Dispersal rates of forage kochia (*Bassia prostrata*) from seeded areas in southern Idaho
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Authors: Jeffrey E. Ott, Francis F. Kilkenny, Jessica Irwin

Forage kochia (*Bassia prostrata*, hereafter ‘kochia’), a short-statured shrub of Eurasian origin, has been widely seeded in the Intermountain West for rangeland revegetation, post-fire rehabilitation and greenstripping. Although popular for revegetation purposes, it can be become troublesome in areas managed for biodiversity conservation. In southwestern Idaho, kochia is considered invasive in slickspot communities where it competes with sensitive endemic peppergrass species *Lepidium papilliferum* and *L. davisii* (Kinter et al. 2012, BLM 2014).

Despite potential impacts on endemic peppergrass species, kochia has been and will likely continue to be seeded in the region where these species occur (BLM 2014). Continued use of kochia in this region has been defended on the grounds that kochia invasions are unlikely if seedings are kept at a reasonable distance from peppergrass sites (BLM 2014). This argument is based on the assumption that kochia is incapable of rapid spread from seedings into nearby unseeded areas. However, our understanding of kochia’s capacity to spread is limited given that relatively few studies have actually addressed this issue.

A recent study carried out by Gray and Muir (2013) in southwestern Idaho suggests that kochia may be capable of spreading farther and faster than previously thought. Gray and Muir (2013) documented occurrences of kochia up to 710 m from boundaries of seeded areas and estimated that kochia had spread into unseeded areas at a mean rate of 25 m/year. Some of the kochia plants observed in unseeded areas by Gray and Muir (2013) were isolated individuals, but they also observed dense stands of kochia that appeared to represent expanding populations. They mapped areas adjacent to seedings where kochia density was at least 1 plant/m^2, and estimated that the recruitment margin of these high-density stands had expanded at a mean rate of 4 m/year (Gray and Muir 2013). Statistical modeling revealed that kochia spread rate was correlated with environmental variables including elevation, grazing intensity, and bare soil cover (Gray and Muir 2013).

Following publication, Gray and Muir’s (2013) study has received criticism over perceived weaknesses in study design. Land managers familiar with seeding history pointed out that Gray and Muir’s (2013) estimates likely contain inaccuracies due to the inclusion of seeding treatments with poorly-defined boundaries. In particular, estimates of kochia spread could be inaccurate at sites where kochia was seeded using aerial broadcast techniques, due to the possibility that kochia seed had drifted beyond mapped seeding boundaries (BLM 2014).

Another limitation of Gray and Muir’s (2013) study is its reliance on data collected during a single year. They inferred that kochia plants located in unseeded areas had spread from adjacent seedings but did not confirm their inferences by tracking changes over time. Repeated measures would provide more robust evidence of kochia expansion beyond seedings, regardless of seeding technique, and would allow rate of spread to be calculated more directly.

We sought to remedy these limitations of Gray and Muir’s (2013) study through a two-pronged approach. First, we re-analyzed Gray and Muir’s original data (collected in 2010) after removing data from sites that had been called into question because of poorly-defined seeding boundaries. This allowed us to refine and clarify conclusions of the original study. Second, we collected new data in 2016 from some of the original study sites, thus adding a temporal dimension that allowed for better quantification of kochia's rate of spread. To accomplish this objective, we developed a new methodology for mapping and monitoring kochia spread adjacent to seeded areas.

Methods

Original Study Data Collection and Analysis

Gray and Muir's (2013) study was carried out in 2010 at 28 sites in southwestern Idaho where kochia had been seeded between 1986 and 2007 (Fig. 1). Many of these seedings were greenstrips adjacent to roads; others were post-fire rehabilitation seedings. Boundaries between seeded and non-seeded areas were identified and data were collected at three 'plots' (areas in the vicinity of a seeding boundary) per site (Fig. 1). At each plot, Gray and Muir (2013) measured vegetation cover by species in seeded and non-seeded areas using line-point-intercept transects positioned perpendicular to the seeding boundary (Fig. 1). They also mapped 'recruitment margins' of kochia in a zone extending into the unseeded area from a 50-m segment of the boundary (Fig. 1). Each recruitment margin delimited an area in which kochia occurred with a density of at least 1 plant/m^2 beyond the edge of the seeding (Fig. 1). They also searched for the farthest kochia plant beyond the recruitment margin in the unseeded area, up to a maximum of 800 m (Fig. 1).

Using a statistical modeling approach, Gray and Muir (2013) assessed whether kochia spread could be predicted from environmental variables collected at each plot. They modeled recruitment margin and farthest plant distances as response variables in models where candidate predictor variables were time since seeding, elevation, mean annual precipitation, grazing intensity (mean and CV of AUM/ha), and non-plant cover types (litter, moss, rock, biological crust, soil, and badger mounds; as measured on the unseeded line-point-intercept transect).

Re-analysis of Original Study Data

We identified sites with questionable seeding boundaries through consultation with BLM staff from the Boise District (Amy Stillman and Kathi Kershaw, pers. comm.) and examination of datasheets, shapefiles and imagery provided by the BLM and authors of the original study. Some sites were found to have questionable seeding boundaries at some plots but not others. Questionable sites and/or plots were omitted in new analyses which aimed to (1) identify correlative relationships between spread distance and environmental variables and (2) predict spread distance based on combinations of strongly-correlated environmental variables. We used the same measures of spread distance (recruitment margin and farthest plant) and the same environmental variables that had been used by Gray and Muir (2013), but we also included additional variables available in their dataset: cover of vascular plant species in the unseeded area and cover of kochia in the seeded area. These variables were included to examine effects of vegetation attributes in the invaded area (i.e. vascular plant species) and propagule pressure in the source area (presumably correlated with kochia cover). Analyses were carried out in R (R Core Team 2012) using Spearman's coefficient for correlation analyses and regression tree analysis for predictive modeling. Optimal regression tree models were selected using ten-fold cross-validation in the R package 'mvpart' (R Core Team 2012).

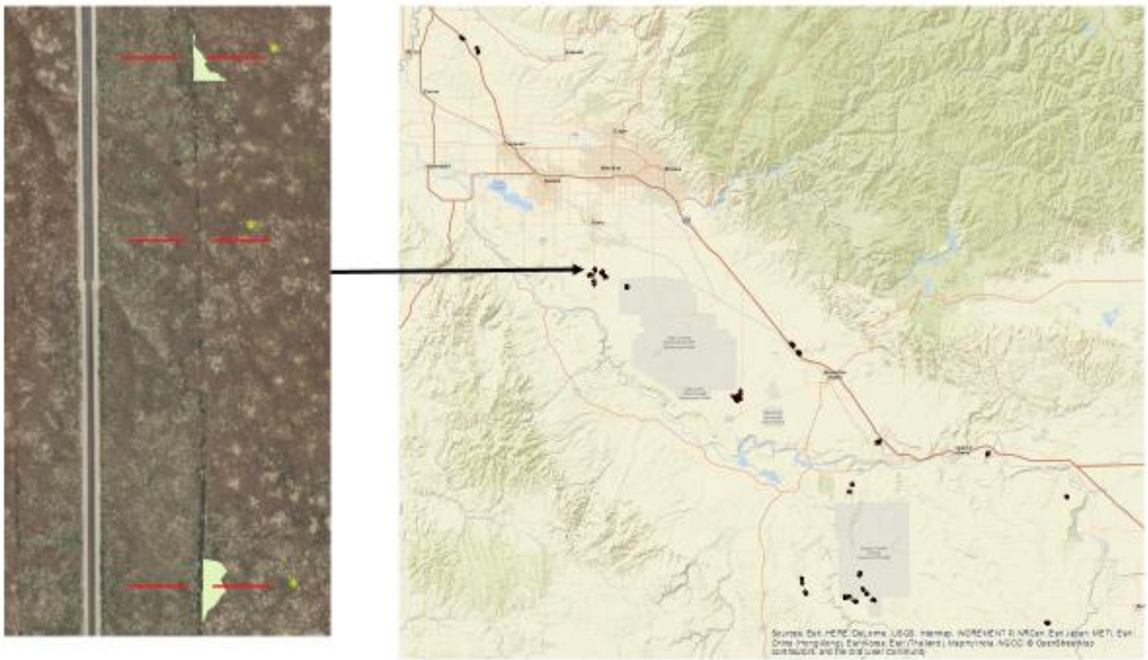


Figure 1. Left: imagery of an example study site established by Gray and Muir (2013), showing three plots where vegetation data were collected from 50 m transects (red lines) on two sides of a seeding boundary, recruitment margins on the unseeded side of the boundary where kochia was present at > 1 plant m^{-2} (green polygons) and hypothetical locations of farthest kochia plants in the vicinity of the recruitment margins (asterisks). Right: Location of kochia study sites (dots on map) established by Gray and Muir (2013) in southwestern Idaho.

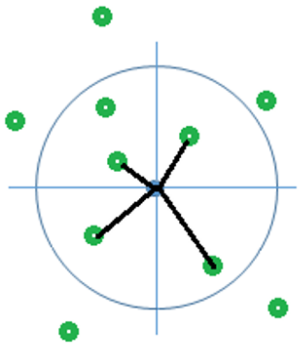
Repeated Measures Data Collection and Analysis

In 2016, we returned to six of the sites established by Gray and Muir (2013) and collected new data on kochia spread from seeding boundaries. Four of the sites are located near Swan Falls Road in the Snake River Birds of Prey National Conservation Area, Ada Co., ID (Swan Falls 2-5), and the other sites are located near Sand Hollow Road, Payette Co., ID (Apple Valley 2), and Interstate 84 near Mountain Home, Elmore Co., ID (I84 MP85 E). Kochia had reportedly been drill seeded at these sites between 1989 and 1997 (Table 1).

Table 1. Kochia study sites established in 2010 and revisited in 2016

Site Name	UTM East	UTM North	Year Seeded
Apple Valley 2	518192	4858740	1997
I84 MP85 E	598710	4782720	1989
Swan Falls 2	547534	4803744	1994
Swan Falls 3	547487	4800480	1994
Swan Falls 4	546378	4802220	1994
Swan Falls 5	550214	4802063	1994

Because of difficulties in replicating Gray and Muir's (2013) original methodology for mapping recruitment margins, we developed and implemented a new methodology that we felt was more objective and repeatable. Our methodology is based on the point quarter density technique (Krebs 1999), wherein distances are measured from a center point to the nearest plant in four directions, and plant density is calculated as an inverse function of distance (Fig. 2). Unlike typical applications of point quarter density, in which point locations are randomly distributed (Krebs 1999), we positioned points at regular intervals along transects. Points were separated by 5 m, and at each point we measured distances to the nearest kochia plant in four directions up to maximum 5 m distance (Fig. 2). This layout allowed us to calculate moving averages of kochia density from the edge of the seeding boundary (or more precisely, the edge of a 15 m buffer from the boundary) outwards into the unseeded areas (Fig. 3). Five parallel transects, one of which coincided with the line-point-intercept transect from the original study, were placed 10 m apart at each plot within the zone where the recruitment margin had previously been mapped (Fig. 3). We extended the transects into the unseeded area, taking measurements every 5 m, until we reached a stopping criteria defined as three consecutive points where no kochia plants were present within 5 m of the points.



$$\text{Density} = \frac{4(4n-1)}{\pi \sum_1^4 d^2}$$

where
n = number of points in sample
d = distance from point to nearest plant in quadrant

Figure 2. Left: Schematic illustration of point quarter density method, where distances are measured from a central point to the nearest plant (green dot) in four quadrants. In our study, we excluded plants beyond a 5-m radius. Right: Equation for converting distance to density for a set of points (or in our case, a single point, n=1, along a transect) (see Krebs 1999, p. 182).

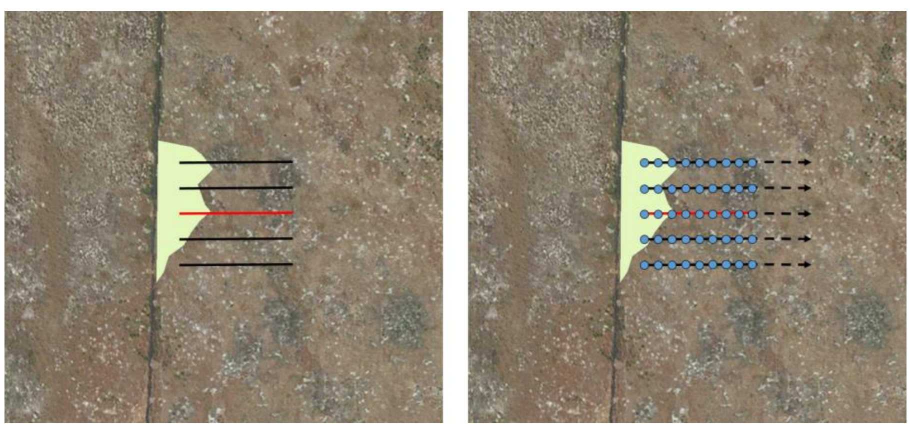


Figure 3. Layout of point-quarter-density transects established in 2016 in relation to transects and recruitment margins mapped in 2010. Left: Previous transect (red line) and four new lateral transects (black lines) overlain on recruitment margin areas (green polygon). Right: Schematic illustration of points (blue dots) positioned at 5-m intervals on transects, extending outward into unseeded area until stopping criteria are reached.

We assessed the amount of kochia spread during the six-year study period by comparing recruitment margins from 2010 with point-quarter-density transect data from 2016. The two data types were spatially superimposed in ArcGIS 10 to determine how much of each transect line was contained within its corresponding recruitment margin polygon. The transect span within the 2010 recruitment margin was used as a reference for comparison with 2016 density estimates along the transect. We assumed that the first point (moving outward into the unseeded area) after which 2016 density dropped below 1 plant/m^2 best approximated the point at which the recruitment margin would have been measured following Gray and Muir's (2013) criteria. Although we did not repeat Gray and Muir's (2013) method for mapping the farthest kochia plant from seeding boundaries, we examined the position of the 2010 farthest plants distances in relation to the farthest plants detected in 2016 on transects.

Results

Re-analysis of Original Study Data

We found that mean and maximum distance measurements were lower than those reported by Gray and Muir (2013) after we omitted sites and plots with questionable seeding boundaries from their dataset (Table 2). The maximum distance to the farthest kochia plant, for example, dropped from 710 m (as reported by Gray and Muir 2013) to 461 m because five plots with maximum distances > 461 m were omitted. This is does not necessarily mean that the higher distances reported by Gray and Muir (2013) are invalid but rather that the revised distances are more conservative estimates based on a more limited, high-quality data subset.

Table 2. Estimates of kochia spread calculated from data collected by Gray and Muir (2013) before and after omitting records with questionable seeding boundaries.

	Original Value	Revised Value
Mean distance to recruitment margin	30 m	10 m
Maximum distance to recruitment margin	197 m	109 m
Mean distance to farthest plant	208 m	88 m
Maximum distance to farthest plant	710 m	461 m

Correlation analyses of the revised dataset revealed that several environmental variables were significantly correlated with distances to the recruitment margin and farthest kochia plant (Table 3). Years since seeding was strongly and positively correlated (Spearman's $R > 0.6$) with both distance measures (Table 3), in agreement with the basic notion that kochia can spread over time. Kochia cover in the seeded area (from which seeds were presumably dispersing) was also strongly and positively correlated with distance measures, especially distance to the recruitment margin (Table 3). This suggests that propagule pressure is an important factor leading to kochia spread from seedings, i.e. more successful seedings with higher cover are more likely to expand their populations beyond seeding boundaries. Attributes of the invaded unseeded area were also found to be correlated with kochia spread: cover of bur buttercup (*Ceratocephala testiculata*), groundsmoke (*Gayophytum* spp.) moss and badger mounds were positively correlated, while cover of crested wheatgrass (*Agropyron cristatum*/*desertorum*), tansymustard (*Descurainia sophia*) and sagebrush (*Artemisia tridentata*) were negatively correlated with one or both distance measures (Table 3). We also found that grazing variability was positively correlated while grazing intensity and elevation were negatively correlated with the recruitment margin, suggesting that more heavily grazed, lower elevation sites may be more susceptible to kochia invasion. These results are similar but not identical to results obtained by Gray and Muir (2013) using different methods. Gray and Muir (2013) found that "in general, distance of the recruitment margin decreased with elevation and increased with variability in yearly grazing intensity and soil cover", and "distance of the farthest [kochia] individual tended to increase with years since seeding, rock cover and badger mound cover."

Table 3. Spearman's correlation coefficient for variables significantly correlated with kochia spread (recruitment margin distance and/or farthest plant distance), calculated from a subset of data collected by Gray and Muir (2013). Coefficients are shown for cases where $P < 0.05$ but omitted otherwise.

	Recruitment Margin	Farthest Plant
Years since seeding	0.62	0.66
Kochia cover in seeding	0.61	0.34
Variability in annual grazing	0.57	0.46
Bur buttercup cover	0.47	0.30
Groundsmoke cover	0.37	--
Badger mound cover	0.32	0.39
Moss cover	0.30	--
Elevation	-0.29	--
Mean AUMs	-0.32	--
Crested wheatgrass cover	-0.35	--
Tansymustard cover	--	-0.35
Sagebrush cover	--	-0.38

Regression tree modeling of the revised dataset affirmed the importance of years since seeding, kochia cover, and badger mound cover as predictors of kochia spread (Fig. 4). Through the modeling procedure we identified years since seeding as the best variable for predicting both recruitment margin distance and farthest plant distance. Our models predicted that sites that had been seeded 18 or more years previously tended to have higher recruitment margin distances (mean = 43 m) and higher farthest plant distances (mean = 327 m) than sites that had been seeded less than 18 years previously (Fig. 4). At sites with less than 18 years since seeding, kochia cover in the seeded area was the best secondary predictor for mean recruitment margin distance (2 m where cover < 37% vs. 22 m where cover ≥ 37%), while badger mound cover in the unseeded area was best for farthest plant distance (40 m where cover < 1% vs. 147 m where cover ≥ 1%) (Fig. 4).

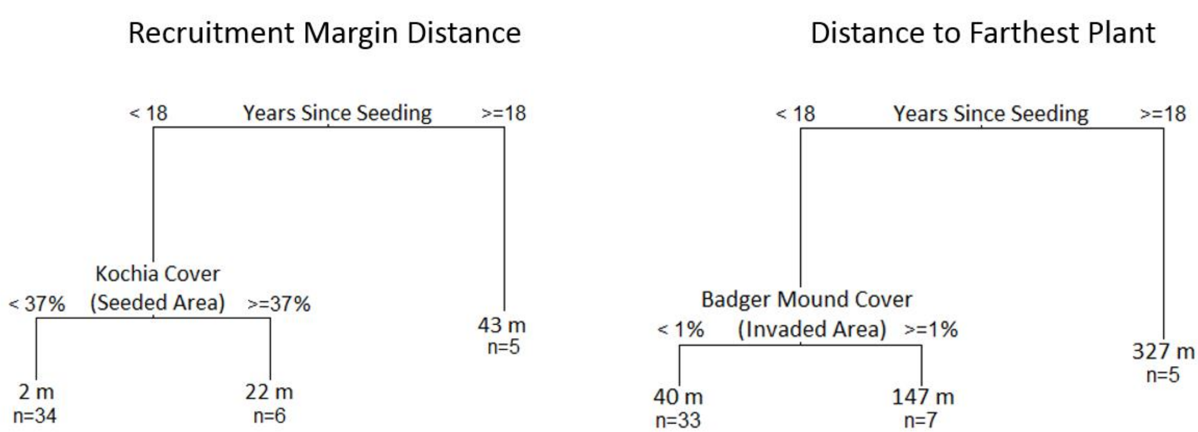


Figure 4. Regression tree models of recruitment margin distance (left) and distance to the farthest kochia plant (right) built from a subset of data collected by Gray and Muir (2013). Branches indicate splits of the dataset based on indicated threshold values of predictor variables. Terminal leaves show mean distance values in meters and the number of plots (n) belonging to each leaf group.

Repeated Measures Data Collection and Analysis

Using the point-quarter-density method, we measured kochia density in 2016 along transects that extended as far as 470 m beyond the seeding boundaries in some cases (Fig. 5). Transect length varied greatly between sites, being lowest at Apple Valley and Swan Falls 4 and highest at Swan Falls 3 and 5 (Fig. 5). Because of our stringent stopping criteria (three consecutive points with no kochia within 5 m), our transects reached areas of low kochia density that in most cases lay beyond the 2010 recruitment margins mapped by Gray and Muir (2013) (Fig. 5). In 12 of 18 plots, our 2016 transects even extended beyond farthest plant distances recorded in 2010 (Fig. 5). Although we did not specifically search for the farthest plants in 2016, the fact that we encountered new farthest plants under the constraints of our sampling methodology strongly suggests that kochia had spread at these plots between 2010 and 2016.

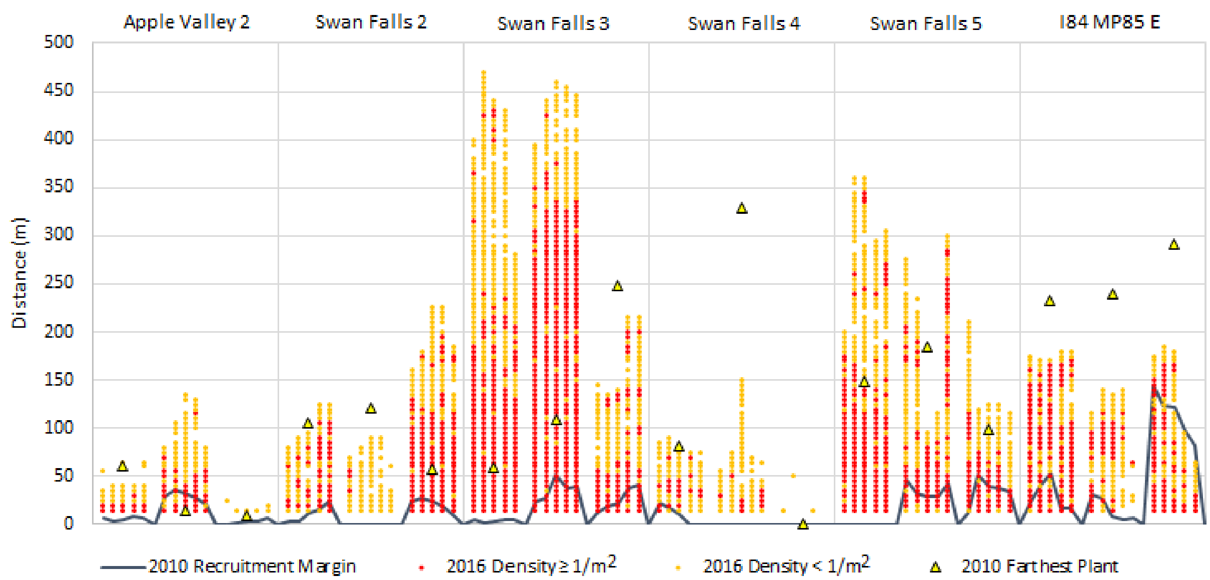


Figure 5. Spatial distribution of kochia in unseeded areas adjacent to seedings at six study sites in southwestern Idaho established by Gray and Muir (2013). The x-axis extends across sites (listed at top), each site containing three plots and five transects per plot. The y-axis is distance from the boundary of the seeding at a given site. Recruitment margins (delimiting zones adjacent to seedings with ≥ 1 kochia plants/m²) and farthest kochia plants mapped in 2010 are overlayed with 2016 kochia density as measured on transects.

The distribution of points with density exceeding 1 kochia plant/m² likewise suggests kochia spread in the form of expanding recruitment margins (Fig. 5, Table 4). Assuming that the first point on the transect where kochia density dropped below 1 plant/m² signaled the end of the 2016 recruitment margin, we inferred that the recruitment margin advanced on average 1.8 m/yr between 2010 and 2016. Recruitment margin spread rates for individual sites varied considerably from these average values, ranging from -5.4 m/yr (an apparent contraction of the margin) at I84 MP85 E to 10.4 m/yr (an exceptionally rapid advance of the margin) at Swan Falls 3 (Table 4). These recruitment margin spread rates tended to be more extreme than those reported by Gray and Muir (2013) for these same sites (Table 4). It is possible that differences in detection methods are at least partially driving these differing spread rate estimates. The spread rates we present in Table 4 are therefore tentative, but nevertheless reflect real patterns that can be seen when comparing 2010 recruitment margins with 2016 kochia density patterns in Figure 5. Moving forward, we should be able to more accurately quantify kochia spread as we return to established transects and repeat our sampling methodology.

Table 4. Estimated spread rates of kochia recruitment margins at six sites in southwestern Idaho in m/yr. Current Estimate: rate calculated from apparent shift of recruitment margin between 2010 and 2016. Previous estimate: rate inferred from mean distance of margin from seeding boundary measured in 2010, divided by years since seeding (Gray and Muir 2013).

	Current Estimate	Previous Estimate
Apple Valley 2	0.6	1.1
Swan Falls 2	2.2	0.7
Swan Falls 3	10.4	1.9
Swan Falls 4	-0.1	0.2
Swan Falls 5	2.8	1.7
I84 MP85 E	-5.4	2.4
Mean: All Six Sites	1.8	1.3

Conclusions and Recommendations

Our study confirmed, in general terms, Gray and Muir's (2013) conclusion that kochia has spread from seedings in southwestern Idaho. Gray and Muir (2013) might have overestimated spread distances by including sites with poorly-defined seeding boundaries (including aerial seedings), as indicated by lower spread distance estimates when their data were re-analyzed with the questionable sites omitted. However, re-analysis did not invalidate Gray and Muir's (2013) inferences regarding kochia spread over time, since we found strong positive correlations between kochia distance measurements and time since seeding even after omitting the questionable sites. Furthermore, we obtained additional, more direct evidence of kochia spread by resampling some of Gray and Muir's (2013) study sites in 2016 and mapping shifts in kochia presence and abundance since 2010. Preliminary findings of our resampling effort suggest that kochia can sometimes spread at rates even higher than those inferred by Gray and Muir (2013), although further monitoring is needed to validate this result.

Like Gray and Muir (2013), we identified environmental variables that appear to influence kochia spread from seeded sites. A previously overlooked but intuitively sensible variable that we found to be important is the amount of kochia in the seeded stand adjacent to the area where kochia is spreading. It may be that kochia spread is in many cases primarily a function of available seed (propagule pressure). Additionally, we found that one site (Swan Falls 3) showed particularly rapid spread between 2010 and 2016, indicating that some spreading kochia populations are generating additional propagule pressure and should be monitored closely. Our results also suggest that kochia is more likely to spread at sites with extensive badger mounds, high variability in annual grazing, and/or high cover of certain plants (bur buttercup, groundsmoke, moss); but less likely to spread at sites that are higher in elevation, have been grazed more intensively, and/or have high cover of certain other plants (sagebrush, crested wheatgrass, tansymustard). Although we cannot determine from our correlative analyses whether any of these site attributes or interacting plant species directly promotes or inhibits kochia spread, they are worth taking into account when considering the risks of kochia spread at a given site. Additional research into factors affecting kochia spread would likely offer further insights.

We believe that our point-quarter-density transect methodology could prove useful for monitoring kochia spread at other sites beyond those we studied. The methodology could easily be modified for less intensive sampling by, for example, using one transect instead of five per site, or increasing the distance between sample points along transects (see Appendix). Use of well-defined, repeatable methods for monitoring kochia spread over time will likely enhance the value of acquired information and reduce uncertainty over its accuracy.

Literature Cited

[BLM] U.S. Department of the Interior, Bureau of Land Management. 2014. Draft Environmental Assessment DOI-BLM-ID-B010-2011-0060-EA: Paradigm Fuel Break Project. Boise BLM District, Four Rivers Office, 3948 Development Avenue, Boise, ID 83705. 115 pp.

Gray, E. C., and P. S. Muir. 2013. Does Kochia prostrata spread from seeded sites? An evaluation from southwestern Idaho, USA. Rangeland Ecology & Management 66:191-203.

Kinter, C. L., D. L. Clay, J. R. Fulkerson, and J. J. Miller. 2012. Habitat Integrity and Population Monitoring of *Lepidium papilliferum* (Slickspot Peppergrass): 2011. Idaho Natural Heritage Program, Idaho Department of Fish and Game, Boise, ID. 61 pp.

Krebs, C. J. 1999. Ecological Methodology, Second Edition. Addison Wesley Longman, Inc., Menlo Park, CA. 620 pp.

R Core Team. 2102. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. www.R-project.org.

Appendix: evaluation of spread monitoring methods

In vegetation monitoring a standard method for measuring the density of plants of interest is to either count or estimate, by various procedures, the number of plants within a small defined space (often 1 m^2 or ½ m^2) at regular intervals along a transect. This is an ideal method for estimating densities in plant communities that are expected to have similar characteristics across the measured area. However, this method is not ideal when attempting to measure plant communities that have not reached relative equilibrium, and may be especially problematic when estimating density for plant species that are actively spreading. We believe that the point-quarter-density estimation methods we outlined in this report are superior to other commonly used density estimation procedures when measuring directional spread of a particular plant species. Of note, when searching in a 5m radius from a central point using our methods a worker covers 78.5 m^2 of area per point along a transect instead of only 1 m^2 using standard methods. Given the estimation procedure we outlined, and observations from this study, this much larger area can often be searched in under two minutes per point along a given transect. This is comparable or well under the amount of time that it takes to estimate density using standard methods, depending on the specific estimation procedures used. However, it is an open question as to how many transects are needed, or at what intervals transects need to be sampled, to determine the distance of spread for a given location.

To help answer this question we compared our full dataset to several reduced datasets to determine whether sparser sampling strategies that require less effort can still yield informative results. Specifically, we took three data reduction steps that each correspond to a progressively sparser sampling strategy:

1) Reduction 1: we reduced the data by removing every other point along each transect to mimic sampling every 10m instead of every 5m but otherwise maintaining our outlined sampling structure.

2) Reduction 2: we maintained the 10m sampling of the previous reduction, and also removed two out of the five transects to mimic measuring only the center and outer edges of a given plot.

3) Reduction 3: we maintained the 10m sampling of the previous reductions, but only used the center transect to mimic measuring a single transect for a given plot.

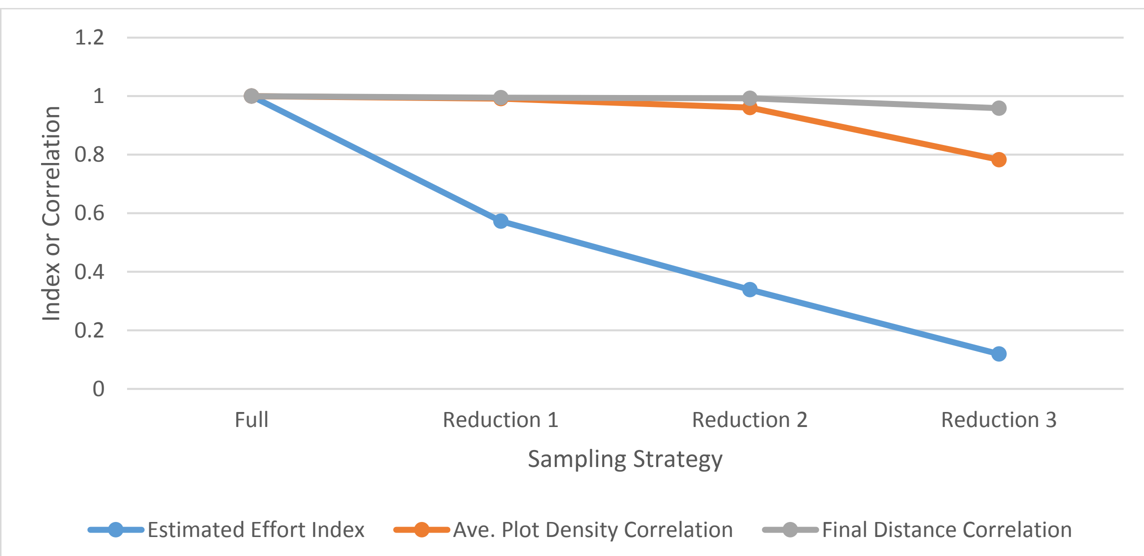
We then compared these reduced strategies to our full dataset by calculating the correlation for the average plot density ($plant/m^2$) of each reduced dataset to the full dataset, and the correlation of the average distance at which the last density of over 1 $plant/m^2$ was measured for each reduced dataset to the full dataset. Under the assumption that the full dataset is closer to the true density that exists on the landscape, a high correlation between the reduced datasets and the full dataset would mean that the reduced datasets are also capturing existing patterns. We also estimated an effort index by calculating the proportion of effort that each reduced dataset would take in comparison to the full dataset. This was done by assuming that each transect would require ten minutes of set up time and that each measurement along a given transect would take two minutes. So, to estimate the amount of time per plot would be:

# of transects per plot (2 minutes (# of sample points along transect) + 10 minutes)

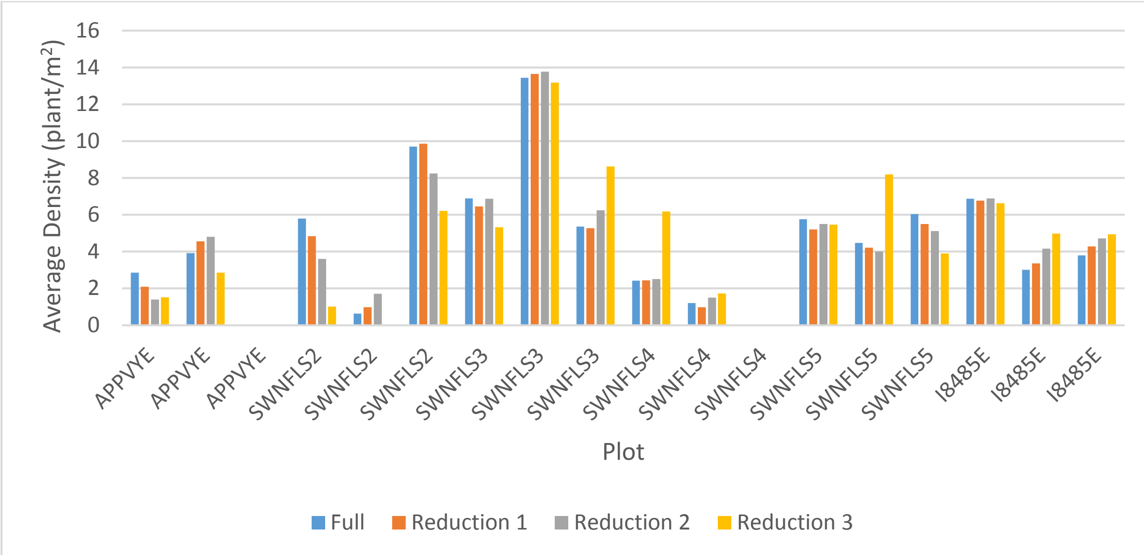
It should be noted that while estimated time intervals were based on observations in the field, they are not intended to perfectly capture the amount of time each transect or plot would take, but rather to provide a framework to estimate the relative effort required for each sampling strategy. The time estimate per plot was then averaged across all sites. The full dataset was given an effort index value of one and the reduced datasets were given an effort index value that was proportional to the full dataset.

The correlations between the full dataset and the reduced datasets were generally very high, with only one correlation (average plot density for the dataset reduction 3) being less than 0.95 (Appendix Figure 1). This indicates that the reduced datasets generally captured existing density patterns. The largest reduction in estimated effort occurred between the full dataset and dataset reduction 1, but the estimated effort index continued to drop substantially for each data reduction (Appendix Figure 1). While the correlations for both average plot density and average distance at which the last density of over 1 plant/m^2 was found were high across all data reductions, the plot-level difference between various dataset reductions and the full dataset varied depending on the specific reductions. Of note, the largest plot-level differences can be seen with dataset reduction 3, and the least with dataset reduction 1 (Appendix Figures 2 and 3).

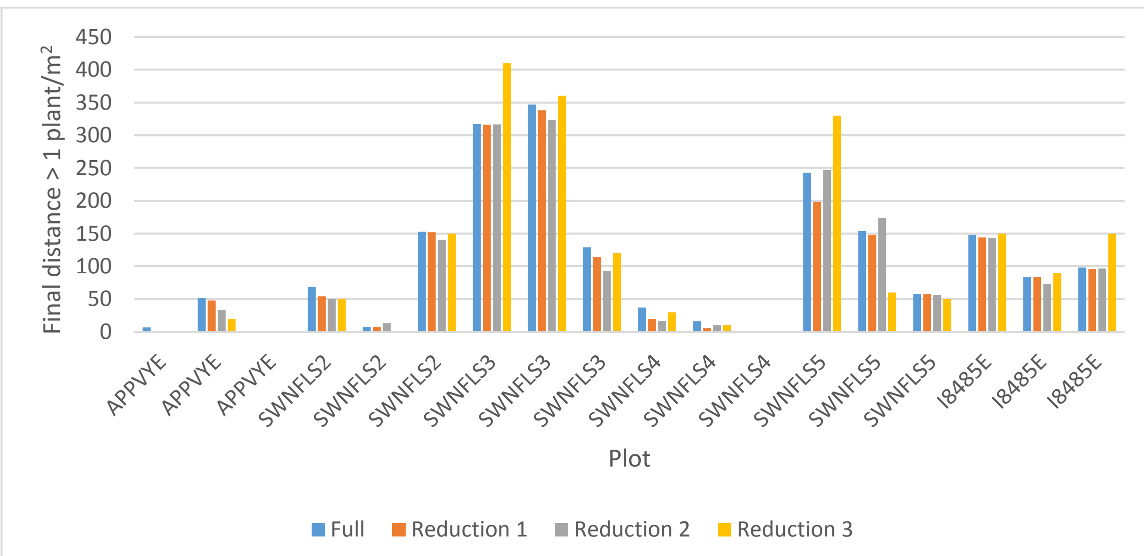
This method evaluation indicates that the full point-quarter-density estimation method that we used is robust, and that reduced sampling would still be able to capture existing spread densities well, even with much sparser sampling than the full method. Importantly, the rate at which data quality was lost (as indicated by the measurement correlations) was much slower than the rate at which effort was reduced, suggesting that this sampling method could be used with minimal effort and still generate relatively accurate results. When trying to understand how and when kochia might be spreading from seedings it may be more important to get information from many sites, rather than maximize data quality at a few sites, and given our findings even rapid assessments can maintain high data quality. This indicates that the method we outlined would be useful for monitoring existing and future kochia seedings to determine spread rates and quickly find seedings which may be spreading rapidly and/or nearing slickspot populations.



Appendix Figure 1. Comparison of the correlations for two measurements (average plot density and final distance) between the full point-quarter-density estimation method (see methods in the main body of this report) and three reduced datasets (see methods in this appendix), and an estimated effort index for each method.



Appendix Figure 2. Plot-level measurements of average kochia density (plant/m^2) by site for the full point-quarter-density estimation method (see methods in the main body of this report) and three reduced datasets (see methods in this appendix).



Appendix Figure 3. Plot-level measurements of final distance at which a density of greater than 1 plant/m^2 was found for the full point-quarter-density estimation method (see methods in the main body of this report) and three reduced datasets (see methods in this appendix).