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Point Mapping Integrates Data Collection and Weed Control Operations

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In this case study, we evaluated a point-mapping method for simultaneously collecting data while controlling three invasive woody plant species: black locust, Chinese privet, and hardy orange. The study in Arkansas Post National Memorial included seven project areas ranging in size from 2.7 to 27.3 ha and spanned six field seasons (2010 to 2015). The control techniques varied depending on plant size and always included the application of herbicide, which also varied over the course of the study to include glyphosate, imazapyr, and triclopyr. Each person responsible for controlling plants simultaneously collected global positioning system point data to estimate the foliar cover of the plants treated. The resulting data demonstrated evidence of decreases in all three plant species in most project areas during the 6-yr period. Initial increases in area treated for some species–area combinations reflected differences in the preliminary efforts required to control invasive plants in entire project areas, but by 2012 six of seven project areas were treated in their entirety. Despite a high level of reduction, in some cases, the plants persisted at low levels even during the sixth year of the project. Our findings support the ability of this method to granularly detect changes in plant abundance while simultaneously controlling invasive plants. With several acknowledged limitations, this streamlined project-based monitoring approach provides data that allow managers to assess the effectiveness of weed control treatments.

Nomenclature: Glyphosate; imazapyr; triclopyr; black locust, *Robinia pseudoacacia* L.; Chinese privet, *Ligustrum sinense* Lour.; hardy orange, *Poncirus trifoliata* (L.) Raf.

Key words: Data collection, effectiveness monitoring, GPS, invasive plants, point data, point mapping, weed mapping, NAISMA.

A focus on the effectiveness of weed management practices, especially as mediated through herbicide use, is a touchstone of weed science (Timmons 2005). As weed science emerged as a discipline in the 1950s, effective herbicide applications were quickly sought and applied in other non-crop systems around the same time period. This included the use of herbicides for site preparation and release of seedlings in forest lands (Wagner et al. 2004), the control of weeds to maximize grass biomass in rangelands (Fisher et al. 1959), and the improvement of habitat for game species (Wagner et al. 2004). The use of herbicides was considered an option in prairie restoration prescriptions by at least the late 1960s (Schramm 1970). The use of herbicides to control invasive plants in undisturbed natural areas (i.e., wildlands) was reported in journals in the 1980s, although early efforts in Yosemite National Park began after World War II (Randall 1996). Since that time, literature on the effectiveness of invasive plant management has become voluminous, with many studies published in the 2000s (Abella 2014; Kettenring and Adams 2011). This pulse of activity may be the outcome of the view of invasive species as potentially harmful and of the establishment of the field of invasion biology in the mid-1980s (Davis 2009).

Effectiveness of Invasive Plant Management in Wildlands as a Critical Measure. Weed management techniques, particularly herbicide use, are now widely applied to invasive plants in wildlands (DiTomaso 2000). Effectiveness in wildlands is measured as desired changes in the plant community and mitigation of environmental impacts in

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Management Implications

To evaluate invasive plant treatments, field practitioners require information on treatment effectiveness. On one hand, practitioners rely on herbicide labels, practical literature (e.g., extension publications), personal communications and experience, and evidence-based studies to know that a proposed treatment should work. To assess the results of a specific project, field practitioners often make qualitative posttreatment assessments in the field. This approach, however, may fail to adequately assess projects in wildlands, which often span large areas and require treatment over several years. Alternatively, managers may set up plot-based studies, although the designs, time, and expertise required to take a quantitative approach may be unrealistic. As another option, we evaluated a point-mapping method in which field personnel concurrently controlled invasive plants and collected data using a global positioning system (GPS) unit. For this approach to work, we first established clear project areas (i.e., management units). To the extent possible, project areas were designed using observable features in the field such as property boundaries, roads, trails, and transitions between vegetation types. While applying treatments, observers collected a GPS point and attributed an absolute areal cover value (i.e., infested area) to represent treatment of a subset of plants (i.e., a patch) within the larger project area (i.e., gross area) using the following scale: 0.1, 1, 5, 10, 20, 50, or 100 m^2. Following training on infested-area estimation, field workers collected data for all plants treated but had discretion to balance the granularity of data collection with treatment efficiency. For example, field workers could choose to estimate the subsets of treated plants using a small increment of 0.1 m^2 or an increment as large as 100 m^2. Within these boundaries, field workers adjusted the increment used to best match field conditions and requirements for operational speed. Presumably, for widely distributed clusters of a few individual plants, the use of small cover increments to estimate infested area would not substantially reduce treatment speed. For more abundant or widespread species, larger increments would allow the infested area to be estimated without negatively impacting operational speed. When an entire project area is treated during each visit, field personnel provide data at the actual project scale. Using this approach over a 6-yr period, we demonstrated significant decreases in three woody plant species—black locust, Chinese privet, and hardy orange. Such data can inform an adaptive management planning process.

addition to the removal of the offending plant species (Skurski et al. 2013). Effectiveness data are critically important for informing invasive plant management projects in wildlands. First, such data make adaptive weed management possible (Shea et al. 2002; Sheley et al. 2010). Without such data, land managers cannot know whether they are accomplishing set goals and, consequently, whether the attendant methods or goals require adjustment. Second, such data allow managers, especially those working on public lands, to increase the transparency of decision-making processes and maintain accountability for their work. This is especially important given academic disagreement on the harm that results from invasive plant species (Davis et al. 2011; Shackelford et al. 2013; Simberloff 2011), which may affect public opinion in the future. While disagreements will likely continue regarding (1) the proper application of the precautionary principle, (2) the actual or potential harm resulting from invasive plant species, (3) the possibility of unintended consequences to human health and the environment due to herbicide use or even due to the removal of the invasive plant itself, and (4) the best use of public funds (Bonanno 2016; Davies and Johnson 2011; Davis 2009), parties on all sides of this debate can at least agree that ineffective practices should not continue.

Approaches to Measuring Treatment Effectiveness. Agricultural experiments set the standard for evaluating the effectiveness of agricultural practices, including weed management. Following the principles of good experimental design, these studies include controls, randomization, and blocking (Elzinga et al. 1998). On the other hand, extension projects have used demonstration sites as case studies that support certain land-use practices (Gardiner et al. 2008; Hodur et al. 2006). Such an approach, while not necessarily involving quantitative study, may still serve to generate agreement on "best practices." Monitoring, designed to track attainment of management objectives in the field, runs on a continuum between these poles of research and simple observation/trial and error (Elzinga et al. 1998). While monitoring always involves the collection of data, the experimental design may not meet the standard required for research (Elzinga et al. 1998). For example, monitoring may lack replication or controls, therefore requiring assumptions about causation. Such designs include before–after or before–after/control–impact designs that may vary with regard to replication (Smith 2002). As practitioners, our view is that the value of a monitoring effort should be assessed in terms of its ability to (1) provide empirical data that confirm or change a decision (Elzinga et al. 1998; Pokorny et al. 2006), while minimizing confirmation bias (Hammond et al. 1999), or (2) generate agreement on a decision among stakeholders (Balint et al. 2011).

Weed mapping holds a central role as a wildland weed management tool (Barnett et al. 2007; Pokorny et al. 2006). In accordance with North American Invasive Species Management Association (NAISMA) standards, weed mapping typically involves delineating a perimeter of a polygon with a minimum area of 0.04 ha or 0.10 acres. The polygon captures the distribution of the plant species, known as the infested area, and not the gross area, which is the larger area in which the plant species is found that also includes unoccupied habitat (NAISMA 2014). Next, visual canopy cover estimates, often made using a cover class scale such as the Daubenmire scale, estimate the percentage of plant cover within either the infested area or the gross area. Multiplying either of these polygon areas by the canopy cover value provides an estimate of absolute plant cover.

Observers are not, however, limited to a single mapping approach, such as the perimeter-walked approach. As applied to big sagebrush (*Artemisia tridentata* Nutt.) patches, the buffered-point method more efficiently mapped weed infestations with similar accuracy when compared with the perimeter-walked method (Christensen et al. 2011).

Weed mapping is generally regarded as a "survey" or "inventory" technique that stands in contrast to monitoring (Dewey and Andersen 2004; Pokorny et al. 2006). Mapping, while less repeatable and given to greater measurement uncertainty compared with monitoring, provides a landscape-scale view of invasive plant abundance and distribution to inform management strategies (Pokorny et al. 2006). When mapping at a landscape scale, several sources of error may be present. First, observers may miss patches due to the study scale, misidentify plants, or inaccurately estimate cover. In addition to such observer error, the numerical ranges associated with cover categories include a high level of explicit measurement error. Global positioning system (GPS)-collected data introduce additional measurement error related to the shape, size, and horizontal accuracy of a mapped polygon (Christensen et al. 2011).

A sharp distinction between inventory/survey and monitoring becomes blurry, however, when mapping is employed to perform "intensive" inventories/surveys (Pokorny et al. 2006). Such inventories are normally on the order of several hundred acres or fewer and may be detailed enough to serve as baseline data for monitoring. Such an approach was used to successfully map and remap weed infestations within Dinosaur National Monument over a 7- to 8-yr period (Ransom et al. 2012). The results demonstrated high levels of canopy reduction for 11 species following herbicide treatment. Such studies, which employ a census in which all patches are fully enumerated, must consider the pros and cons of such an approach. On the surface, a census has the advantage of being comprehensive and producing a "true" result without sampling error (Sutherland 2006). The counterargument to such putative clarity is that the effort and cost to collect such data may greatly exceed that required for a still useful sample. Furthermore, the issue of plant detectability, though present in all ecological studies, may be greater in mapping studies, thus compromising what appears to be a straightforward count (Sutherland 2006). The reduced scale of intensive mapping surveys is designed, however, to mitigate these potential study flaws.

Case Study. The case study presented here evaluates an intensive survey design to monitor the effectiveness of invasive plant control during typical field projects in wildlands. Such projects, due in part to the sensitivity of the sites, likely involve application of herbicides using multiperson ground crews with backpack sprayers. The mapping approach uses GPS point features to record the relative locations and direct estimates of the infested areas observed in patches nested within well-defined project areas. Field personnel collect infestation point data while applying treatments. For this reason, we intended to design a streamlined approach that would minimize the impact of simultaneous data collection on the efficiency of treatment application. Much like the approach taken at Dinosaur National Monument (Ransom et al. 2012), our method produced an intensive inventory (i.e., a census) of the invasive plants within each project area. Here we assess the ability of point-mapping data to provide a clear picture of treatment effectiveness, while discussing its use and limitations.

Materials and Methods

Study Site. We conducted the study in Arkansas Post National Memorial (APNM) in Gillett, AR (Figure 1). The study area in APNM encompassed 86.7 ha, consisting primarily of bottomland hardwood forest with a long history of intensive use and disturbance. Dominant bottomland tree species included green ash (*Fraxinus pennsylvanica* L.), sweetgum (*Liquidambar styraciflua* L.), water oak (*Quercus nigra* L.), and cherrybark oak (*Q. pagoda* Raf.), while post oak (*Q. stellata* Wagenh.) and loblolly pine (*Pinus taeda* L.) occurred along drier ridges. The nonnative Chinese privet (*Ligustrum sinense* Lour.) and hardy orange [*Poncirus trifoliata* (L.) Raf] comprised much of the midstory.

Species Included in the Study. In this study, we included three woody plant species—*L. sinense*, *P. trifoliata*, and black locust (*Robinia pseudoacacia* L.)—that we treated consistently between 2010 and 2015. Of these species, Chinese privet and black locust have been ranked as invasive plants on a national list (NatureServe 2015), while state lists, such as those for Georgia and Texas, identify hardy orange as invasive (Georgia Exotic Pest Plant Council 2015; Texas Invasives 2015). Unlike Chinese privet and hardy orange, both introduced from Asia, black locust is native to the interior Appalachian and Ozark highlands of the United States, but not to the Mississippi Alluvial Valley where APNM is located (Stone 2009). As a multispecies control project, we also treated Chinese wisteria [*Wisteria sinensis* (Sims) DC.], common periwinkle (*Vinca minor* L.), honey locust (*Gleditsia tricanthos* L.), Mary's stiltgrass [*Microstegium vimineum* (Trin.) A. Camus var. imberbe (Nees) Honda], and Johnsongrass [*Sorghum halepense* (L.) Pers.]. We did not include these species in the analysis due to inconsistent or incomplete treatment during the study period.

Project Areas. We established seven project areas in APNM (Figure 1). These areas, numbered 1 through 7, covered 2.7, 8.4, 12.9, 10.2, 13.7, 11.5, and 27.3 ha, respectively. We designed project areas to encompass an area where complete coverage was possible within a reasonable period of time. We also used readily observable landscape

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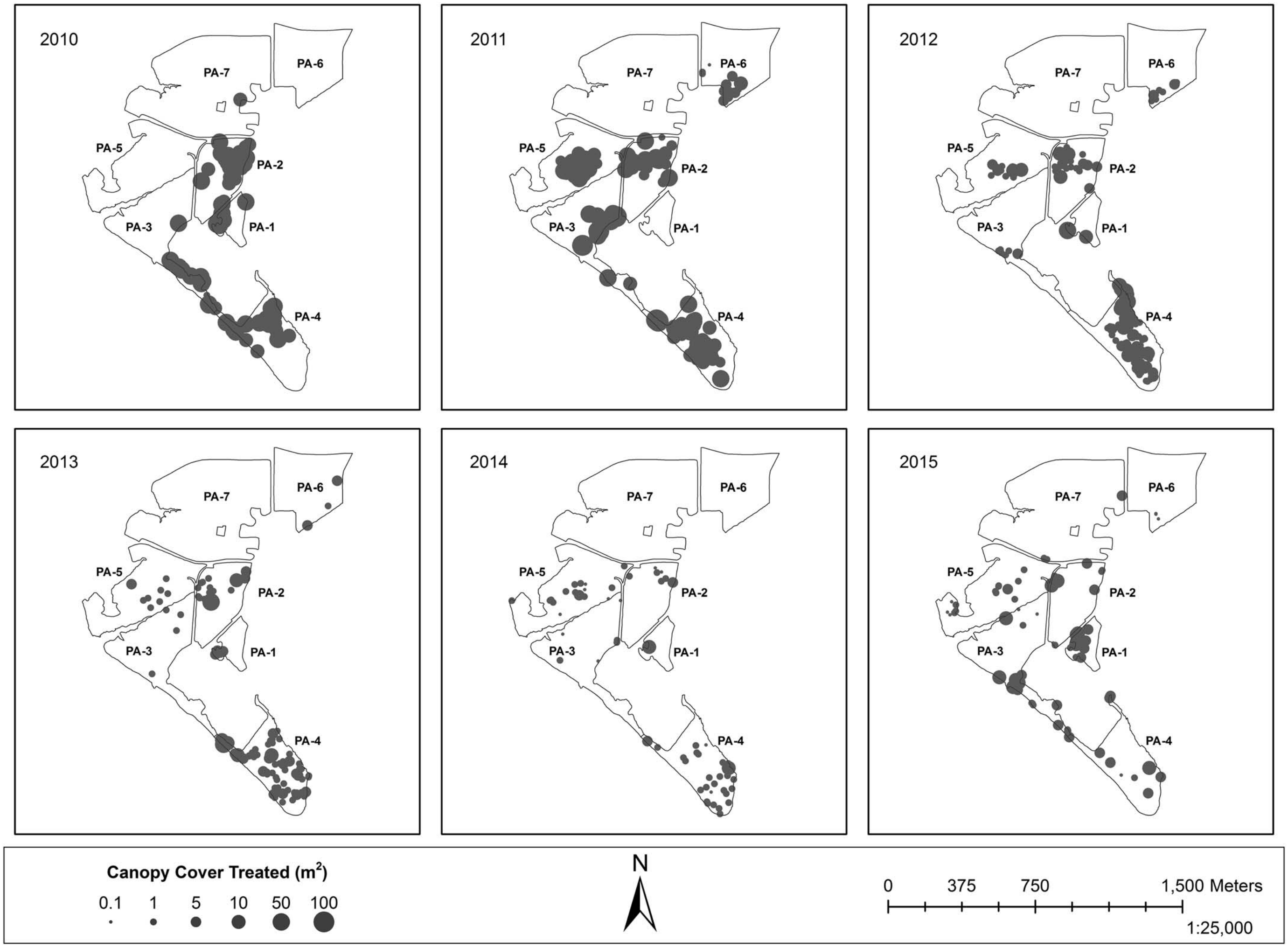

Figure 1. Point-mapping data for Chinese privet in Arkansas Post National Memorial, 2010–2015. Each point represents the infested area of plants that workers treated with herbicides within a given patch as an absolute measure in square meters. Infested area was estimated using the following scale: 0.1, 1, 5, 10, 20, 50, or 100 m^2. PA-1 was not treated in 2011; PA-6 was not treated in 2010 or 2014; and PA-7 was not treated in 2013 or 2014. By 2012, all plants within project areas where treatment occurred, except PA-7, were treated in their entirety. PA, project area.

features such as roads, trails, and transitions between vegetation types to make these areas highly identifiable in the field. Project areas follow the concept of "gross area" defined by NAISMA (2014).

Plant Treatment. Ten different field staff worked on the project. Field crews had full discretion to select the best treatment technique. Workers generally maintained a grid pattern to systematically cover the project area. Depending on plant size, the methods used to control these species ranged from cutting with chainsaws and brush cutters followed by herbicide application (i.e., cut-stump application) during early project stages to hand tools followed by herbicide application or foliar herbicide treatment during later project stages when fewer, smaller stems were present. Workers applied herbicides in all instances in which cutting occurred. The herbicides used during the course of the study are shown in Table 1. Approximate diameter of average "large" stems ranged from 5 cm for *P. trifoliata* to 20 cm for *L. sinense* and *R. pseudoacacia*. When workers were moving through project areas, completeness of treatments was self-assessed and distances between workers or routes were 15 m or less as workers stayed within sight of one another.

Invasive plants were controlled in project areas in each year (2010 to 2015) with the following exceptions: project area 1 was not treated in 2011; project area 6 was not treated in 2010 or 2014; and project area 7 was not treated in 2013 or 2014. Prior to 2012, project areas were only partially

Table 1. List of herbicides used to control woody plant species during the 6-yr study (2010–2015) at Arkansas Post National Memorial.

Name	Foliar/cut-stump treatment (% conc.)	Year applied	Manufacturer	Location	Website
Glyphosate (Round-Up ProMax®)	5%/50%	2011	Monsanto	St. Louis, MO	http://www.monsanto.com/products/pages/roundup-promax.aspx
Imazapyr (Nufarm Polaris®)	1%/10%	2011	Nufarm Americas	Morrisville, NC	http://www.nufarm.com/USIVM/Nufarmpolaris
	1%/10%	2012			
	1%/10%	2013			
Imazapyr (Nufarm Polaris® AC)	0.5%/NA	2014	Nufarm Americas	Morrisville, NC	http://www.nufarm.com/USIVM/NufarmPolarisrAC
Imazapyr (Nufarm Polaris® AC Complete)	0.5%/10%	2015	Nufarm Americas	Morrisville, NC	http://www.nufarm.com/USIVM/NufarmPolarisrACComplete
Triclopyr (Garlon® 4 Ultra)	5%/20%	2010	Dow AgroSciences	Indianapolis, IN	http://www.dowagro.com/en-us/vm/products/garlon-4-ultra
	5%/20%	2011			

treated due to the time required for initial control efforts. By 2012, all project areas, except for project area 7, were canvassed entirely for treatment. The area that included the targeted plants in project area 7, however, was treated consistently in all years in which treatment occurred.

Data Collection. In the course of controlling invasive plants, field workers periodically paused to visually estimate infested areas (per NAISMA 2014) as the areal cover of treated subsets of invasives within project areas and to record the value and relative location of those plants using a single GPS point. Each field worker carried a Trimble Juno SB or 3B GPS unit with CyberTracker software (currently v. 3.389, http://www.cybertracker.org, Cape Town, South Africa) for this purpose. The following scale was used to estimate infested area: 0.1, 1, 5, 10, 20, 50, or 100 m^2. (The 20-m^2 option was only available in 2011, 2012, and 2013 due to efforts to streamline the graphical user interface.) The smallest increment, 0.1 m^2, was highly granular and was used to represent individual or very small groups of plants as needed. This approach varied slightly with other widely used weed-mapping methods (Christensen et al. 2011) in that infested area is estimated directly rather than as a product of a canopy cover (i.e., percent cover) within a larger polygon. For the purposes of this study, canopy cover (per NAISMA 2014) within the infested area is 100%. Prior to field operations, workers trained in the visual estimation of infested area using circular hoops ranging up to 10 m^2 in size.

This approach, like most weed-mapping methods, addressed the difficulty of distinguishing among patches of plants. Delineation is especially difficult when plants are ubiquitous and evenly distributed throughout a site. With this method, field workers simply defined patches as areas treated between data-collection events, leading to model cycle of treat a patch–visually estimate infested area within the patch–collect GPS point to capture data–repeat. This meant that the size of these patches need not be measured, only the infested area within these patches. The use of dyes and signs of cut woody stems enabled workers to only estimate infested area in nonoverlapping patches. Despite significant observer flexibility, patch size and shape was not completely unconstrained. First, the infested area within a single patch was capped and could not exceed 100 m^2. Second, patch size and shape could not exceed that in which an observer was able to visually and mentally track and estimate plant cover.

The flexibility granted to observers in using many small patches or fewer larger patches was intended to allow adaptation to site conditions and project demands. Many factors, including the size, arrangement, and demographic stage of a plant species and the environment itself, affected the ability of each field worker to accurately estimate infested areas in the landscape. Furthermore, workers were allowed to balance the granularity of data collection with their sense of their ability to estimate accurately while maintaining a desired level of productivity. Such differences, inherent to all mapping approaches, are not problematic provided that infested area increments are estimated accurately.

As an additional step to maximize situational flexibility, field workers controlled the order of treatment, infested area estimation, and GPS data collection. In some cases, data collection was prospective, in that workers scoped out an area to be treated, collected a GPS point, and then proceeded with treatments. In other cases, data collection was retrospective, with field workers mentally tracking the canopy cover of plants while treating those plants. Upon reaching a stopping point, field workers then recorded a GPS point. A hybrid of the prospective and retrospective approaches was also possible, in that field workers began tracking infested area as they treated and then at some point looked ahead to add additional area that they would treat. The recorded GPS point integrated the previously treated plants and the soon-to-be-treated plants.

As a result of these methodological decisions, this approach resulted in an unspecified and variable amount of uncertainty in the relationship between points and plant locations. Points were always collected near the patch containing the plants in question, although the exact distance to those plants within the patch was unknown. Additional positional inaccuracy resulted from collecting only one position per point and potentially high position dilution of precision (PDOP). However, in the event that positional error placed a point outside the appropriate project area, we used time stamps and field logs to identify those points and remap them to the corresponding project area. Because the project area served as the unit of statistical analysis in this method, the spatial uncertainty associated with points inside the project area is not highly problematic. This acceptance of spatial uncertainty in favor of speed and flexibility of data collection is the key distinguishing feature of the method presented here.

Analysis. After mapping was completed, each project area contained multiple points representing the infested area of treated invasive plant species. We then summed these cover estimates by species within each project area for each year, resulting in an estimate of the total infestations of Chinese privet, hardy orange, and black locust for each of the seven project areas during the years 2010 to 2015. Graphical inspection of data revealed a lack of normality. A logarithmic transformation [$\log_{10}(x+1)$] was successful for Chinese privet and hardy orange, but not black locust, as the data contained too many zeros. The last-measured and next-measured method of imputation (Johnson and Soma 2012) was used to replace missing values (i.e., taking the average of the previous observed value and subsequent value). When missing values occurred at the beginning of the data record (e.g., 2010), they were replaced with the subsequent value. Using each project area as the experimental unit ($n=7$), a repeated-measures analysis of variance (ANOVA) was performed for both Chinese privet and hardy orange. Mauchly's test was used to evaluate the assumption of sphericity. Because data for black locust could not be transformed to normality, a Friedman test, the nonparametric analogue to repeated-measures ANOVA, was used. All statistics were conducted with SPSS v. 20.0.

Results and Discussion

In this case study, the cumulative infested area of Chinese privet, hardy orange, and black locust treated during the entire span of the project equaled 1.5% of the total study area or 1.26 ha (i.e., all seven project areas). For black locust, abundance varied significantly over time based on the Friedman test ($\chi^2=18.44$, df $=5$, $P<0.002$; Figure 2). In the repeated-measures analyses, Mauchly's test indicated the assumption of sphericity had not been violated for Chinese privet ($\chi^2=22.46$, df$=14$, $P=0.11$; Figure 3). This assumption was violated for hardy orange ($\chi^2=26.22$, df$=14$, $P=0.045$; Figure 4), however, and the Greenhouse-Geisser correction was applied for the analysis of this species. There was a significant effect of time on abundance for both species (Chinese privet: $F(5, 30)=3.63$, $P=0.011$; hardy orange: $F(5, 30)=5.63$, $P=0.024$). There was a significant linear component for both species (Chinese privet: $F(1, 6)=8.77$, $P=0.025$; hardy orange: $F(1, 6)=10.29$, $P=0.018$), but no significant quadratic component ($P>0.05$ for both), indicating a linear decline in both species over time.

The combination of treatments over this time period appears to have effectively reduced the populations of Chinese privet, hardy orange, and black locust plants in APNM. A total of 18 of the 20 project area–species combinations showed invasive plant cover levels that were

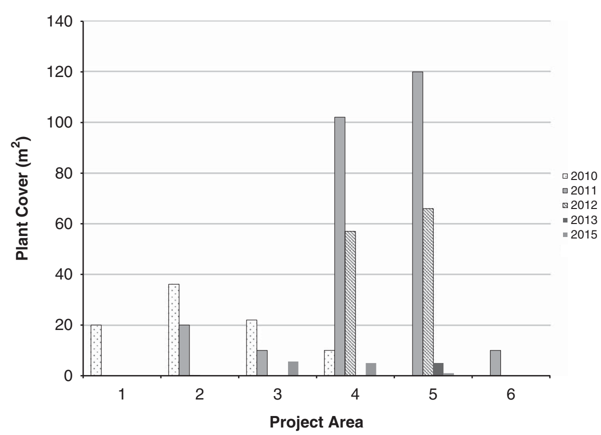

Figure 2. Infested area (in square meters) of black locust in six project areas in Arkansas Post National Memorial from 2010 to 2015. Plants were controlled using herbicide during this time period. PA-1 was not treated in 2011; and PA-6 was not treated in 2010 or 2014. PA, project area.

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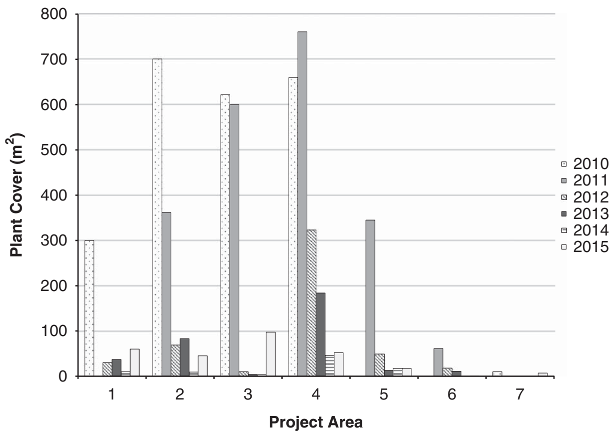

Figure 3. Infested area (in square meters) of Chinese privet in seven project areas in Arkansas Post National Memorial from 2010 to 2015. Plants were controlled using herbicide during this time period. PA-1 was not treated in 2011; PA-6 was not treated in 2010 or 2014; and PA-7 was not treated in 2013 or 2014. PA, project area.

always greater in 2010 to 2012 than in 2013 to 2015 (Figures 2–4). Apparent increases in cover in some project areas–species combinations between 2010 and 2012 were likely due to partial coverage in these areas rather than actual population increases. As of 2015, the reduction in plant cover averaged 82.5%, 82.2%, and 94.9% for Chinese privet, hardy orange, and black locust, respectively, compared with the maximum cover documented for each project areas–species combination (Table 2). This is an encouraging result that supports the utility of this repeated mapping method, which shares considerable similarity with

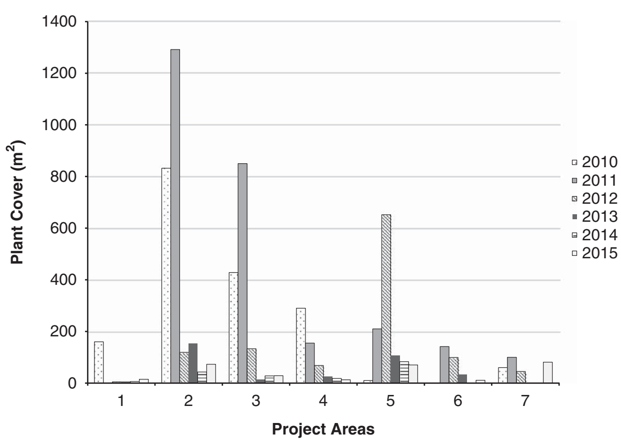

Figure 4. Infested area (in square meters) of hardy orange in seven project areas in Arkansas Post National Memorial from 2010 to 2015. Plants were controlled using herbicide during this time period. PA-1 was not treated in 2011; PA-6 was not treated in 2010 or 2014; and PA-7 was not treated in 2013 or 2014. PA, project area.

Table 2. Reduction in infested area of black locust, Chinese privet, and hardy orange as of 2015 compared with the maximum cover observed during a single year (i.e., the highest level of plant cover treated during any year, 2010–2014) as observed in seven project areas in Arkansas Post National Memorial.

	Reduction (%) in plant infested area		
	Black locust	Chinese privet	Hardy orange
Project Area 1	100	80	91
Project Area 2	100	94	94
Project Area 3	75	84	97
Project Area 4	95	93	96
Project Area 5	99	95	89
Project Area 6	100	100	92
Project Area 7	—	30	19

the approach taken at Dinosaur National Monument (Ransom et al. 2012).

Missed and Misidentified Plant Errors. Even with each observer's best efforts, some proportion of plants were likely overlooked or misidentified. When employing the approach used in this study, observers used a grid pattern to systematically cover the entire area. This approach, used in search and rescue efforts after targeted searches have failed, follows the recommendation to use patterned searches when conducting censuses of rare plants (Tienes et al. 2010). We expect that the incidence of missed plants may be slightly higher with this method compared with a study in which treatment was not taking place simultaneously. The cognitive friction resulting from task switching or multitasking is the suspected cause. While field operators are normally not botanists, many have experience identifying invasive plants in the field. Furthermore, observers are only required to visually recognize a relatively small number of species. For this reason, we expect that identification errors will be far less common than missed plant errors.

Spatial Error. This trade-off favoring efficiency and flexibility over spatial certainty is a limitation of the method, in that the latitude given to workers led to uncertainty between the location of a collected point and the plants represented by that point. This contrasts with the buffered-point method, in which the center of the patch is mapped, or the perimeter-walked method, in which the patch is mapped (Christensen et al. 2011). In this study, an observer might treat a small area of plants and then collect a GPS point directly above those plants. In this case, treatment and data-collection locations were tightly linked (i.e., on-target collection). On the other hand, a worker may have looked ahead to an area that constitutes a given increment, including the 50- or 100-m^2 increments, and then collected

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a point to account for this area before treating (i.e., pretreatment collection). Points were also potentially collected as a backward-looking exercise, in which a worker treated up to a given threshold and then recorded that increment (i.e., posttreatment collection). A combination of these approaches was also possible (i.e., midtreatment collection). Pre-, post-, and midtreatment point collection approaches are especially efficient when encountering high levels of invasive plants that would require too much time to map using smaller, on-target increments or polygons.

Despite the fact that we can only certify the accuracy of mapped points to the project area, but not within the project area, the data are suitable for many uses and accuracy can be improved as needed. For example, although use of the data for spatial modeling may be limited, the data are likely still highly useful for general planning. As a first option for improving spatial accuracy, use of a small measurement increment such as 0.1 or 1 m^2 will ensure that points will be collected in the vicinity of plants. For additional quality assurance, data collection could be modified to require more explicit mapping rules, collection of additional positions per point, and limits on PDOP. A less rigorous quality-control option involves using a GPS offset to map the point to a central position within the treated patch. The obvious trade-off with the improvements is the additional time required to increase the accuracy of these measurements.

Visual Estimation Error. The use of the infested area scale (increments of 0.1, 1, 5, 10, 20, 50, or 100 m^2) also resulted in some level of observer error. In this exercise, observers "filled the basket," which refers to the process of mentally visualizing distributed plants within variously sized plots. With a minimum increment of 0.1 m^2, observers have relatively fine-scale measurement options at their disposal. Even this increment, however, may have overestimated isolated, individual plants to some extent. The scale also provided a range of choices to support accurate measurement of infested area. For example, while choices were available to exactly record 13 m^2 (10 m^2 + 3 × 1 m^2 increments), observers were more likely to round this down to 10 m^2. These rounding errors exist in all vegetation studies and are likely greatly reduced in this study due to the relatively small increment sizes. Inter- and intra-observer error in visual estimates, as in most vegetation studies (Morrison 2016), is undoubtedly present and likely varies based on the data-collection method used (on-target vs. pre-, mid- or posttreatment) and the size of the increment (i.e., 0.1 vs. 100 m^2), as well as the plant, survey timing, structure of the population (e.g., a mix of differently sized individuals of woody plants), and even observer fatigue level. While the latitude granted to workers is responsible for some level of error, a maximum increment of 100 m^2 caps this error. Even this largest increment is only 25% of the minimum mapping unit size (0.1 ac) that NAISMA recommends for weed mapping. By point of contrast, mapping with the buffered-point method requires two estimates: an estimate of patch size assisted and an estimate of percent cover (Christensen et al. 2011). While we have not directly compared the accuracy of the approach in this study to other methods, the design presented here at least offers the possibility of more granular data collection with the potential for similar measurement errors. Comparison of these approaches should be the subject of future studies.

Importance of Fixed Project Areas. The use of fixed project areas is essential for this approach to allow observers to detect changes in infested area between time periods. For treatment data to serve as a census of plant abundance, the technique required that field workers find and treat all plant occurrences in the project area. This approach can be viewed as a form of destructive sampling. Under these conditions, the technique captures presence and absence data, overcoming one of the main criticisms of mapping data (Barnett et al. 2007). Project areas also serve as useful spatial units for tracking metrics such as effort, herbicide application, and other vital project information. The data collection can be augmented with the continuous, background collection of observer locations that allows for an assessment of the thoroughness of treatment in a project area.

Fixed project areas may cause concern for some managers due to perceived inflexibility that these areas generate. First, while annual retreatment that this study required is often needed to locate missed plants, resprouting plants, new establishments, and secondary infestations, this step can add expense if less intensive, targeted canvassing could provide similarly good results. At some point, managers may determine that abundance levels are low enough that additional monitoring is not valuable. Second, managers will also find that working within a single project area and treating that area to completion increases data quality, especially when project areas are contiguous. For example, unique time stamps associated with points allow correction in instances when horizontal GPS error maps a point into an incorrect, neighboring project area. As such, working within project areas will affect work planning and scheduling. Third, managers may wish to increase the size of project areas over time. While such an increase may reset the baseline and temporarily obscure changes in plant cover resulting from treatment, such a change can be undertaken without completely undermining data value.

Efficiency/Advantages Compared with Sampling Approaches. Based on the results of this study, we see several potential advantages of this approach, as it can be designed to customize the operator's time investment to some extent and is relatively quick. When treating a single species, operators are normally only required to push two buttons within the

CyberTracker interface on the GPS unit—an estimate of the infested area and a log button. As a census, this approach can be used for multiple invasive plant species simultaneously and implemented with normal field staff. Developing appropriate sampling designs, on the other hand, often requires expertise of personnel familiar with experimental design and statistical analysis. In the best-case scenario, pilot data guide sampling design decisions—a requirement that further complicates application of sampling approaches to multiple species. As an example, when species are not widespread, sampling data may fail to locate enough occurrences to develop statistically robust inferences. While we do not recommend this approach over monitoring, we are comfortable recommending it over no data collection. Given limited time and resources and the pressing need for effectiveness data, inventory/mapping approaches at the site scale may also provide a rapid and quantifiable method for assessing change in invasive plant abundance.

Insights and Limitations of Weed-focused Effectiveness Monitoring. Our data agree with many other data sets that show that while herbicides are often effective in reducing weed populations, plants may be encountered even after several years of treatment (Figures 2–4). In an economic framework, managers should treat weed infestations until the cost of treatment exceeds the cost of associated impacts. In practice, quantifying impact is difficult (Simberloff et al. 2013), so we suggest treating entire project areas at a frequency that largely prevents reproduction in target weeds or until managers have narrowed down the potential habitat within the project area. Even with these benchmarks in place, periodic monitoring will be a necessary insurance policy to maintain the initial project gains.

The data developed in this study can guide an adaptive management process. While plant community response may require evaluation in many situations, invasive plant abundance provides a minimum "tripwire" (Heath and Heath 2013) that alerts stakeholders of failing practices or generates support for successful population reductions. We recognize, however, that invasive plants can be drivers (Lindenmayer et al. 2015) but also merely passengers or symptoms of environmental change (MacDougall and Turkington 2005). In early detection studies in which the plant may have limited influence on the larger community, invasive plant abundance may be the only metric available to assess a project. In fact, early detection–rapid response (EDRR) projects may be the best investment of limited conservation funds (Rejmánek and Pitcairn 2002). EDRR projects should require limited herbicide use, which may limit nontarget effects on native species (Rinella et al. 2009) or colonization of new invasive plant species (i.e., secondary infestation; Pearson and Ortega 2009). Furthermore, while this method works best with herbicide treatments that require complete canvassing of a project area, this does not preclude evaluating the effects of other simultaneous interventions. For example, as an application of ecologically based invasive plant management, Sheley et al. (2006) used herbicide in conjunction with various site-preparation, seeding, and cover crop combinations applied at a project area scale. Such treatments could also be evaluated using the methods described in this paper.

Admittedly, the data as collected during this project are uncontrolled before–after studies and do not isolate variables that lead to more rapid understanding in the way that hypothesis testing can. For example, untreated areas are not maintained out of concern for additional invasive plant spread. The method is, however, highly scalable and therefore applicable to a wide range of projects. The ability to generate evidence-based effectiveness data for a large number of projects may suggest patterns that lead to hypothesis testing. The relative value of inductive and deductive approaches in advancing restoration is at least debatable (see Cabin 2007; Giardina et al. 2007). We believe that well-documented case studies using the approach described in this paper, much like the reporting of unique individual medical cases, can improve land management practices in wildlands. Another advantage of this approach is the greater realism associated with the types of activities monitored. These studies reflect conditions and contingencies that are inherent in but potentially ignored when scaling up the results of controlled studies to invasive plant control projects in wildlands.

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