Examples of how these concerns could be incorporated into a management prioritization framework include the following: (1) targeting the removal of dominant, commonly recognized invasive plants like kudzu or giant reed (*Arundo donax* L.) within the viewsheds of popular visitor interpretive stops within a national park, (2) targeting control of deep-rooted invasive shrubs and trees such as saltcedar (*Tamarix ramosissima*

Table 2. Bootstrapped 95% confidence intervals for the mean difference in priority values of locations representing species-centric and integrated, multi-objective strategies.

	Confidence intervals	
Species	2.50%	97.50%
Albizia julibrissin	4246.385	4439.331
Ligustrum sinense	688.851	779.985
Pueraria montana	2857.259	2981.882
Aggregate	2690.775	2763.142

Ledeb.) in riparian corridors within a water conservation district in the southwestern United States to limit hydraulic lift and transpiration-related water loss, (3) targeting infestations along property boundaries to help eliminate the concerns neighboring landowners may have about the spread of particular species onto their property, (4) characterizing the effect of downy brome (*Bromus tectorum* L.) infestations on wildfire risk and in relation to the location of fire defenses, (5) evaluating how slope steepness and distance from roads affects the feasibility of accessing sites with different control equipment (e.g., backpack sprayers, all-terrain vehicle–mounted spray system), and (6) targeting infestations near trailheads.

Our application of the AHP used available data, expert opinion, and science-based heuristics to inform the prioritization, but it can also be expanded to include new insights provided by additional data, stakeholders, or models of relevant system processes. This ability to flexibly use available information limits the need to make up-front investments in acquiring detailed species-specific data or models, which can stall management efforts and divert funding. Consequently, it accommodates the position taken by Simberloff (2003), who acknowledges detailed information about species' population biology can provide additional insights to refine management strategies, but also advocates that such information is typically not necessary to make informed, well-justified management decisions. Flexibility in the use of available information also enables a cyclic decision-making process wherein feedback of information can increase refinement of the hierarchy structure and acceptance of the AHP outcome.

An appealing feature of MCDA for invasive plant management prioritization is the ability to use heuristics and expert knowledge to inform the decision analysis. This is particularly valuable when specific information or models of relevant processes are unavailable, or the validity of applying them across multiple scales is untested. For example, the conclusion made by Moody and Mack (1988), that the most cost-effective management strategy is to first control small isolated infestations, remains a key guiding principle and has been validated multiple times in different models (e.g., Grevstad 2005; Higgins et al. 2000). However, generalizations about optimal strategies should be made with caution, and where additional information about economics, dispersal, and demographics is available, it should be appropriately incorporated (Coutts et al. 2011; Epanchin-Niell and Hastings 2010). Exceptions to generalizations are expected due to the complexity of interactions between species' autecologies and local environments, as well as variation in management goals (e.g., eradication vs. containment) and budgets. However, multispecies management strategies will likely need to rely upon general concepts that are reduced to heuristics given the paucity of data to support detailed local models for all relevant species.

Higgins et al. (2000) argued that the critical importance of invasion rates in defining management strategies limits the utility of static, rule-based decision support systems. However, we propose that rule-based decision support can be effective and are a vast improvement to status quo, ad hoc management. When new information about abundance and distribution, or invasion dynamics, are regularly incorporated into an adaptive decision process, rule-based decision support can inform highly dynamic management programs. Ideally, new information about distribution and abundance would become available (e.g., via an appropriately scaled survey effort) as the accuracy of the existing information is perceived to wane. In this sense, the output of rule-based decision support seems no less limiting than that offered by a process-based model, wherein it would be questionable to generate output for an extended time period and then blindly implement management without ever checking how well the output reflects reality in an inherently uncertain system. Estimates of spread rates are notoriously uncertain (Melbourne and Hastings 2009), and active adaptive management is a useful approach for managing spreading invasions in the face of uncertainty (Shea et al. 2002).

We used a suite of simple metrics to assess weight sensitivity, revealing the variable influence of different weights in the decision hierarchy and locations where a high degree of confidence could be placed in investing upfront management efforts. Incorporating results of the spatial SA into the management decision-making process not only affected the amount of area and the locations identified for management, but also led to reduced management costs assuming equal areas treated. Roura-Pascual et al. (2010) introduced a novel use of H and earth mover's distance to evaluate sensitivity of their grid-based management prioritization model to changes in weights. Unfortunately, these global metrics provide no localized information about spatial variation of uncertainty, which is valuable for interpreting outputs of AHP and other MCDA. Additionally, calculating H demands that the continuous MCDA output be categorized into a discrete number of classes. This categorization process can be done in any number of ways (e.g., various quantiles, equal intervals, natural breaks, etc.), and will not only affect the values that are derived, but also one's potential ability to interpret comparisons between original and perturbed outputs. Like several other landscape metrics, H can also exhibit nonmonotonic behavior as a function of the proportion of the study landscape represented by classes, complicating its interpretation (e.g., Li et al. 2005; Trani and Giles 1999). Although these approaches to spatial SA are promising, additional research is needed to guide their application and interpretation (Roura-Pascual et al. 2010).

Although our study was conducted on lands under DoD stewardship, other public land stewards have also recognized the challenges associated with establishing effective and defensible invasive plant management programs and are creating policies that require structured decision making (e.g., U.S. Department of Agriculture–Forest Service's National Forest System Invasive Species Management Policy. FR 76(233): 75860–75866; 5 Dec 2011).

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