

Research

Trained Dogs Outperform Human Surveyors in the Detection of Rare Spotted Knapweed (*Centaurea stoebe*)

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Invasive plants have devastating effects on ecosystems and biodiversity that early intervention can prevent. Eradication or containment of new invasions is difficult to achieve because of constraints posed by the low density and detectability of individuals. Domestic dogs trained to cue on distinctive scents might provide an effective method to detect spotted knapweed. The objective of this study was to compare the accuracy and detection distances of dogs to humans in locating new spotted knapweed (*Centaurea stoebe*) invasions. Three dogs, trained to detect knapweed using scent discrimination and tracking techniques, were compared with human surveyors. Seven sampling units (0.5 ha [1.2 ac]) were delineated in a grazed dryland pasture. Dogs, with their handlers, and human surveyors performed line-transect surveys in fall 2005 and spring, summer, and fall 2006. Dog accuracy for large-size knapweed targets (infestations 0.52 m³ [18.4 ft³]) was similar to human accuracy and better than humans (94 vs. 78%) for medium-size targets (infestations 0.13m³). Dog accuracy (67%) was greater (> 81% probability) than humans (34%) for small targets (plants; 0.02 m³). Overall dog accuracy (81%) and *F*-measure scores (86%) were better than human scores, 59% and 74%, respectively. Human precision was greater (100%) than dogs at 94%. Dogs detected a larger percentage of small targets (80%) at distances greater than 7.9 m (26 ft) compared with humans at only 20%. Our results indicate dogs are more accurate than humans are, especially at critical detection of small spotted knapweed plants, and from greater distances. Invasive plant monitoring using detection dogs can provide greater overall accuracy of plant detection.

Nomenclature: Domestic dogs, *Canis familiaris* L.; spotted knapweed, *Centaurea stoebe* L.

Key words: Weeds, rangeland, eradication, rare plant monitoring, vapor detection, search dog.

Invasive plants can replace native species (Dukes and Mooney 2004), alter ecosystem function and threaten biodiversity (Braithwaite et al. 1989; Musil 1993), and cause damaging economic effects for land managers in western North America. Early detection and containment or eradication of new invasions can slow their spread (Moody and Mack 1988), prevent future weed problems (Hobbs and Humphries 1995), and reduce ultimate management costs (Higgins et al. 2000). Eradication requires near-perfect control for many years, yet finding juvenile and small adult plants is challenging (Tomley and

Panetta 2002), and sampling becomes increasingly difficult on large sites as management reduces weed density over time (Panetta 2007). The detection of rare individuals, or those occurring in low abundance in an area of occupancy (Gaston 1997), is a common problem but is critical for invasive plant eradication and important for accurate and unbiased occupancy estimates of rare native species (MacKenzie et al. 2002).

Domestic dogs, trained to search for the presence of specific odors and referred to as detection dogs, might provide an effective and reliable detection method for rare plants based on their ability to cover large areas thoroughly (Killam 1990) and to accurately discriminate specific odors (Williams and Johnston 2002). For example, detection dogs with associated handlers have been used to locate buried land mines (McLean 2003), human remains (Killam 1990), cadavers (Rebmann et al. 2000), desert tortoises

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Interpretive Summary

Monitoring invasive plant populations is an essential aspect of the eradication process to locate and remove every individual. Eradication is difficult because small, obscure plants often escape detection and reproduce, increasing the time needed for extirpation. Our study investigated the performance of trained dogs in comparison to human surveyors, the standard detection method, to search for and locate rare spotted knapweed targets over multiple seasons. We found detection dogs were as accurate as humans at identifying large-size spotted knapweed infestations (0.52 m^3) and more accurate than humans (94 vs. 78%) with medium infestations (0.13 m^3). Dog accuracy was much better than humans (67 vs. 35%) with small infestations (plants; 0.02 m^3). In addition, dogs were able to identify small infestations from greater distances than humans. Humans were more selective to larger knapweed targets with stronger visual signals, causing a sampling bias against the detection of small plant targets. Our study demonstrates detection dogs can contribute to effective search protocols by thoroughly covering large areas and increasing the probability small and inconspicuous plant targets will be detected.

(*Gopherus agassizii* C.; Cablk and Heaton 2006), San Joaquin kit fox (*Vulpes macrotis mutica* Merriam) scat (Smith et al. 2003), and the presence of black-footed ferrets (*Mustela nigripes* Audubon and Bachman; Reindl-Thompson et al. 2006). Detection dogs are probably best noted for their use in the field as hunting dogs and in search and rescue to locate missing people or avalanche and disaster victims (Syrotuck 1972). Detection dogs typically search an area by working back and forth in a serpentine pattern while continuously sampling small amounts of odor. When the dog detects a trace of the target scent it follows the odor gradient to its source and gives a trained alert using a reward-based system.

Given that all plant species produce blends of volatile organic compounds with distinctive odors, it seems likely that dogs could be trained to identify the unique signature odors of a plant species or genus in the field. We conducted this study to determine whether dogs could be trained to search for and locate an invasive plant species in a natural setting. We chose spotted knapweed (*Centaurea stoebe* L.) as the experimental model based on its availability, ecological and economic importance, and the precedence established by the successful invasion of western North America (Callaway and Vivanco 2007). The objectives of this study were to test the hypotheses that dogs (1) detect rare spotted knapweed with equal or better accuracy than humans, and (2) detect rare spotted knapweed at greater detection distances than humans.

Materials and Methods

Scent Discrimination and Search Training. Dogs were trained to discriminate the odor of spotted knapweed in the

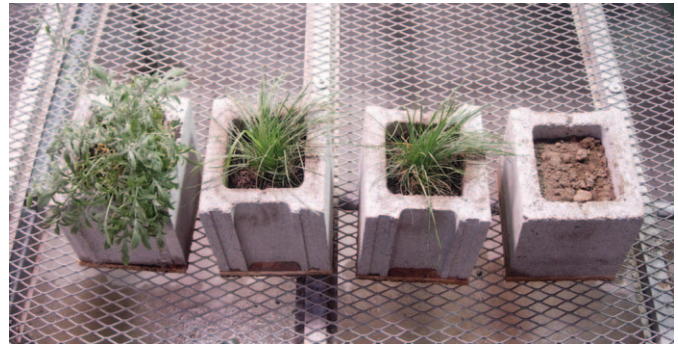


Figure 1. Field-collected spotted knapweed (left), crested wheatgrass (middle), and soil (right), planted in single hollow, concrete bricks attached to a wood base.

framework of signal-detection theory and operant conditioning (Lieberman 1999). The training procedure consisted of discrete trials with one of two explicit stimuli (signal plus noise or noise alone; Green and Swets 1966). Four to six hollow, concrete bricks were placed 3 m (9 ft) apart in a line. Target knapweed plants (*signal*) were placed in one brick, and the remaining bricks contained nontarget (*noise*) crested wheatgrass plants [*Agropyron cristatum* (L.) Gaertn.], natural field soil, or were left empty (Figure 1). A second hollow, concrete brick was stacked on top of the filled concrete bricks to prevent visual cues to the dogs. Each dog sampled the odor (off-leash) from the concrete bricks. Handlers were initially aware of the target location, which was randomized for each trial. A previously trained alert response (scratching or sitting) to the target odor was rewarded with play and praise. Missed targets resulted in task repetition, and false-positives (alert response to target odor absence) resulted in verbal correction with task repetition. Blank trials without the target odor (*noise alone*) were randomly included at low frequencies (2 or 3 out of 10 trials), based on handler discretion to prevent canine expectations of a reward on every occasion. Once the dogs were competent at discriminating between knapweed targets and controls based on $\geq 80\%$ correct-response scores, they advanced to blind trials, where the handlers were unaware of the identity of each brick. Blind trials ensured unintended cues from the handlers were not influencing the odor-selection process by the dogs.

Search training was conducted in flat, open perennial grasslands. Natural-occurring knapweed plants or fresh-cut knapweed material (about 30 to 50 g [1.1 to 1.8 oz] of leaves and stems) was placed at random locations within the search area. Handlers were initially aware of knapweed target locations to evaluate dog scenting behavior. Missed targets resulted in a repeated search of the target area until the dog responded with an alert response. Later, blank searches (noise-alone trials) were introduced to enforce an expectation targets can be absent. Blind trials were also included, during which the handlers were unaware of target locations.

Table 1. Range and means (\pm SE) for weather conditions at study site between 6:00 and 10:00 A.M. in (a) September 17 to 29, 2005, (b) May 15 to 25, 2006, (c) July 10 to 23, 2006, and (d) September 9 to 26, 2006.

| Season | Temperature | | Relative humidity | | Wind speed | |
|----------------|-------------|-----------|-------------------|-----------|------------|-----------|
| | Range | Mean (SE) | Range | Mean (SE) | Range | Mean (SE) |
| | C | | % | | m/s | |
| a. Fall 2005 | -1.7, 39 | 6.8 (0.7) | 31, 97 | 74 (2.1) | 0, 5 | 1.8 (0.2) |
| b. Spring 2006 | 6, 24 | 15 (0.6) | 90, 98 | 95 (0.3) | 0, 8.6 | 1.9 (0.3) |
| c. Summer 2006 | 8.3, 25 | 17 (0.6) | 27, 94 | 54 (2.0) | 0, 3.4 | 1.8 (0.1) |
| d. Fall 2006 | -0.6, 17 | 7.1 (0.4) | 30, 97 | 73 (1.7) | 0, 6.9 | 2.1 (0.2) |

Dog and Human Surveyors. One mixed-breed Shepherd and two German Shepherds were selected to participate in this study with their handlers. The dogs varied in detection work experience. *Nightmare* was a 4-yr-old female with 1 yr of spotted knapweed scent training.¹ *Tsavo* was a 6-yr-old male with 3 yr of carnivore scat-detection training, and *Rio* was a 9-yr-old male with 6 yr of carnivore scat-detection training.² Twelve human surveyors participated in this study. New surveyor groups consisting of three people were replaced for each of the four sets of seasonal trials. This was done to avoid bias associated with knowledge gained of the experimental site from prior searches. Surveyors had approximately 2 yr of spotted knapweed detection experience before the study. All surveyors were similar in backgrounds, allowing for generalization to experienced surveyors.

Field Experiment Site and Test Procedure. The field experiment was conducted in Gallatin County near Belgrade, MT (45°46'N, 111°9'W; 1,360 m elevation), in a 67-ha (166-ac) dryland pasture dominated by crested wheatgrass and seasonally grazed by cattle in the summer and fall. The mean annual temperature is 5.5 C (41.9 F), annual precipitation is 35.7 cm (14.1 in), and the frost-free period is 115 d. The field experiment consisted of four sets of seasonal trials that occurred in fall 2005 (September 17 to 29), spring 2006 (May 15 to 25), summer 2006 (July 10 to 23), and fall 2006 (September 9 to 26). Seven sampling units (rectangular area; 0.5 ha) were defined within the pasture according to the spatial distribution of natural knapweed targets and experiment-site limitations, including fence lines. Thirteen targets were present among the seven sampling units as five individual plants and eight infestations (multiple plants) for the first three seasonal trials. One plant target died after the summer seasonal trial; thus, the total number of targets in the last seasonal trial was 12. Target size, density, and percentage of grass cover were characterized three times (May, July, September) in 2006. Mean (\pm SE) height and width of knapweed plants were 20 cm (\pm 0.9) and 29 cm (\pm 1.2), respectively. Mean infestation area, or the smallest area occupied by an

infestation including the outermost plants, was 8.3 m² (\pm 5.1)(89 ft²). The large variance in infestation area was due to differences in patch size and quality, e.g., infestations ranged from 3 plants 1.0 m⁻² patch to 25 plants 42 m⁻² patch. Mean infestation density was 9.6 plants infestation⁻¹ (SE = 2.9). Mean interseasonal canopy cover and grass height were 53% (SE = 1.1) and 12 cm (SE = 0.3), respectively. Ambient temperature, relative humidity, and wind speed data were obtained from a Federal Aviation Administration automated weather station located 3.2 km (2.0 mi) from the study site. The range and average of weather conditions among seasonal trials are given in Table 1.

Human surveyors and dogs with their original handlers independently performed line-transect sampling for stationary populations (Anderson et al. 1979) using a census-based approach. Parallel transect lines were established at 5-m intervals and defined with survey flags. The narrow-transect width (10 m) provided a high probability of target detection and ensured sites were adequately searched in similar time periods to reduce sampling bias related to quick or incomplete search efforts. Dogs were off-leash and performed the search on their own and ahead of the handlers (~10 to 15 m). The role of the handlers was to interpret dog behavior and to control for dog-related and weather-related sampling bias by ensuring adequate coverage of the sampling units by the dogs and observing air currents that affect odor availability, much like a person operating vapor sensor equipment. Handlers were not aware of target locations and instructed not to look for targets so dog performance would not be biased. Dog trials were videotaped to document scent detection and eliminate observer bias. Dog and human surveyors searched between 6:00 and 10:00 A.M. Trials were not conducted during inclement weather. Dogs were deployed at 24-h intervals to allow for dispersion of any odor cues.

Parameters Measured and Statistical Analyses. Knapweed target size was indexed based on the volume of a cylinder ($\pi \times r^2 \times ht$) that would completely cover each plant. Infestation volume was calculated by summing the

volume of individual plants. The 13 targets were classified into three size categories with the *k*-means algorithm for clustering (Tou and Gonzalez 1974) using MATLAB (Version 7.4) statistics toolbox.³

Signal detection theory (Green and Swets 1966) was applied to assess the binary decision making for subjects (yes, there was a signal; no, there was not a signal) and its relationship to signal presence or absence. The purpose of analyzing response outcomes was to evaluate response bias and the ability of subjects to discern between signal and noise. Four possible response outcomes for the detection task included *true positive* (TP) or hit, *false positive* (FP; Type I error) or false alert, *false negative* (FN; Type II error) or miss, and *true negative* (TN) or correct rejection to target absence. Dog and human trials were scored for sensitivity (accuracy or recall), precision, and *F* measure. These performance measures are from detection theory (receiver operating characteristic [ROC] analysis; Egan 1975) and commonly used in information-retrieval analysis because the scores do not require true negative data (Han and Kamber 2006). In ROC analysis, accuracy is the proportion of TP and TN results (Fawcett 2006). Our experiment did not address true negatives. Therefore, we defined accuracy as the hit rate using the formula for sensitivity (*Sn*), which refers to the proportion of TP divided by the sum of TP and FN. Allowances are not made for chance agreement, however, when false positives are commonly subtracted from the hit rate. To evaluate random error and qualify accuracy, we accounted for false positives in our precision and *F* measure scores. Precision (*Prec*) was defined as the proportion of TP divided by the sum of TP and FP. Accuracy was also evaluated using Type II *F* measure values, or the combined performance of precision and sensitivity [= $2(Prec \times Sn)/(Prec + Sn)$]. Sensitivity and *F* measure refer to the discriminative ability of the method to detect a signal from background noise (Macmillian and Creelman 2005). Confidence intervals (95% CI) for sensitivity, precision, and *F* measure were estimated using standard methods for proportions.

Because detection is a binary task, we treated this experiment as a series of independent Bernoulli trials of success and failure (i.e., either the target is detected or not), which results in a binomial distribution. On each trial, the probability of success is *p*, which yields value 1, and the probability of failure is *q* = 1 - *p*, which yields value 0, and *p* + *q* = 1. However, based on the lack of an a priori binomial probability, we calculated the exact probabilities (*P* values) of human performance (1) equaling or bettering dog (human ≥ dog, conservative statistic), and (2) bettering dog (human > dog, less-conservative statistic) over four seasonal trials and among target sizes by full permutation tests (Good 1994) with probability *p*. The probability of dog performance (1) equaling or bettering human (dog ≥ human), and (2) bettering human (dog >

Table 2. Knapweed target characteristics and size category as defined by *k*-means clustering.

| Target | No. of plants | Volume (SE) | Size category ^a |
|--------|---------------|----------------|----------------------------|
| | | m ³ | |
| 1 | 1 | 0.006 (0.002) | S |
| 2 | 1 | 0.053 (0.031) | S |
| 3 | 1 | 0.025 (0.015) | S |
| 4 | 6 | 0.106 (0.030) | M |
| 5 | 22 | 0.720 (0.252) | L |
| 6 | 4 | 0.141 (0.034) | M |
| 7 | 4 | 0.437 (0.132) | L |
| 8 | 6 | 0.138 (0.018) | M |
| 9 | 1 | 0.014 (0.007) | S |
| 10 | 23 | 0.390 (0.107) | L |
| 11 | 3 | 0.004 (0.001) | S |
| 12 | 1 | 0.012 (0.007) | S |
| 13 | 9 | 0.025 (0.029) | S |

^a Abbreviations: S, small (0.004–0.053 m³); M, medium (0.106–0.141 m³); and L, large (0.39–0.72 m³).

human) was determined with the probability 1 - *p*. Therefore, the probability that humans outperform dogs is one minus the probability they will not outperform dogs.

Detection distances, or the length between the surveyor and target, were measured to compare the distance over which the target signals were detectable to dogs and humans. Distances were determined at first visual detection for humans and first scent detection for dogs. The dog detection point was verified with video and defined where a noticeable difference in search behavior was observed, e.g., changes in pace, direction, and sniffing behavior. Detection distances were divided into three groups (near, intermediate, and far) by discretization using equal-frequency binning (Grzymala-Busse 2002). Permutation and discretization was implemented with MATLAB (Version 7.4)³ scripts.

Results and Discussion

Knapweed targets were divided into small (0.02 ± 0.01 m³ [0.71 ± 0.35 ft³]; *n* = 7), medium (0.13 ± 0.01 m³; *n* = 3), and large (0.52 ± 0.10 m³; *n* = 3) categories by *k*-means clustering (Table 2). High variability in target volume resulted from an increase in aboveground growth between the spring and summer trials and a reduction in aboveground biomass from browsing by cattle between the summer and fall trials. Target 9 died between the end of the summer trials (July 23) and the beginning of the fall trials (September 9).

The summary of response outcomes (defined above) show the Bernoulli trial scores (Table 3) for hit or miss and indicate the dog method detected more targets than the

Table 3. Summary of response outcomes by dog and human surveyors to target presence ($n = 153$; TP and FN) and absence (FP).^a

| Surveyor | Response | Season | | | | | | | | | | | | Total |
|----------|----------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|-------|
| | | Fall 2005 | | | Spring 2006 | | | Summer 2006 | | | Fall 2006 | | | |
| | | D ₁ | D ₂ | D ₃ | D ₁ | D ₂ | D ₃ | D ₁ | D ₂ | D ₃ | D ₁ | D ₂ | D ₃ | |
| Dog | TP | 11 | 10 | 11 | 9 | 8 | 10 | 12 | 10 | 12 | 10 | 10 | 11 | 124 |
| | FN | 2 | 3 | 2 | 4 | 5 | 3 | 1 | 3 | 1 | 2 | 2 | 1 | 29 |
| | FP | 0 | 2 | 0 | 1 | 0 | 1 | 1 | 0 | 0 | 0 | 2 | 1 | 8 |
| | | H ₁ | H ₂ | H ₃ | H ₁ | H ₂ | H ₃ | H ₁ | H ₂ | H ₃ | H ₁ | H ₂ | H ₃ | |
| Human | TP | 7 | 9 | 7 | 6 | 5 | 7 | 9 | 8 | 9 | 8 | 7 | 8 | 90 |
| | FN | 6 | 4 | 6 | 7 | 8 | 6 | 4 | 5 | 4 | 4 | 5 | 4 | 63 |
| | FP | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

^aAbbreviations: TP, true positive (hit); FN, false negative (miss); FP, false positive (false alert); D₁, dog 1, Nightmare; D₂, dog 2, Tsavo; D₃, dog 3, Rio; H₁, human 1; H₂, human 2; H₃, human 3.

human method (TP = 124 vs. 90, respectively). Interdog variability in performance was largely due to natural differences in sampling behavior and temperament traits. For instance, although Tsavo displayed obedience and enthusiasm to work, he gave more false alerts (FP = 4) and less hits (TP = 38) than the other two dogs (Table 3). We attributed mistakes and lower accuracy to distraction by ground squirrels (*Spermophilus* spp.), resulting from high prey drive to chase and catch small animals. Rio performed slightly better than Nightmare as a result of two additional hits (TP = 44 vs. 42, respectively) due to his slow searching behavior (discussed later). Both dogs had two false alerts (FP). Overall accuracy (81%) for the dog method was greater than the human method (59%). Dog accuracy for small (67%) and medium (94%) size targets was better than human accuracy (35 and 78%, respectively) but similar for large targets (Table 4). Overall *F* measure (mean, 86%; 95% CI, 85 to 87%) of the dog method was greater than the human method (mean, 74%; 95% CI, 72 to 75%). Overall precision of the dogs was lower (mean, 94%; 95% CI, 93 to 95%) than humans (100%), indicating both methods have high precision and, thus, low response bias or minimum systematic errors. The accuracy and *F* measure scores suggest the dog method has

more discriminative ability for knapweed than the human method. Dog performance is subject to odor availability as a function of handler skills (Gutzwiller 1990). Our design minimized handler error and influence, so performance could be attributed to dogs. Odor availability was controlled over seasonal trials by maintaining a constant search strategy (i.e., parallel line-transect searches), conducting searches in the early morning hours, and selecting similar sampling units (flat ground with short vegetative cover; see Materials and Methods).

The probabilities of dog equaling or outperforming human (conservative measure) and dog outperforming human (less-conservative measure) are shown in Table 5. The conservative results (dog \geq human) show the detection performance of dogs is equal to or better than humans among target sizes and over seasons, except in one observation (medium-size target, fall 2006), where dogs were better than humans about half of the time [49.8%; $(1 - 0.502) \times 100$] because of odor evaporation resulting from marginal weather conditions (i.e., high heat and low moisture). Overall, these conservative results suggest dogs significantly outperform humans with small and medium size targets and perform equally well with large targets over seasons. More specifically, dog accuracy for large targets (100%) was as good as human accuracy (94%) and much better than humans for medium (94 vs. 78%) and small (67 vs. 35%) size targets. An interesting finding is that dogs were consistently more accurate than humans with important small targets at 81% probability and better. The less-conservative results (dog $>$ human) show dogs outperform humans at least 92.7% [$(1 - 0.073) \times 100$] of the time among target sizes and over seasons, except again in the previously mentioned observation (medium size target, fall 2006), where dogs outperformed humans at 87.3% probability [$(1 - 0.127) \times 100$]. Overall, these

Table 4. Summary of dog and human surveyor accuracy scores by target size.

| Surveyor | Target size category | | | Overall accuracy |
|----------|----------------------|-------------|-------------|------------------|
| | Small | Medium | Large | |
| | mean % (95% CI) | | | |
| Dog | 67.1 (2.50) | 94.4 (2.06) | 100.0 | 81.1 (1.49) |
| Human | 34.7 (1.56) | 77.8 (3.44) | 94.4 (2.06) | 58.9 (1.59) |

Table 5. Probability ($1 - p$) of dog equaling or outperforming human (dog \geq human) and dog outperforming human (dog $>$ human) for three target size categories (small, medium, and large) over seasonal trials.

| Season | Target size category | | | | | |
|-------------|----------------------|---------------|-------------------|---------------|-------------------|---------------|
| | Small | | Medium | | Large | |
| | Dog \geq human | Dog $>$ human | Dog \geq human | Dog $>$ human | Dog \geq human | Dog $>$ human |
| Fall 2005 | 0.981 | 0.998 | 0.748 | 0.998 | 0.00 ^a | 0.998 |
| Spring 2006 | 0.806 | 0.927 | 0.811 | 0.967 | 0.748 | 0.998 |
| Summer 2006 | 0.996 | 0.998 | 0.00 ^a | 0.998 | 0.00 ^a | 0.998 |
| Fall 2006 | 0.981 | 0.998 | 0.498 | 0.873 | 0.00 ^a | 0.998 |

^aValue of 0.00 means dog and human performances were equal.

less-conservative results indicate dogs consistently outperform humans over seasons and among target sizes. In particular, we found dogs were more accurate than humans with small targets (67 vs. 35%, respectively) at 93% probability and better. The moderately high sensitivity (81%) and F measure (86%) of the dog method compared with the human method (sensitivity, 59%; F measure, 74%) explain our observations on better dog performance, i.e., better dog accuracy was due to the ability of canines to discriminate target signals, including small or low-level signals, from background noise (explained below) given the experimental conditions. In a similar study with desert tortoises, Cablk and Heaton (2006) found dogs detected smaller tortoises (30 mm [1.2 in] midline carapace length [MCL]) compared with humans (110 mm MCL). In our study, dog and human surveyors show high precision (94% and 100%, respectively). Dog precision was lower than humans because of eight false alerts (FP) by dogs compared with none for humans (Table 3) resulting from corrections in perceptual judgment before a response. We attributed false alerts by dogs to natural factors, such as scent pools remote from the source (Rebmann et al. 2000) and behavioral variations. Although dogs gave a higher level of false positives (Type I error), which may incur a cost (e.g., credibility loss), the risk is acceptable to the lower level of false negatives (Type II error) that have higher relative costs when missed plants reproduce.

The ability of dogs to locate small knapweed plants that escape detection by humans is because dogs use olfaction to identify targets, whereas humans rely on vision. Dogs possess hundreds of different receptor types organized by similarity to encode specific proteins, which then converge upon two precise loci in the olfactory bulb (Buck 1996; Buck and Axel 1991; Mombaerts et al. 1996) to increase signal-to-noise ratios by averaging out uncorrelated noise via postsynaptic summation (Laurent 1999). The ability to reduce input noise might help explain why dogs can detect odor concentrations of about 0.001 ppmv (or 1 part per billion; Waggoner et al. 1998). In contrast, mammalian vision systems process only a subset of all visual

information by three peripheral receptor types (i.e., red, blue, and green; Young–Helmholtz theory) and are strongly affected by noise (Tanner and Swets 1954). It is interesting that humans were more selective to larger targets, whereas small targets were frequently under-sampled. We believe humans were most successful with larger targets because of stronger visual signals that likely surpassed the background noise of surrounding vegetation. We reason dogs were less affected by noise and, therefore, sensitive to each target size, including small plants with low signal strength.

Dog and human surveyor performance was influenced by seasonal effects on knapweed targets and site conditions. We believe lower performance by dogs and humans in the spring trials compared with the summer and fall trials (Table 5) was due to difficulties in perceiving plant targets. During the spring trials, all vegetation was uniform in size and color, and targets were less visually conspicuous to humans compared with other seasons. In the case of dogs, target odors were likely trapped by dense vegetation or counteracted by the comparatively high levels of volatile compounds produced by the actively growing vegetation (which reduced target odor intensity or masked target odor quality). That is, high levels of extraneous plant odors, which are somewhat chemically similar to knapweed, might have interfered with perception of the target odor by neural inhibition or by competition for olfactory receptor sites (Cain and Drexler 1974; O'Connell and Akers 1989). During the summer and fall trials, knapweed plants were more noticeable to humans because they remained green with purple flowers against background grasses that were dormant and yellow. Cattle grazing also improved the detectability of targets by reducing the aboveground biomass of perennial grasses to increase target visibility and odor transport. These factors together likely acted to improve both dog and human performance.

Distances of detected targets ranged from 1.0 to 62.2 m for dogs ($n = 124$) and 0.4 to 31.1 m for humans ($n = 90$). Dog and human surveyors detected targets from distances > 20 m in 19 of 52 (37%) and 2 of 18 (11%)

Table 6. Mean (\pm SE) for detection distance of dog and human surveyors grouped by target size.

| Target size | Dog | | Human | |
|-------------|------------|-----------|-----------|-----------|
| | Distance | Frequency | Distance | Frequency |
| | m | | m | |
| | mean (SE) | | mean (SE) | |
| Small | 8.5 (1.3) | 54 | 4.6 (0.6) | 28 |
| Medium | 12.8 (2.8) | 34 | 4.5 (0.5) | 28 |
| Large | 12.6 (1.9) | 36 | 7.4 (1.1) | 34 |

cases, respectively. We observed dog detection distances > 50 m were rare (3 of 52 cases; 6%). Target detections ($n = 214$) were grouped into three distance bins of approximately equal size ($n \approx 71$). Near, intermediate, and far distance bins correspond to distances of < 3.7 m, 3.8 to 7.8 m, and > 7.9 m. The mean values of these frequencies, i.e., detection distances, were grouped by target size (Table 6) and plotted as histograms (Figure 2). From the constructed histograms, the estimated frequency of detected targets by target size was visually evaluated for each distance bin. The characteristic feature of these histograms is the difference in detected targets, in particular small targets, identified at far distances by dogs and humans. Out of 25 small target detections in the far distance category (> 7.9 m), there were 20 detections made by dogs (80%) and only 5 detections made by humans (20%). These results suggest dogs are better at detecting small targets at greater distances than humans are at detecting them. More specifically, dogs found 54 small knapweed targets of which 37% were detected at far distances, and humans found 28 small targets of which 17% were detected at far distances. These observations further validate (1) the high sensitivity of the dog's olfactory system to detect weak signals, even as these signals are dissipated with distance; and (2) the low sensitivity of the human vision system which requires small targets be proximate before they can be detected, if they are identified at all. The range of distances over which knapweed targets were detectable to dogs (1.0 to 62.2 m) given the site conditions, i.e., short vegetative cover and flat ground, is similar to other dog studies involving desert tortoise detection (0.5 to 62.8 m) in open desert-shrub habitat (Cablak et al. 2008). Although the dogs in our study were trained to indicate the source of the target odor, i.e., the knapweed plant, future detection distance studies might consider training dogs to indicate detection at the first whiff of the target odor for quantitative measures of detection distance.

Dog teams have considerable potential for invasive plant eradication by improving accuracy for small, infrequent plants, which are undersampled by human surveyors. Monitoring should, therefore, rely on multiple methods to sample populations satisfactorily. We reason detection dogs

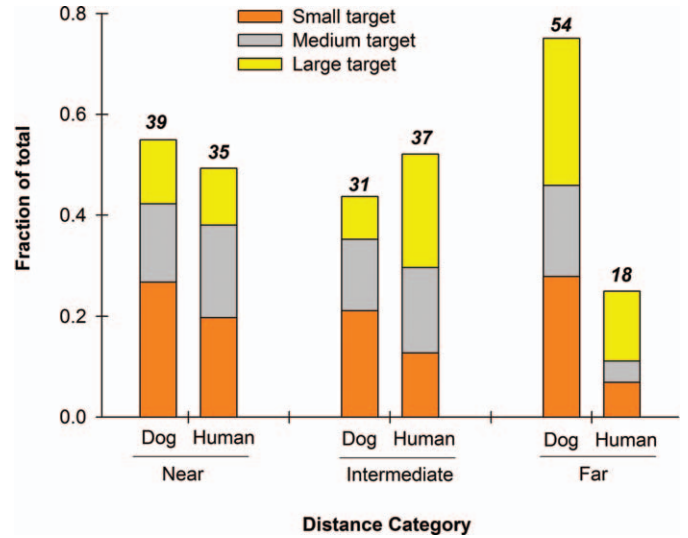


Figure 2. Target size distribution of successful detections at near (0.4 to 3.7 m; $n = 74$), intermediate (3.8 to 7.8 m; $n = 68$), and far (7.9 to 62.2 m; $n = 72$) distance categories for dog and human surveyors. Numbers above stacked bars indicate the sum of counts for each.

can provide a useful auxiliary system to human surveyors, particularly in areas known to contain low-density plants that require high levels of detection. The frequency and temporal spacing of surveys and numbers of humans and dogs in a search team will fluctuate based on accuracy requirements, individual performances, site conditions and search area, target detectability, detection rates, and the length of the prereproductive phase of the plant species (Panetta 2007; Panetta and Timmins 2004).

Future studies should focus on the control of environmental and biological variables that affect the accuracy of rare-plant detection by dogs, like search duration, vegetation, weather, and behavioral traits. Although mean (\pm SE) search duration of dogs (24 ± 0.9 min) was similar to humans (26 ± 1.1 min), dogs were considerably more effective because more plants were detected per unit of time and area. Our sampling units were located on flat ground in grazed grasslands that were relatively structurally uniform. Future studies in structurally complex sites (multiple plant species and canopy layers) might result in longer search times and lower accuracy because dense vegetation would likely impede the transport of target plant odors. Weather factors also affect odor availability and detection in response to wind, temperature, and moisture (Gutzwiller 1990; Phelan and Webb 2003; Syrotuck 1972), and drive discontinuous odor signals in field settings (Bach and Phelan 2003). Strategies to minimize dog-induced detection bias (misses or Type II errors) include searching in the early morning hours to control for daily weather cycles when solar radiation frequency and evaporation potential is low. Odor availability

is greatest with high soil-moisture content and relative humidity, cool air and soil temperature, and low wind velocities (Phelan and Webb 2003).

Search accuracy might also be improved and detection bias reduced by selecting slow-searching dogs with the ability to concentrate in field settings. For instance, Rio had a slower mean (\pm SE) search time (31 ± 1.5 min) than Nightmare (19 ± 0.9 min) and Tsavo (23 ± 1.1 min) and was responsible for 80% (four out of five) of the unique interseasonal detections by dogs. Because olfaction is a low-bandwidth sense that occurs on a relatively slow timescale, when compared with vision (Laurent 1999), searching at slow speeds permits longer odor exposures and better discrimination accuracy for weak signals (Rinberg 2006). High levels of concentration needed to search at slow speeds are the preferred sampling behavior of dogs trained to detect land mines (Bach and Phelan 2003) and may have been important in this study because spotted knapweed roots were found to release odors detectable to dogs (K. M. Goodwin et al., unpublished data). We believe the techniques described in this study are applicable to the arena of rare and endangered plant species detection. Visual surveys for these plants often reflect only adult life stages, whereas nonflowering plants and inconspicuous life stages can often be overlooked under intense searches (Palmer 1987). Clearly, the scent training and field search techniques we employed could easily be extended to detection of other plant species and represents an exciting opportunity for future research.

Sources of Materials

¹ Rocky Mountain Command Dogs, Virginia City, MT.

² Working Dogs for Conservation Foundation, Three Forks, MT.

³ MATLAB, Version 7.4, statistical software, The Math Works, Natick, MA.

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