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Source: Invasive Plant Science and Management, 5(2):178-193. 2012.
Published By: Weed Science Society of America
DOI: http://dx.doi.org/10.1614/IPSM-D-11-00022.1
URL: http://www.bioone.org/doi/full/10.1614/IPSM-D-11-00022.1

Invasive Plant Science and Management 2012 5:178–193

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Early detection of an invading nonindigenous plant species (NIS) may be critical for efficient and effective management. Adaptive survey sampling methods may provide unbiased sampling for best estimates of distribution of rare and spatially clustered populations of plants in the early stages of invasion. However, there are few examples of these methods being used for nonnative plant surveys in which travelling distances away from an initial or source patch, or away from a road or trail, can be time consuming due to the topography and vegetation. Nor is there guidance as to which of the many adaptive methods would be most appropriate as a basis for invasive plant mapping and subsequent management. Here we used an empirical complete census of four invader species in early to middle stages of invasion in a management area to assess the effectiveness and efficiency of three nonadaptive methods, four adaptive cluster methods, and four adaptive web sampling methods that all originated from transects. The adaptive methods generally sampled more NIS-occupied cells and patches than standard transect approaches. Sampling along roads only was time-efficient and effective, but only for species with restricted distribution along the roads. When populations were more patchy and dispersed over the landscape the adaptive cluster starting at the road generally proved to be the most time-efficient and effective NIS detection method.

Key words: Canada thistle, *Cirsium arvense* (L.) Scop., Dalmatian toadflax, *Linaria dalmatica* (L.) P. Mill., smooth brome, *Bromus inermis* Leyss., common St. Johnswort, *Hypericum perforatu*m L., early detection rapid response, EDRR, nonnative plants, survey, weed mapping, exotic species, inventory, census.

Land managers often have three main objectives associated with NIS management. The first is to maximize patch detection at the earliest stages of invasion to increase the success of management directed at eradication. The second objective is to estimate the area infested by a NIS to aid with management planning. A third objective, not typically identified by managers but important for prioritization of NIS populations for management, is to understand the distribution of the NIS populations on the landscape (Rew et al. 2007) in order to create predictive maps (habitat suitability maps) of the entire area of interest, not just the area sampled (Rew et al. 2005). It is rarely feasible to perform an inventory of an entire management area. Therefore, to achieve the above objectives, some form of sampling is required. We created a study that simulated a range of sampling methods on a real-world fully censused NIS management area, to determine which sampling methods best fulfill the above objectives.

The popular early detection rapid response (EDRR) management approach is dependent on effective detection when metapopulations are scattered small patches (Maxwell et al. 2008; Moody and Mack 1988; Stanaway et al. 2010). The large spatial extent of some managed areas coupled with limited resources and competing priorities usually makes it impossible to conduct a complete ground-based NIS inventory and mapping effort. In these circumstances, information must be obtained through subsampling the area (survey). During initial stages of invasion, NIS can be sparsely distributed as individuals or small clusters of individuals making their detection difficult for human observers and for remote sensed imagery. When the lands under management are extensive, even during

DOI: 10.1614/IPSM-D-11-00022.1

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Management Implications

It is often not possible or cost-effective to conduct a complete inventory of potentially invasive plant species in large management areas, particularly at the early stages of invasion when populations may be infrequent and dispersed on the landscape. Detection at the early stages of invasion may be crucial for effective and cost-effective management. Thus managers must have survey methods that are effective and efficient for estimating the distribution of invading species. To accomplish different survey goals, which may include finding early invading populations, locating many different invasive plant species, finding the most populations of a single species, or collecting information to characterize species distributions, knowing which survey technique to use is critical. We tested three standard and eight adaptive survey methods on a virtual landscape populated with four empirically censused invasive plant species: Canada thistle, Dalmatian toadflax, smooth brome, and common St. Johnswort. The species exhibited somewhat different growth forms, reproductive patterns, and seed dispersal distances and were in different stages of invasion. Random transects with adaptive cluster sampling generally performed best when the survey goal was to find the largest number of populations in the shortest amount of time for species that were well established and occupied areas away from the road. If the species was in the early stages of invasion and only occupied roadside habitat, surveying along roads performed best. When the survey goal was to accurately assess the proportion of the landscape infested by each species, stratified random targeted transects without adaptive sampling performed best for all species. However, managers should be aware that adaptive sampling methods overestimate infested area. This study indicates that adaptive sampling methods can improve nonindigenous species patch detection for management, but regardless of the sampling method, detection remains relative low (maximum of 33% of patches) with typical management constraints and therefore seriously challenges the concept of early detection and rapid response.

later stages of infestation when NIS local abundance has increased, detection can be difficult because the plants are distributed in infrequent patches across the landscape. In these situations, improving patch detection with conventional (roadside or nonadaptive transect) sampling methods requires increasing the sample size, which results in more time to detect patches, i.e., less efficiency (Morrison et al. 2008).

Adaptive sampling, in which the selection of additional sampling units is initiated if a NIS is observed (Thompson 2002), is an alternative to conventional sampling. Adaptive sampling methods are reported to be an improvement in detection and mapping distribution effectiveness and efficiency over conventional methods for sampling rare, spatially clustered populations (Christman 2000; Smith et al. 2004). Adaptive cluster sampling methods include a fixed initial sample set, and for each sample unit within the initial sample set, if the value of the variable of interest satisfies a specified condition, neighboring units are added to the sample set (Thompson 1990, 1991a, 1991b, 2002, 2004; Thompson and Seber 1996; Salehi and Seber 1997; Smith et al. 2004). Spatial adjacency or other criteria can be used to define "neighboring" units. Adaptive web sampling and link-based sampling are flexible classes of adaptive designs for sampling distributions that form spatial networks (Thompson 2006; Vincent 2008). In these methods, additional sampling units can be based on the spatial structure of the population (Thompson 2006).

Researchers have investigated the effectiveness and cost and time efficiency of adaptive cluster sampling designs for rare herbaceous plants (Philippi 2005; Prather 2006; Morrison et al. 2008; Rew et al. 2006) and trees (Acharya et al. 2004). Prather (2006) provided one example of the application of adaptive sampling to surveying NIS, but did not explore the many possible permutations to the adaptive methods. The use of adaptive cluster sampling methods, in general, and adaptive web methods, specifically, for surveying NIS has not to our knowledge been thoroughly tested. We used a comprehensive census of four NIS to compare a range of adaptive sampling methods for detection, distribution estimation, and time efficiency that could be recommended for use by managers.

A complete census of four NIS (Lehnhoff and Lawrence 2010), representing a range of different reproductive and dispersal mechanisms and subsequent different spatial distributions in a real management area, was used as a constant landscape to conduct a comparison of the simulated sampling methods. Thus we set out to provide a sampling recommendation associated with a species' biological characteristics along a continuum represented by the species we selected for this study. NIS presence and absence were recorded along the path of a virtual surveyor. We compared standard methods used to survey NIS (random targeted transect adapted from Rew et al. [2006], and roadside census, which is commonly used by managers), as well as adaptive cluster sampling and adaptive web sampling methods (Thompson 2006).

Materials and Methods

Study Area. The management area considered for our sampling simulations occurred within the Little Bighorn Battlefield National Monument, administered by the U.S. National Park Service. The monument is located in southeastern Montana and its native vegetation consists primarily of northern shortgrass prairie dominated by native perennial grasses in the genera *Agropyron, Poa, Stipa,* and *Bouteloua*, with occasional swales consisting of western snowberry (*Symphoricarpos occidentalis* Hook.), prairie rose (*Rosa arkansana* Porter), chokecherry (*Prunus virginiana* L.) and silver sagebrush (*Artemisia cana* Pursh) shrub species (Bock and Bock 2006). In 2010, a complete NIS inventory (census) was performed within the monument boundary (Lehnhoff and Lawrence 2010), creating a base map for the simulation study. Virtual surveys were conducted within an

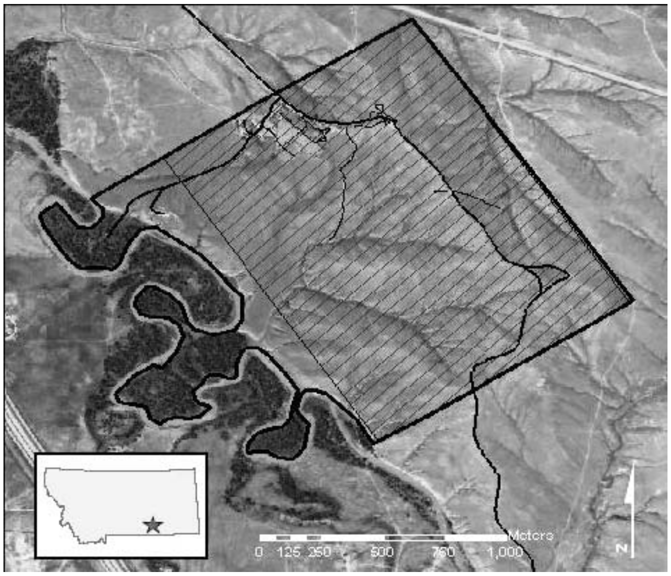

Figure 1. Arial photo of the management area with the 195-ha study area (hatched) at Little Bighorn Battlefield National Monument, Crow Agency, Montana (45° 34′ 12″N, 107° 27′ 0″W).

inventoried (full census) study area of 195 ha (482 ac), not including an adjacent riparian area (Figure 1). There was one main road traversing the study site, as well as smaller roads and interpretative trails. Roads and trails were collectively referred to as rights-of-way (RoWs).

Target NIS Populations. Four of the inventoried (fully censused) NIS in the management area were used in this study: smooth brome (*Bromus inermis* Leyss.), Canada thistle [*Cirsium arvense* (L.) Scop.], common St. Johnswort (*Hypericum perforatum* L.), and Dalmatian toadflax [*Linaria dalmatica* (L.) P. Mill.]. These species were chosen because they represent a range of distributions (initial to later stages of invasion), primary dispersal mechanisms (short or long), and primary reproductive strategies (sexual or vegetative) resulting in different visual patterns of individual plants across the study site. Smooth brome is a rhizomatous grass in a late stage of invasion, Canada thistle is a rhizomatous and wind-dispersed forb in an early to middle stage of invasion, common St. Johnswort is a nonrhizomatous and non–wind-dispersed forb in middle to late stage of invasion, and Dalmatian toadflax is a rhizomatous and non–wind-dispersed forb in an early stage of invasion (Figure 2). Smooth brome was distributed widely in dispersed patches throughout the study site; common St. Johnswort was similarly prevalent in abundance, but existed, on average, in smaller patches in a more clustered pattern; Canada thistle was not as abundant, occurring in large clustered patches; and Dalmatian toadflax, a more recently introduced species, occurred in small, highly clustered patches that were not widely distributed. Common St. Johnswort and Dalmatian toadflax were actively managed in the past, whereas smooth brome and Canada thistle were not.

Simulation Design. Our simulation study consisted of placing transects on the mapped portion of the management area and virtually sampling 15 contiguous 10 by 10–m (32.8 by 32.8–ft) cells along each transect. Sampling simulations were conducted in ArcGIS (ArcGIS 9 Desktop. version 9.3.1, ESRI, Redlands, CA) and Python (version 2.5, Python Software Foundation, http://www.python.org.). All transects started at randomly selected points along the RoW to simulate maximized efficiency at the onset of sampling. In each simulated sampling session the same sample set of transects was recorded and used to ensure any difference between methods could be attributed to the sampling methods themselves and not differences in the placement of transects. One hundred simulations were run for each sampling design. The transect number for each simulation was set at 13 or 26, approximately 1 and 2% of the study area prior to adaptive sampling. Sampling 1% of a management area would be considered the upper limit for most government agencies responsible for large tracts of land (Roy Rankin, National Park Service, personal communication).

Survey Methods

Three nonadaptive and eight adaptive (four adaptive web and four adaptive cluster) methods were simulated. All but one sampling strategy had transects point away from the RoW and because preferential roadside sampling is a common practice among land managers (Sharma and Raghubanshi 2009), we included a design to mimic roadside sampling (RdTr). Road transects included sampling 15 consecutive cells along both sides of the RoW and consequently had twice as many cells as all other methods. Therefore, 15 of the 30 10 by 10–m cells were randomly selected for each road transect to make them consistent in area sampled with other nonadaptive methods. The other two nonadaptive methods included stratified random transects (SRT) where presence and absence of a NIS was recorded in a 10-m-wide, 150-m-long straight transect, again with 10 by 10–m cells. These transects extended away from RoWs on a random compass direction, were constrained to lie entirely within the study area, and ended at least 40 m from any RoW (Figure 3a). The third nonadaptive method, SRT with patch dimension (RTPD), recorded patch size in addition to recording the presence or absence of NIS along the transect, but was otherwise identical to SRT. Rew et al. (2006) found estimating the average patch area and using the estimation in conjunction with number of patches detected provided a more accurate estimate of the percentage of landscape

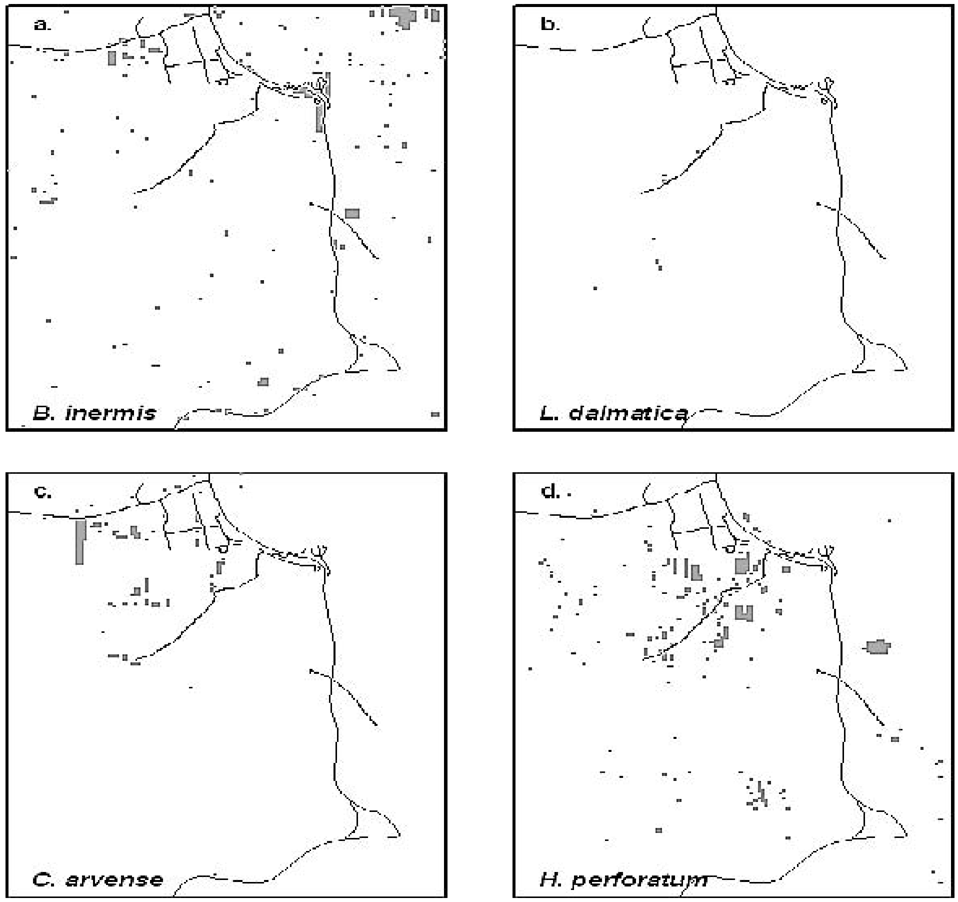

Figure 2. Distribution and number (lower right corner) of patches (grey pixels) and number of 10 by 10–m cells occupied (in parentheses) of (a) smooth brome, (b) Dalmatian toadflax, (c) Canada thistle, and (d) and common St. Johnswort, relative to rights of way (black lines) in the study area.

infested. The three nonadaptive methods were chosen for comparison with adaptive sampling designs because they are commonly used for sampling NIS (Huebner 2007; Rew et al. 2006; Sharma and Raghubanshi 2009).

The adaptive methods built on the SRT and followed a two-stage sequential design, similar to those of Thompson (1991a) and Salehi and Smith (2005), where a secondary sampling set of units was selected once a NIS was found present within a 10-m by 10–m transect cell. Seven of the adaptive designs included a species-specific dispersal distance (20, 30, or 50 m or two, three, or five cells) selection to constrain distance travelled to the next sample away from the original transect. Adding the dispersal distance variable increased the adaptive sampling methods to 25.

All adaptive sampling methods, except the adaptive king (described below), required a dispersal distance that determined a maximum survey distance (MSD) to determine or constrain the location of samples to a logistically reasonable distance beyond the transect. The dispersal distance represented one-half of the maximum primary wind dispersal distance of seed for each species based on terminal velocity and horizontal wind speed of 400 m s^{-1} (Cousens and Mortimer 1995). The MSD was the maximum length, both parallel and perpendicular to a transect, that a surveyor had to walk to include additional sample cells beyond the transect.

Two types of adaptive sampling were tested: adaptive cluster and adaptive web. Adaptive cluster sampling methods capitalize on the clustered spatial pattern of individuals in a population that may be caused by a diversity of abiotic and biotic processes such as dispersal patterns (Cousens and Mortimer 1995) or exogenous processes such as soil moisture gradients. The design requires an inclusion criterion that, when met, triggers the inclusion of additional sampling units. The inclusion criterion we used for all the simulated adaptive sampling designs was the presence of NIS. Limited application of adaptive cluster sampling may be due to the fact that final sample size is not known a priori and can end up being large and thus potentially inefficient (Brown 2003; Smith et al. 2004; Su and Quinn 2003). To prevent excessive sampling, we used MSD to place pragmatic limits on the number of cells sampled (Gattone and Battista 2011). The distances were used to define the survey limit from an occupied NIS cell located within a transect. If the NIS patch boundary fell outside the MSD, the patch was deemed too large and cluster sampling was not performed. If cluster sampling was performed, no cells located outside the MSD were sampled (Figures 3b and 3c). Thus, the maximum search distance (MsD), not to be confused with MSD (maximum survey distance), was reset each time that a NIS was identified in a new cell outside the original transect (Figure 3b). Cluster sampling was not performed along the entire length of a transect; instead, sessions of cluster and transect (returning to the original transect) sampling were performed in an alternating fashion to increase efficiency. Each cluster sampling session was established for a distance equal to the MSD along the original transect.

Eight adaptive sampling designs were simulated: four adaptive cluster methods and four adaptive web methods.

Adaptive Cluster Methods. Stratified random transect with adaptive cluster sampling (RTAC) required a dispersal distance (20, 30, or 50 m) to define the MSD (Figures 3b and 3c). All cells within an original transect were surveyed one at a time, starting with the cell next to a RoW (Figure 3a). If one or more NIS patches were detected within a cell along the transect, cluster sampling began. Cluster sampling was carried out by first delineating the NIS patch perimeter. If the patch was contained within the MsD, a set of concentric "rings" around the outside of the patch were added to the survey as described by Prather (2006) and Rew et al. (2006). The process began with sampling the ring immediately adjacent to the NIS patch and continued with increasing size of concentric circles to the MSD defined by the preselected species-specific dispersal distance. The virtual surveyor sampled the cells contained in the first ring one at a time, starting with the cell directly to the north, and circling in either a clockwise or counter-clockwise direction. The initial direction was randomly chosen and rings in the set were surveyed in alternating directions. If more NIS were detected within a ring cell, the remaining cells in the current ring and any remaining rings were not surveyed, and the ring procedure began anew at the next NIS patch encountered in the ring.

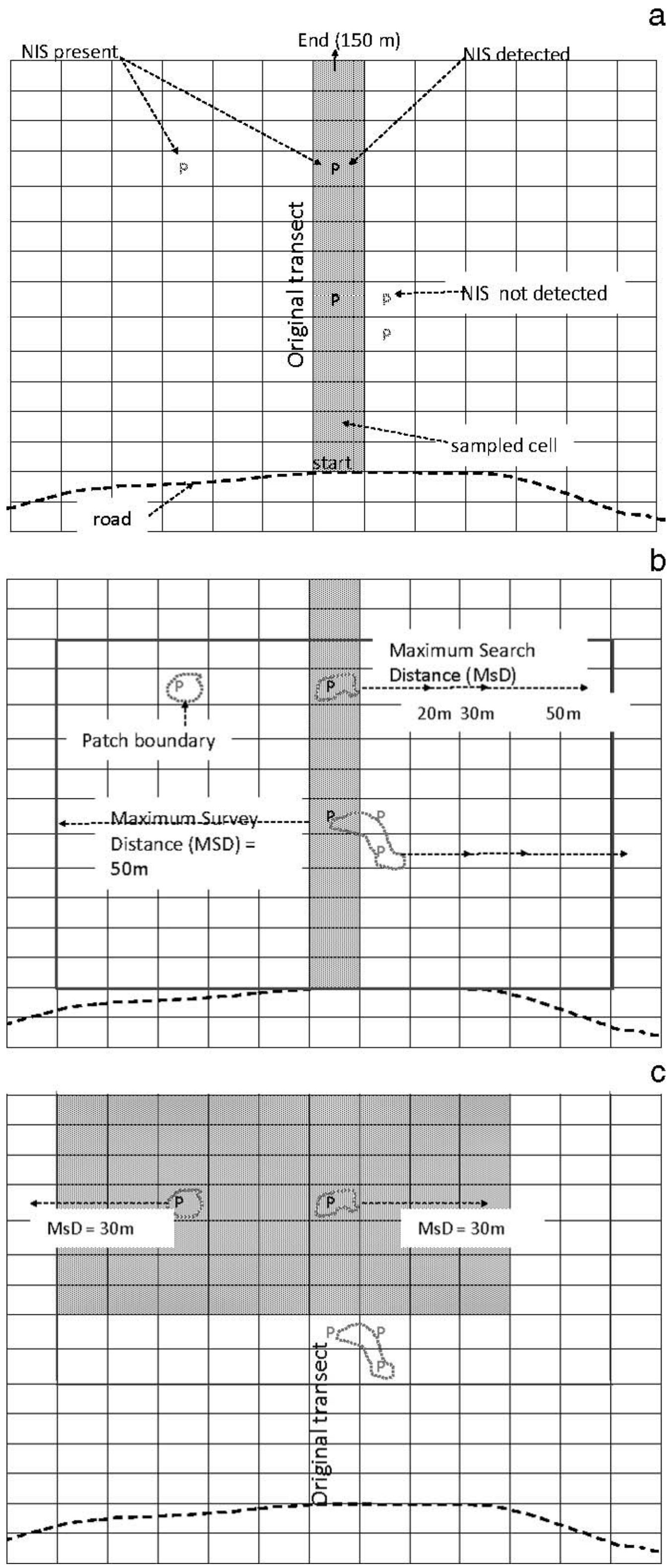

Figure 3. (a) Diagram of portion of simulated stratified random transect method with unsampled cells (10 by 10 m) in white, sampled cells shaded, detected nonindigenous species (NIS) patches (**P**), and nondetected NIS patches (P) along the original transect; (b) NIS patch boundaries (dotted lines) and arrows showing maximum survey distance (MSD) and maximum search distance (MsD) used with random transect with adaptive cluster sampling method (sampling starts at road); (c) stratified random transect with adaptive cluster sampling alternate method where sampling was constrained to not begin along the original transect until a distance equal to the MSD was reached.

The maximum area to be surveyed was determined by the MSD for the first patch detected. Adaptive sampling continued until (1) all rings within the search area were surveyed and no NIS patches were detected, (2) all cells within the maximum search area were surveyed, or (3) the boundary of the MSD was reached. When any of these conditions were met, the surveyor moved back to the original transect cell that triggered the adaptive sampling and continued sampling along the original transect.

Stratified random transect with adaptive cluster sampling alternate (RTACT) was exactly the same as RTAC except that cluster sampling was not initiated along the transect until a NIS patch was reached that was greater than the MSD along the original transect (Figure 3c). This approach was added to avoid oversampling roadside populations.

Adaptive king sampling (AK) proceeded along a transect in the same way as SRT until a NIS was encountered and then would additionally survey neighboring cells (Figure 4a). The neighborhood was defined as the eight adjacent cells surrounding an occupied cell (a king's move in the game of chess). The virtual surveyor sampled the cells in the neighborhood one at a time starting with the cell directly to the north and moving in a clockwise direction. If no additional NIS were detected in any of the neighborhood cells, the surveyor moved back to the original transect and continued sampling along it (Figure 4a). If additional NIS were detected in any of the neighborhood cells, a new "king's move" neighborhood was added to the survey. Only cells not previously surveyed or added to the sample were included in the new neighborhood. The surveyor always finished surveying the cells in the current neighborhood before moving to the next neighborhood regardless of NIS occupation. Neighborhoods were surveyed in the order they were detected and added to the survey, and surveying always took place in a clockwise direction within each neighborhood. Surveying recursively in this manner continued until (1) no neighboring cells contained NIS, (2) the number of neighborhood cells surveyed reached 50, or (3) the MSD was reached.

Adaptive modified king 360 (AK360) was an adaptive sampling approach included as a modified version of the AK design in which, upon observing a NIS presence in the original transect, instead of adding the immediate neighboring cells to the sample, the surveyor randomly selected a cell that was within a circle centered at the currently occupied transect cell and at a radius equal to the MsD (Figure 4b). If one or more NIS individuals were detected in the MsD random cell, additional neighbor cells were added to the survey and sampled as described for the AK design.

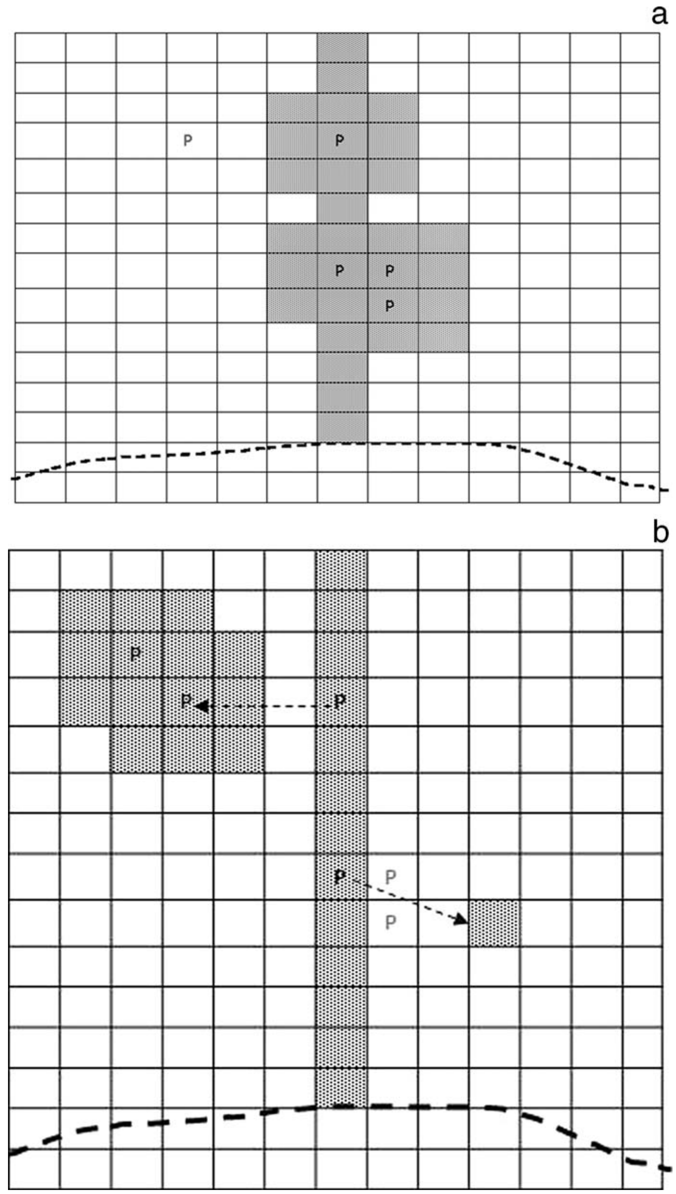

Figure 4. Diagram of portion of simulated sampling using adaptive cluster designs (a) adaptive king and (b) adaptive king 360 (AK360), where white cells represent nonsampled, shaded cells represent sampled, **P** represents detected nonindigenous species (NIS) patches, P represents nondetected NIS patches, and the dashed line indicates a road. In (b) the AK360 design, arrows indicate the cell selected randomly within a circle of radius equal to the maximum search distance (in this case 30 m) and centered on the transect cell where NIS were detected.

Adaptive Web Methods. Adaptive web methods use spatial relationships with other variables as part of the inclusion criterion for adding additional sampling units to a survey around a NIS-occupied cell on the original transect. We used adjacency and limited distance as the spatial relationships. Inclusion in the sample beyond the original transect was determined with a probability test where a random value below a predetermined probability (p) would signal inclusion of an adjacent cell or a random value $> p$ would result in choosing a random cell (hereafter referred to as a restricted- random cell) within a predefined belt superimposed on the original transect. The adaptive web belt extended the species-specific dispersal distance perpendicular to and on both sides of the original transect. If the restricted-random cell was occupied by the target NIS then the process of selecting further samples continued with the same rules, selecting all "king's-move" adjacent cells or more restricted-random cells based on the *p*-test.

Basic adaptive web with random belt selection (BRB) used 0.90 for the probability of adding a neighboring cell to the sample once a NIS was detected in the original transect. The BRB method imposed a maximum limit of 50 cells that could be sampled adaptively following a NIS occurrence (occupied cell) in the original transect (Figure 5a). In this design, all cells within a transect were surveyed one at a time, starting with the cell next to a RoW. If one or more NIS patch was found within a transect cell, a uniform random number (*p*) was chosen for each nonsampled cell in the "king's-move" neighborhood of the transect cell. If the random number was less than *p*, the neighboring cell was added to the sampled cells; otherwise, a random cell was selected and added to the survey from within the belt created at the predetermined MsD on either side and parallel to the transect .

All NIS-occupied cells added to the survey because of their adjacency to NIS-occupied cells were sampled first in order to minimize surveyor walking distance. The virtual surveyor then sampled cells not previously sampled based on the *p* test and the most efficient travel route to the next restricted-random cell. Once a new restricted-random cell was identified, if a NIS presence was recorded the "kings-move" neighborhood for it was sampled just as the neighborhood adjacent to the original transect occupied cell was sampled (described above). Surveying recursively in this manner continued until (1) no more cells were found to be NIS-occupied, (2) the number of neighborhood cells surveyed reached 50, or (3) the boundary of the survey area was reached.

If after all the neighborhood cells were surveyed and the maximum number of cells to survey adaptively had not been reached, the surveyor would select random previously unsampled cells from within the transect belt (sampled cells without arrows to them; Figure 5a). The randomly selected cells added to the sample were arranged and surveyed in an order that minimized walking distance. If NIS were detected while surveying these random cells, the selection process described above was repeated, and as before, the cells selected from the neighborhoods were sampled first, before continuing with the cells selected randomly (e.g., Figure 5a, upper left randomly selected occupied cell with no arrow to it). Surveying adaptively in this manner continued until (1) all cells added adaptively were surveyed, (2) the number of cells surveyed adaptively reached 50, or (3) the boundary of the survey area was reached. When any of these conditions were met, the

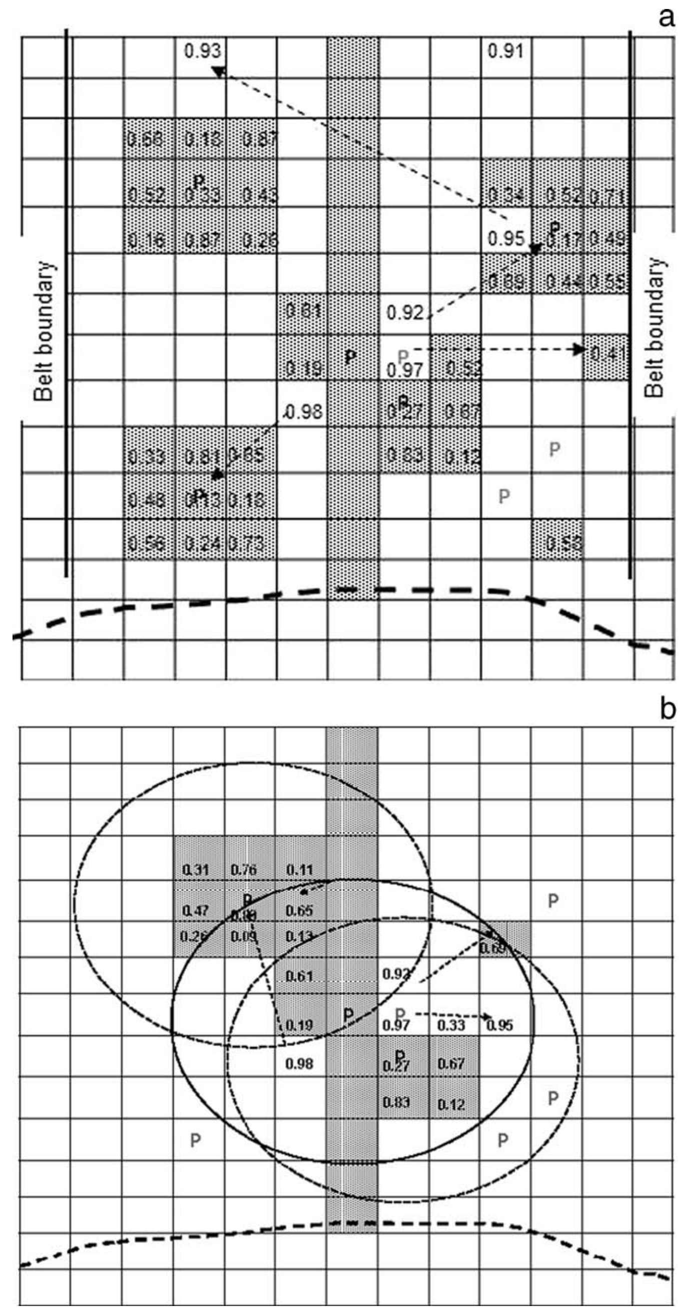

Figure 5. Diagram of portion of simulated sampling associated with the first patch detected then triggering further adaptive web sampling designs: (a) basic adaptive web with random belt selection and (b) basic adaptive web with circle selection (B360) where white cells represent nonsampled, shaded cells represent sampled, **P** represents detected nonindigenous species (NIS) patches, P represents non-detected NIS patches, bold lines parallel to original transect at maximum survey distance represent the belt boundary (in this case equal to 50 m), and the dashed line indicates a road (RoW). Values (*p*) in selected cells were used to decide if cell would be included in sample survey ($p \leq 0.90$ included) otherwise arrow indicates next random cell within belt or maximum search distance (MsD) (for B360) to be tested for inclusion in sample. Cells sampled away from original transect not adjacent to occupied cells and without an arrow were randomly selected within the belt or MsD.

Table 1. Mean proportion (pD) of patches detected by each method for each species using 13 or 26 transects and a dispersal distance of 50 m.

	13 Transects				26 Transects			
Method[a]	Canada thistle	Common St. Johnswort	Smooth brome	Dalmatian toadflax	Canada thistle	Common St. Johnswort	Smooth brome	Dalmatian toadflax
RdTr	0.0309	0.0130	0.0528	0.0161	0.0630	0.0281	0.1040	0.0330
SRT	0.0409	0.0173	0.0323	0.0004	0.0743	0.0412	0.0606	0.0004
RTPD	0.0470	0.0204	0.0339	0.0004	0.0848	0.0486	0.0636	0.004
RTAC	0.0870	0.0578	0.0776	0.0004	0.1661	0.1164	0.1307	0.0007
RTACT	0.0778	0.0453	0.0491	0.0004	0.1491	0.0901	0.0946	0.0004
AK	0.0470	0.0204	0.0339	0.0004	0.0848	0.0486	0.0636	0.0004
AK360	0.0439	0.0191	0.0341	0.0004	0.0822	0.0458	0.0653	0.0004
BRB	0.0474	0.0212	0.0360	0.0004	0.0870	0.0507	0.0651	0.0004
B360	0.0500	0.0215	0.0363	0.0004	0.0874	0.0519	0.0667	0.0004
LHV360	0.0613	0.0316	0.0501	0.0004	0.1117	0.0704	0.0877	0.0004
LHVRB	0.0548	0.0332	0.0511	0.0004	0.1087	0.0701	0.0859	0.0004

[a] Abbreviations: RdTr, roadside sampling; SRT, stratified random transects; RTPD, SRT with patch dimension; RTAC, random transect with adaptive cluster; RTACT, stratified random transect with adaptive cluster sampling alternate; AK, adaptive king; AK360, adaptive king 360; BRB, basic adaptive web with random belt selection; B360, basic adaptive web with circle selection; LHV360, local habitat variability adaptive web with circle selection; LHVRB, local habitat variability adaptive web with random belt selection.

virtual surveyor moved back to the transect cell that triggered the adaptive sampling and continued along the original transect.

Basic adaptive web with circle selection (B360) was implemented in the same way as BRB, with one difference. During the selection process, when a random cell needed to be selected and added to the sample, the selection was not made from the cells located in a fixed belt surrounding the transect; instead, it was made from the cells located within a circle centered at the current occupied cell being surveyed. The radius of the circle was set at the predetermined MsD (Figure 5b).

Local habitat variability adaptive web with random belt selection (LHVRB) was an adaptive web sampling design that incorporated a measure of local environmental heterogeneity into the selection process for determining additional cells to sample. The assumption was that the more homogeneous the habitat was in the neighborhood where an initial NIS was found, the greater the chance that an additional NIS would be detected in that neighborhood. We assigned a local habitat value (LHV) to each cell in the survey area based on aspect derived from the digital elevation map under the assumption that terrain aspect was a major explanatory variable determining the distribution of the selected species. For example, if the aspect was the same in the nine-cell neighborhood centered on the occupied cell, the LHV would be 1; if there were two aspects in the neighborhood, the LHV would be 2; and if all of the cells had different aspects, the LHV would be 9. We chose to base the LHV on terrain aspect because it exhibited the greatest variability across the management area and is often an explanatory value related to NIS occurrence. LHV could logically be substituted with probability of occurrence or habitat suitability values derived from multiple variables known to drive distribution of NIS (Rew et al. 2006).

Instead of using a fixed value for p for this method, the probability of adding a neighboring cell to the sample once a NIS was found varied as a function of LHV: $p = 1.0 - (\text{LHV}/9.0) + 0.1$. All other design factors and rules were exactly the same as for BRB, described above.

Local habitat variability adaptive web with circle selection (LHV360) was implemented in the same manner as the B360 design, except varied as a function of LHV, as described under LHVRB.

Sampling Methods Performance Assessment. Method performance was based on how effectively a method detected NIS patches for a given species (objective 1), how accurately each method estimated the total area infested by each species (objective 2), and the time efficiency of the different methods (objective 3). The assessment methods were chosen because they tend to be most directly relevant to current management considerations. The sampling methods presented in this paper were not assessed for their adequacy to estimate spatial distribution of NIS species or for use in accurate occupancy maps. Each method's potential to maximize detection of patches was assessed by calculating the proportion of patches detected (pD) for each species (patches intersected/total patches in the management area for a given species). The management

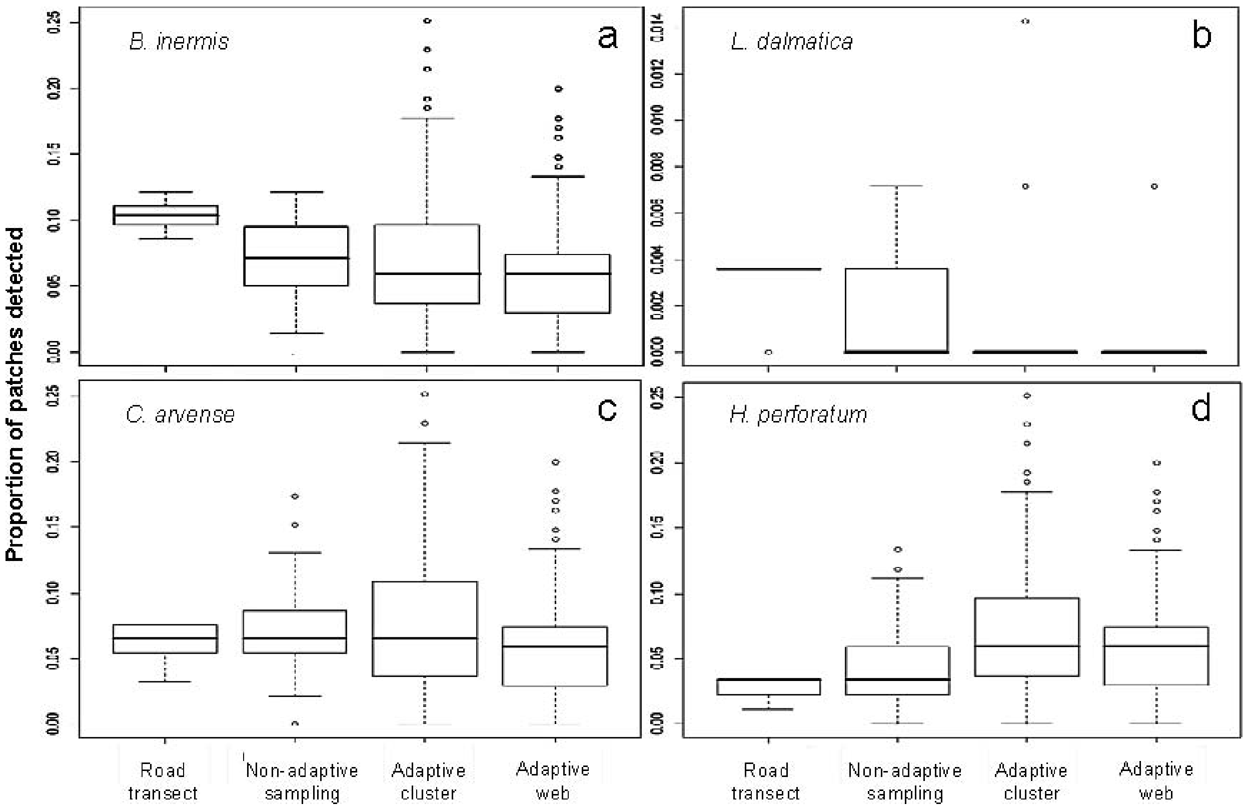

Figure 6. Simulation results comparing patches detected among general categories of methods using 26 transects and a dispersal distance of 50 m replicated 100 times for (a) smooth brome, (b) Dalmatian toadflax, (c) Canada thistle, and (d) and common St. Johnswort. The bold line in the box was the median, the box was 50% of data, whisker included 95% of data, and open circles were outliers for each simulated sampling approach.

implication is directly tied to EDRR, so once any part of a patch is detected the manager can eradicate the entire patch. The closer pD was to 1.0 the more likely EDRR could be successful.

The proportion of occupied cells detected in the sample relative to the proportion of occupied cells on the whole landscape (management area) (pCD/pCO) was used to determine accuracy of estimating the proportion of area infested (occupied cells visited/total cells visited divided by the number of total cells occupied/the total cells in the management area for a given species). A ratio of 1.0 indicates a completely accurate estimate of the proportional area infested by a NIS. Values below 1.0 indicate an underestimate of area infested and values above 1.0 indicate overestimates. One would expect adaptive sampling methods, by their very nature, to produce overestimates of proportional area infested. Managers are often required to present estimates of NIS area infested in their management area for budgeting and other planning activities, so we provide these results to illustrate the degree of bias when using these methods for estimating the proportion of area infested. The time required to perform each method was used to compare time efficiency because some methods may be effective at detecting patches, but require covering far more ground and thus take longer to achieve. The time required to conduct a survey was calculated postsimulation using the virtual surveyor's travel logs and assuming a travel speed of 1 km h^{-1} (0.6 mi h^{-1}) while surveying and 3 km h^{-1} walking between transects and sample cells. Method efficiency was assessed by determining the proportion of patches detected/hours spent sampling (pD h^{-1}) for each species and the proportion of occupied cells detected per hour (pC h^{-1}) for each species.

Sampling methods were compared qualitatively using box and whisker plots. Since the goal of the research was to provide an assessment of the relative advantages of the different methods for the stated objectives, the box plots provided best unbiased comparisons. Multiple means comparisons based on ANOVA were not used due to violation of assumptions. Nonparametric procedures were rejected because they require choosing a control method to compare with and there was no method to logically use as a control. All of the analyses were conducted in R (version 2.11.1, R Development Core Team. Vienna, Austria).

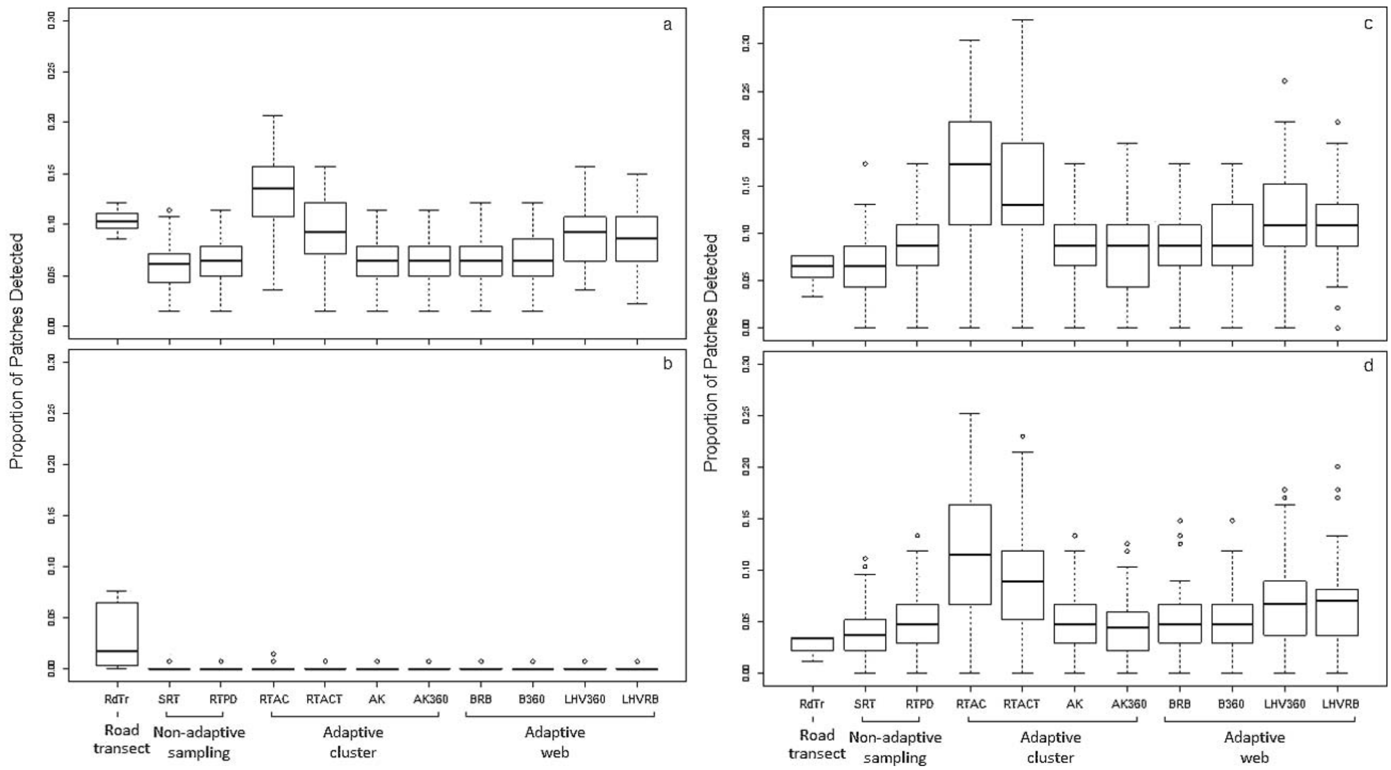

Figure 7. The proportion of (a) smooth brome, (b) Dalmatian toadflax, (c) Canada thistle, and (d) common St. Johnswort patches detected for each method, where the bold line in the box was the median, the box was 50% of data, whisker included 95% of data, and open circles were outliers. These were simulation results for the 26 transects and the 50-m dispersal distance case.

Results and Discussion

The NIS distributions used in our simulations were consistent with previously observed sites and studies where an association between NIS and anthropogenic disturbance such as RoWs was apparent (Gelbard and Belnap 2003; Parendes and Jones 2000; Pauchard and Alaback 2004; Sharma and Raghubanshi 2009; Spellerberg 1998; Watkins et al. 2003;).

Effectiveness of Patch Detection. The first objective was to determine the effectiveness and efficiency of the sampling methods to maximize patch detection for maximizing the success of EDRR. The maximum number of patches detected with any of the sampling methods was 34 for smooth brome and common St. Johnswort, 15 for Canada thistle, and 2 for Dalmatian toadflax. This represented 24, 25, 33, and 29% of the total patches for these species, respectively (calculated from values in Figure 2). Most NIS are likely to be introduced to an area along roads and many species show some degree of aggregation. Therefore, the methods described here should optimize NIS population detection. However, it would take considerably more sampling effort, regardless of the method, to detect all patches and effectively implement EDRR for these species in this typical management area. So if the detection probability is high, intensive monitoring for new patches along roads may allow EDRR to succeed with the caveat that the expense of detection is likely to increase linearly as a function of declining occurrence.

The mean proportion of patches detected increased, approximately doubling, with a doubling of the number of transects (13 to 26) in the study area for all species except Dalmatian toadflax (Table 1). The best methods were only detecting a mean of about 9, 6, 8, and 2% of the Canada thistle, common St. Johnswort, smooth brome, and Dalmatian toadflax patches, respectively. Increasing the assigned dispersal distance from 20 to 50 m expanded the search area and increased the proportion of patches detected for some methods (data not shown). Additional comparisons of methods were limited to the results from the simulations with 26 transects and a dispersal distance of 50 m because patterns in method performance were consistent regardless of transect number and dispersal distance. Differences among methods were amplified and in some cases made significantly different ($P < 0.05$ in multiple means comparisons) by using more transects (26) and larger search area (50 m). Dalmatian toadflax was highly clustered and there were only seven patches in total and these were restricted to a small portion of the study area (Figure 2). Therefore, only general statements about method performance were included for Dalmatian toadflax.

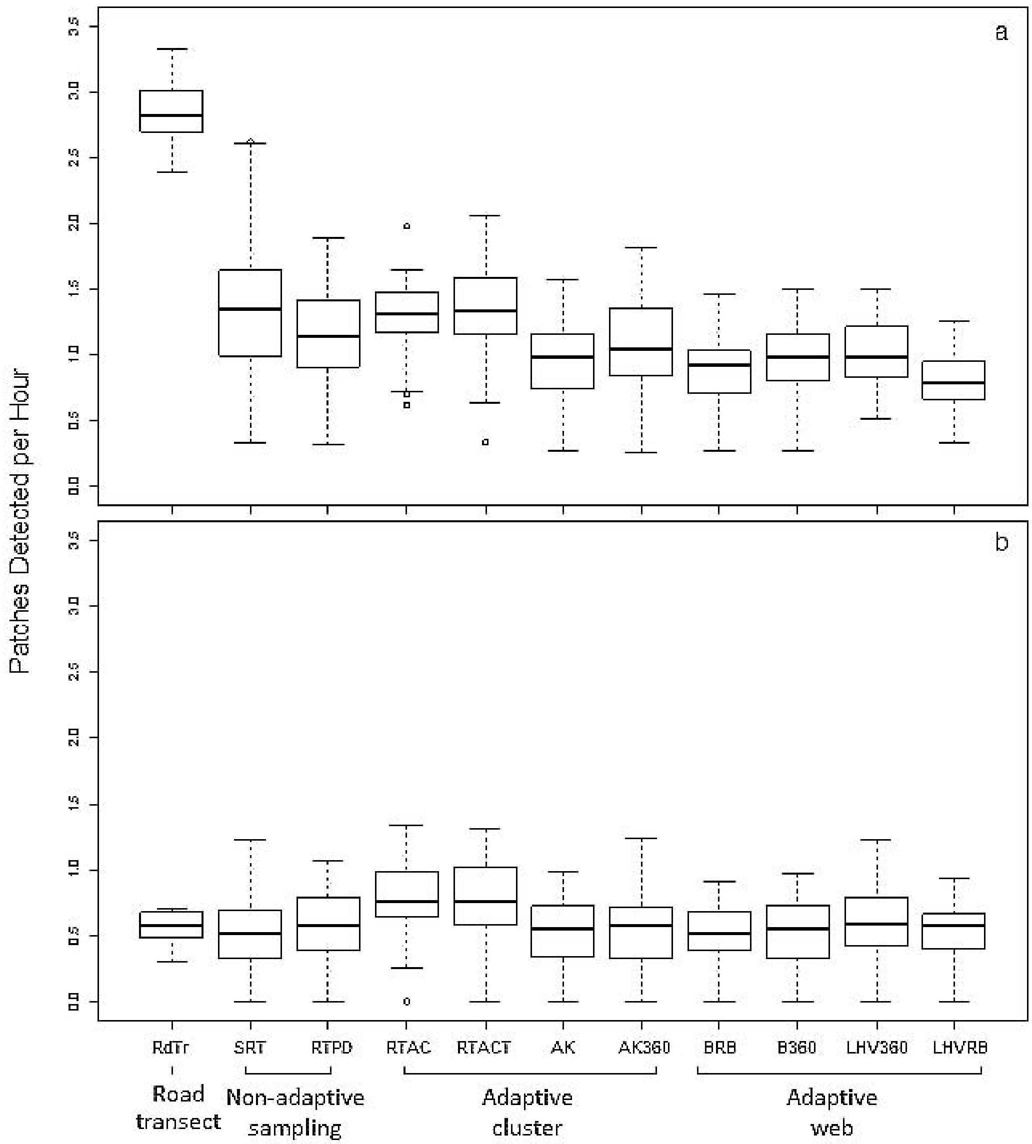

Figure 8. The number of (a) smooth brome and (b) Canada thistle patches detected per hour of sampling for each method, where the bold line in the box was the median, the box was 50% of data, whisker included 95% of data, and open circles were outliers. These were simulation results for the 26 transects and the 50-m dispersal distance case.

Comparison of the general categories of sampling methods for proportion of patches detected indicated that sampling along roads may be the best sampling method for the very patchy and aggregated metapopulation species (e.g., smooth brome and Dalmatian toadflax; Figure 6a and 6b, respectively). These species were aggregated near the roads probably because they were likely introduced along the road, were relatively new to the area, or both. This characteristic distribution should aid in the success of EDRR as it is currently implemented. However, the proportion of patches detected was so low that none of the methods could be judged as performing adequately to accomplish effective EDRR management. This is important as the basic transects sampled 1% (13) or 2% (26) of total area—more than many land managers can achieve under current budgets. For Canada thistle and common St. Johnswort, which were less associated with RoWs, there was no apparent benefit for patch detection of the adaptive sampling methods when they were grouped (Figures 6c and 6d, respectively).

Specific methods were compared for their potential to detect a high proportion of patches of each species. The adaptive cluster method (RTAC) outperformed all methods for all species (Figures 7a, 7c, and 7d) except for Dalmatian toadflax (Figure 7b) where RdTr sampling a distance equal to the transects detected more than a single patch. The RTACT method was consistently the second best method for detecting patches for all species except Dalmatian toadflax. RTACT differed from RTAC by delaying the

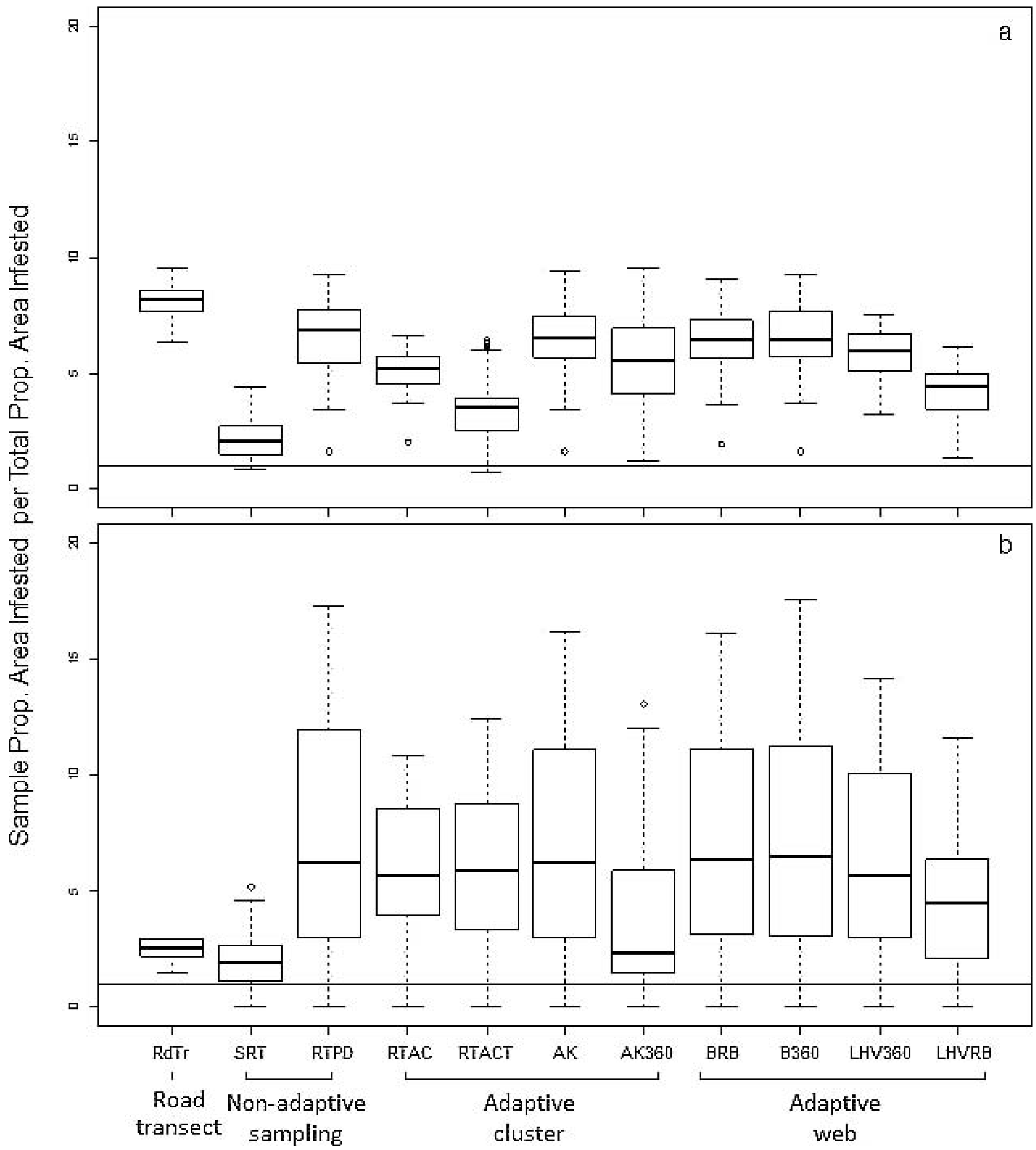

Figure 9. The sample estimated (a) smooth brome and (b) Canada thistle area infested per total area infested in the management area for each method, where the bold line in the box was the median, the box was 50% of data, whisker included 95% of data, and open circles are outliers. The line at 1.0 on y-axis was where the estimate from sample was equivalent to the actual area infested. These were simulation results for the 26 transects and the 50-m dispersal distance case.

onset of adaptive sampling until the MsD was traversed away from the road before invoking cluster sampling. The adaptive web sampling methods that utilized previous habitat knowledge about the species and sampled 360° around a NIS occurrence (LHV360 and LHVRB) consistently showed promise for patch detection (Figures 7a, 7c, and 7d). With greater information on habitat requirements as well as a greater variation in habitat quality across the management area, the adaptive web approaches may become superior to the adaptive cluster approaches.

Time Efficiency for Patch Detection. Specific sampling methods were compared for their time efficiency for detecting patches using the number of patches detected per hour of sampling. Smooth brome, because of its distribution near the roads, was most efficiently sampled along the roads (Figure 8a). Canada thistle (Figure 8b) and common St. Johnswort (not shown because it was similar to Canada thistle) were very similar among methods with RTAC (an adaptive cluster method) again outperforming the other methods for these highly dispersed species in a later stage of invasion.

Sampling for Infested Area Estimates. Managers may be interested in using the designs we explored for estimating the total area infested by NIS. Adaptive methods, ideal for

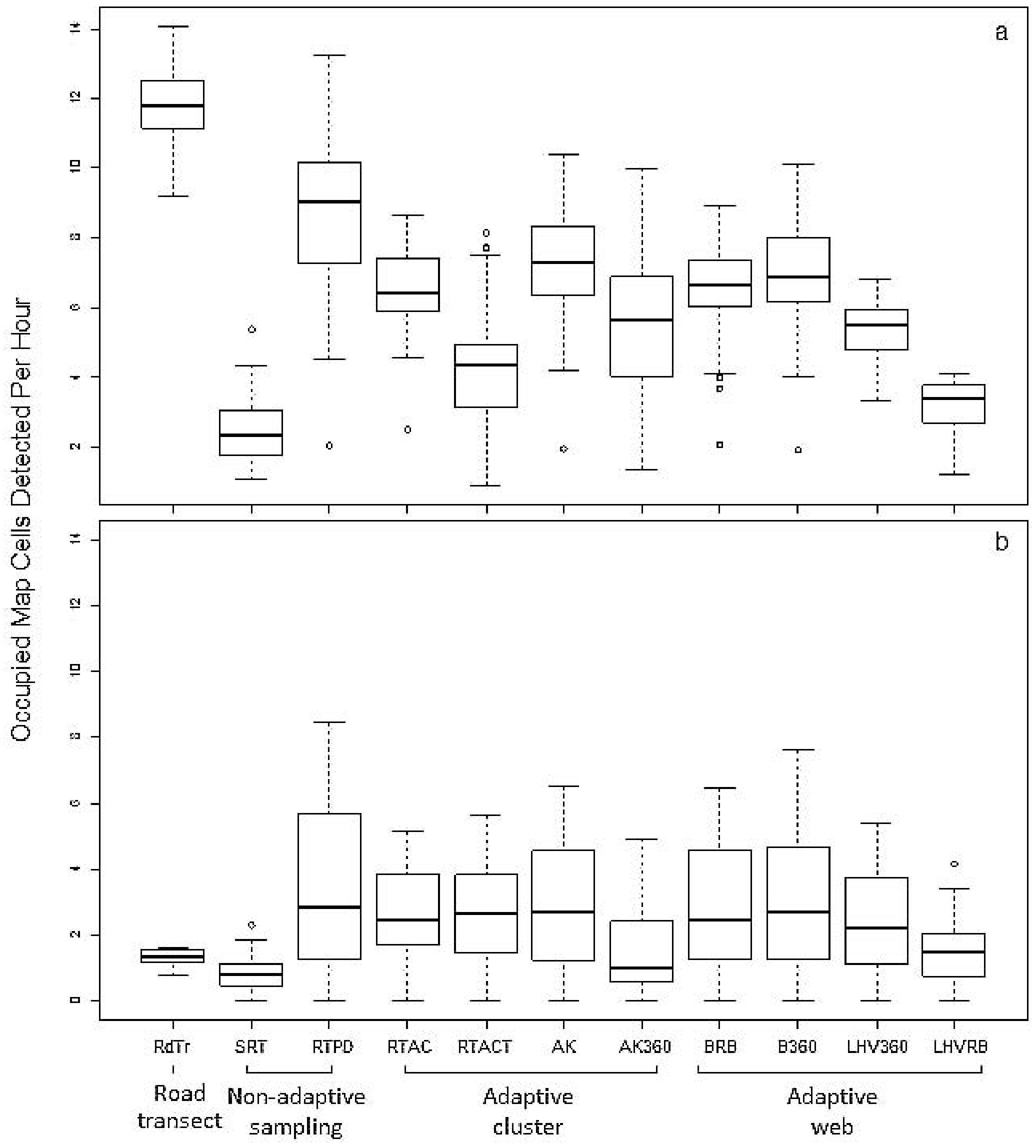

Figure 10. The number of (a) smooth brome– and (b) Canada thistle–occupied map cells detected per hour of sampling for each method, where the bold line in the box was the median, the box was 50% of data, whisker included 95% of data, and open circles were outliers. These were simulation results for the 26 transects and the 50-m dispersal distance case.

maximizing patch detection or occupied cell detection, preferentially sample adjacent cells, which are more likely to also have a NIS present. If the sampling design was a simple random sample of cells throughout the study region, an unbiased estimate for the proportion of total area infected is simply the number of cells infested divided by the total number of cells surveyed. We know a priori using this estimate as a summary measure for our designs should produce overestimates of the total area infested; however, we do so to demonstrate the bias if these methods are used for the objective of making infested area estimates.

Specific methods were compared qualitatively with box plots to determine how much each deviated from 1.0 for the ratio of the estimated proportion of area infested from the sample to the known proportion of area infested. All sampling methods consistently overestimated area infested for smooth brome (Figure 9a). Again, this result was due to the aggregation of smooth brome around roads and all of the methods used roads as a starting point. The nonadaptive sampling approach of SRTs perpendicular to the road produced fewer overestimates of area infested for Canada thistle (Figure 9b), although on average the method was still a slight overestimate. The overestimation of area infested is likely because the transects were short and did not maximize distance from all RoWs, unlike SRT in Rew et al. (2006). Results for common St. Johnswort (data not shown) were almost identical to those for Canada thistle.

Table 2. Matrix to help identify best sampling methods for nonindigenous species patch detection and infested area estimates based on species typology. Shading indicates strength of factor (i.e., darker is stronger).

Species type		Canada thistle	Common St. Johnswort	Smooth brome	Dalmatian toadflax
Reproductive mechanism	Sexual				
	Vegetative				
Dispersal potential	Long				
	Short				
~Time since introduction	≤ 5 yr				
	> 5 ≤ 10 yr				
	> 10 yr				
Patch detection: first (second) best methods		RTAC[a] (RTACT)	RTAC (RTACT)	RTAC (RTACT)	RdTr (many)
Infested area estimate: first (second) best methods		RdTr, SRT (AK360)	RdTr, SRT (4 adaptive)	SRT (RTACT)	RdTr
Time efficiency: first (second) best methods		RTAC, RTACT (NA)	RTAC (RTACT)	RdTr (=SRT, RTAC/RTACT)	RdTr (many)

[a] Abbreviations: RdTr, road transect or roadside sampling; SRT, stratified random transects; RTAC, random transect with adaptive cluster; RTACT, stratified random transect with adaptive cluster sampling alternate; AK360, adaptive king 360.

As expected, the adaptive sampling approaches generally overestimated the total area infested for all species. We used a naïve estimator for the proportion of area infested, but our goal was to demonstrate, for a manager, the potential overestimation of total area infested if these adaptive methods are used with a simple random sample estimator.

Time Efficiency for Area Estimates. Specific sampling methods were compared for their time efficiency for detecting NIS-occupied cells on the map, as opposed to patches, using the number of cells detected per hour of sampling. This was a measure of efficiency of discovering all of the areas occupied by NIS leading to an estimate of area infested and to a more complete understanding of the diversity of habitats occupied by the species. We were seeking the method that most efficiently identified occupied cells in the widest range of habitats so that populations could be identified for monitoring. Habitat associations can be used to prioritize NIS populations for management, since populations can be expected to show variation in invasive potential across a range of habitats (Lehnhoff et al. 2008; Maxwell et al. 2009; Rew et al. 2007). Although there was not a high degree of variation in vegetative communities (habitat) across the selected management area, several of the adaptive web methods incorporated a cell inclusion criterion based on habitat (in this case, aspect variability). Therefore, we could determine if these particular methods had a better ability to detect occupied cells compared to those methods that did not incorporate the habitat factor. Smooth brome was most efficiently sampled along the roads because of its distribution concentrated near the roads (Figure 10a). For Canada thistle (Figure 10b) and common St. Johnswort (not shown as it was similar to Canada thistle) the adaptive web methods incorporating the habitat inclusion criterion performed well, but not as well as the nonadaptive method (RTPD), which efficiently documents occupied cells by following patch outlines.

Study Site Implications. We used a real-world study area where a full census of all NIS was available on which to conduct our simulated sampling. There are very few sites with a full NIS census so the potential to find replicates with the same or even similar species to achieve the best study conditions was not possible. Alternatively, we could have created distributions of NIS, but any model we may use to distribute the populations would inherently bias toward sampling methods that may respond to drivers used in the model. Therefore, although a single site was not ideal, we are satisfied that it represented a typical NIS-infested management area with no known biasing variable influencing the distribution of the chosen species.

The species used for our survey sampling methods comparison represent a typology range for herbaceous NIS that have historically invaded and spread in the western United States. These species vary in their reproductive mechanisms (i.e., an emphasis on sexual or asexual reproduction), dispersal mechanisms (i.e., long-distance wind-dispersed to short-distance rhizome/lateral-root dependent), and probable time since introduction. There were no records available to allow us to determine the precise time of introduction, but the different distributions coupled with knowledge of dispersal potential and distribution patterns for these species observed in other areas where time since introduction was known allowed us to rank species for each of the characteristics. In addition, we used the typology to associate best sampling methods for patch detection and estimates of area infested (Table 2).

In summary, adaptive cluster survey and sampling design that began sampling nearest the road (RTAC) performed best for detecting NIS patches for species that efficiently disperse or have had time to disperse and establish throughout the management area. Sampling along the road (RdTr method) was effective for both patch detection and estimates of area infested for species that were more recently introduced or those that are patchy and have low dispersal potential and thus remain near the roads. This study provides further evidence that roads represent corridors for introduction of NIS and any management that can be imposed to prevent dispersal along these corridors may be the best way to prevent invasions of NIS. This study also demonstrates that typical budget constraints that limit sampling to less than 2% of a management area, regardless of the sampling methodology, are unlikely to provide high enough detection to make EDRR successful. The adaptive cluster and web sampling methods can improve detection and time efficiency for species that are not restricted to RoWs. Adaptive cluster and web sampling methods provide inflated estimates of NIS-infested areas.

Acknowledgments

Funding was from the U.S. Army Corps of Engineers – Engineering Research and Development Center, Construction Engineering Research Laboratory grant W9132T-09-2-0012. Thanks to Little Bighorn Battlefield National Monument for supply of research site and plant distribution data.

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Received March 28, 2011, and approved January 5, 2012.