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Chapter 10: Occurrence of Non-Native Invasive Plants: The Role of Anthropogenic Features

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Abstract. The invasion of non-native plants in the Wyoming Basins Ecoregional Assessment (WBEA) area is a major economic and ecological stress, with invasions thought to be hastened by energy developments. Given the potential impacts of non-native invasive plants and the rapid changes in land use in the WBEA, broad-scale assessments and predictive models of non-native invasive plant distribution are needed. Using this information, the current extent of populations for targeting treatment and monitoring can be identified, the habitat affinities for forecasting where weeds may establish next determined, and the responses to individual human disturbances (such as energy developments) predicted. To address these needs, we conducted vegetation surveys across the WBEA area at 317 individual survey blocks (five plots per survey block) during the summers of 2005 and 2006. Survey blocks were stratified by both human disturbance and habitat productivity; in each of five plots per survey block the occurrence of 23 common non-native invasive plants was recorded during early and late season surveys. Here, we report on the four most common invasive plants, crested wheatgrass (*Agropyron cristatum*), cheatgrass (*Bromus tectorum*), halogeton (*Halogeton glomeratus*), and Russian thistle (*Salsola* spp.). Occurrence models were generated for each species using random-effects logistic regression to account for nesting of plots within sample sites. Predictors of occupancy included local habitat, abiotic condition, and distance to anthropogenic features. Although occurrences of all four invasive plants were affected by habitat, abiotic, and anthropogenic factors, cheatgrass and Russian thistle were most strongly associated with anthropogenic disturbance, primarily major roads and energy well sites. We assessed relationships between environmental and anthropogenic predictors and species occurrences to identify the major factors affecting current species distribution, examined shape of the response in occurrence in relation to proximity to individual anthropogenic disturbances, and provided spatial predictions of the locations where invasive plants are most likely to occur.

Key words: cheatgrass, crested wheatgrass, energy development, exotic species, halogeton, occurrence, Russian thistle, sagebrush, species distribution, Wyoming.

Energy developments in Colorado, Montana, Utah, and especially Wyoming are largely associated with the sagebrush (*Artemisia* ssp.) ecosystem, a common interior western United States vegetation type named for the dominant shrub species, big sagebrush (*A. tridentata*). Many wildlife species, including pygmy rabbit (*Brachylagus idahoensis*) and greater sage-grouse (*Centrocercus urophasianus*), depend on sagebrush (Green and Flinders 1980, Connelly et al. 2011) and are threatened by the loss and fragmentation of sagebrush habitat (Connelly et al. 2000, Hanser and Huntly 2006, Walker et al. 2007, Aldridge et al. 2008, Doherty et al. 2008). Linear access and transmission corridors associated with energy development also provide preferred habitat and migration corridors for non-native invasive plant species (Bergquist et al. 2007).

In fact, roads and vehicle traffic now provide one of the most effective conduits for non-native plant dispersal, with transport of seed or plant parts on tires/mud and movement of seed through vehicle-related air turbulence being common (Gelbard and Belnap 2003, Davies and Sheley 2007, von der Lippe and Kowarik 2007). As example, in three road tunnels in Berlin, Germany, seed rain due to vehicle transport represented 12.5% of the total flora (197 of 1,606 species; 50% of which were exotics), demonstrating the significance of vehicle-mediated dispersal of plants (von der Lippe and Kowarik 2007). As a consequence of increased plant dispersal, as well as the disturbed nature of road edges, road right-of-ways are often dominated by non-native invasive plants threatening adjacent native habitats (Parendes and Jones 2000, Gelbard and Belnap 2003). With 20% of the continental United States within 127 m of a road and 83% within 1,061 m of a road (Riitters and Wickham 2003), the majority of U.S. lands are threatened by non-native invasive plants. In fact, invasive weeds are estimated to occupy 188,000 km^2 and have an annual spread rate of 8-12% on U.S. federal lands (U.S. Government Accountability Office 2005).

As non-native invasive plants spread into native habitats, they alter ecosystem function (Brooks et al. 2004), with the sagebrush ecosystem being particularly sensitive. Cheatgrass (*Bromus tectorum*) invasions of sagebrush habitats have resulted in dramatic reductions in fire return intervals from historic intervals of 30 to 100 years, or even much longer (centuries), to less than five years following cheatgrass invasion (Whisenant 1990, Baker 2006). At this fire frequency, the defining structural element of the ecosystem – sagebrush – is lost and replaced instead by annual grasses, predominately cheatgrass (Mack 1981, Whisenant 1990, Brooks et al. 2004, Baker 2006). Not surprisingly, the loss of this sagebrush structure and food resource results in cascading losses to sagebrush-obligate species (Knick et al. 2003, Knick et al. 2008).

In addition to major ecological changes, non-native invasive species also cause significant economic damage. Pimentel et al. (2005) estimated that invasive species result in annual economic damages of $138 billion, with $5 billion spent annually on invasive species control and annual forage loss on pastures estimated at $1 billion. Because energy developments are the major source of new roads and, more generally, surface disturbances favored by invasive plants within the sagebrush ecosystem, it is not surprising that energy developments in the sagebrush ecosystem are a major concern for western ranchers, with losses in forage occurring both through direct disturbance (loss of range) or indirectly through invasion by non-native plants into pastures adjacent to energy developments.

Despite these threats, there is no regionally consistent source of information describing where non-native invasive species are most likely to occur across the Wyoming Basins Ecoregional Assessment (WBEA) area or how environmental factors and/or types of human disturbance, such as energy developments, hasten invasions by non-native plants in the sagebrush ecosystem. Understanding these relationships and mapping these threats will inform management of invasive plants in the WBEA area and thus improve our ability to maintain the economic and ecological health of sagebrush ecosystem. Our objectives were two-fold: (1) evaluate the effects of environmental conditions (e.g., habitats and abiotic factors [e.g., climate, topography, and soils]) and anthropogenic stressors on the presence-absence of non-native invasive plants measured at field sites across the WBEA; and (2) to predict (map) probable habitat (occurrence) for non-native invasive plants across the WBEA area to assist with land use planning, decision-making, and prioritization of management actions. For this assessment we chose the following four invasive plant species because they were common throughout the WBEA area: (1) crested wheatgrass (*Agropyron cristatum*), (2) cheatgrass, (3) halogeton (*Halogeton glomeratus*), and (4) Russian thistle (*Salsola* spp.).

METHODS

Field Surveys

Vegetation sampling was completed in 2005 and 2006 at 317 survey blocks located across the WBEA area (Ch. 4). Survey blocks measured 270 m by 270 m (7.29 ha) with five 20-m radius (1,257 m^2) plots systematically located in the survey block at 45º, 135º, 225º, and 315º angles and at a 127.3-m distance from the survey block center resulting in 1,585 total plots. Each survey block was visited twice within a season (1 June – 2 July and 6 July – 2 September) in order to capture the phenology of plants and to reduce observer bias (observers were switched between sampling sessions).

Shrub, grass (non-native and native), and forb (non-native and native) cover was estimated using an ordinal rank scheme: 1 = ≤1%; 2 = 2–5%; 3 = 6–10%; 4 = 11–25%; 5 = 26–50%; 6 = 51–75%; and 7 = 76–100% (modified from Daubenmire 1959). In addition to shrub cover by species, the following estimates were measured in each plot: (1) live shrub canopy cover (total canopy cover of all shrub species combined); (2) dead shrub canopy cover (total, includes the dead portions of live shrubs and cover of shrubs that were 100% dead); (3) bare ground (including rocks, but not rocky outcrops); (4) litter, defined as dead biotic material on the ground (did not include standing dead shrub material, but included vegetation such as dead mats of phlox [*Phlox* spp.], dead grasses, etc.); (5) rocky outcrop (rocky structures projecting above the ground surface or large fields of boulders or very rocky areas [measured in five height classes: 0–10 cm, >10–25 cm, >25–50 cm, >50–75 cm, and >75 cm]); (6) native forb cover (total for all species combined, includes any native forbs for which cover was recorded separately in previous sampling); (7) non-native forb cover (includes any non-native forbs on our list [Appendix 4.3] and non-native plants not on our list); (8) native grass cover (includes any native grasses for which cover was recorded separately in previous sampling); and (9) non-native grass cover (includes non-native grasses on our list and others not on the list [Appendix 4.3]). We also estimated percent cover for 20 target non-native invasive plant species (Appendix 4.3). Non-native invasive target species were selected based on discussions with staff from U.S. Bureau of Land Management (BLM) Field Offices throughout the study area, the Wyoming BLM State Invasive Weed Coordinator, our prior field experience, current state lists of invasive or noxious plants, and several publications that describe invasive plants in the sagebrush ecosystem or arid rangelands of the western U.S. (e.g., Pyke 2000).

Shrub height (live and dead) was measured at four cardinal directions along the periphery of each circle and at the center of each vegetation plot. For each measurement location, the height of the nearest live or dead shrub was measured within a 2-m circle (five vegetation plots per survey block, total height measurements per survey block = 25). Those sites containing no shrubs received a zero height score.

For tree species, the number of trees was counted according to four height classes: <1 m, >1–5 m, >5–8 m, and >8 m. For juniper (*Juniperus* spp.), we also assigned successional classes: (1) pre-settlement = old trees, (2) mixed = old and young trees, and (3) post-settlement = young trees.

We assessed plant community dominance within plots by ranking dominant species by class. Dominance was based on the percent canopy among all species present in the plot within that class (e.g., native forb, shrub). We recorded the name of the dominant shrub, native grass, native forb, exotic grass, and non-native forb, by species, for each plot. If no individual species was clearly dominant for that class of vegetation, we recorded the two co-dominant species. If dominants or co-dominants were not apparent, we noted that fact and did not assign a dominance rank to any species. A dominant native forb was listed only if cover exceeded 5%. Here we report on the occurrence of the four most common non-native invasive species – cheatgrass, crested wheatgrass, halogeton, and Russian thistle – encountered within the plots over the two seasonal periods (seasonal observations were combined).

Environmental and Anthropogenic Predictors of Invasive Plant Occurrence

To predict non-native invasive plant occurrence and to evaluate the responses of species to environmental and anthropogenic features, we used field plot measures of non-native invasive plant occurrence and a suite of common Geographic Information Systems (GIS) predictor variables consisting of vegetation productivity, distance to anthropogenic features, and abiotic environments (e.g., terrain-derived variables, soil characteristics, and climate). Unlike prior work in this volume, vegetation characteristics measured in field plots were used rather than from remote sensing products because direct measures of vegetation cover were made at the scale relevant to the plants being assessed. To thematically link these field measures to spatial data, we used the collected vegetation characteristics to classify each plot to the appropriate ecological system (Comer et al. 2003), the classification system used in the LANDFIRE existing vegetation type (LANDFIRE 2007) spatial dataset, and we applied the crosswalk used to reclassify the spatial data (Appendix 1.1) to label plots as either sagebrush or non-sagebrush. Vegetation productivity was measured as the maximum Normalized Difference Vegetation Index (NDVI) for the growing season (May through August) using Moderate Resolution Imaging Spectroradiometer (MODIS) satellite imagery (Carroll et al. 2006). Distances from anthropogenic disturbances were measured in a GIS for 10 feature types that included: agriculture (AG), communication towers (TOWER), oil-gas wells as of August 2005 (WELL), pipelines (PIPE), power lines (POWER), populated areas defined in year 2005 (POP), railroads (RAIL), secondary roads (2RD), major roads (MjRD), and all road types (RD). Both Euclidian distance and distance decay functions were used. Distance decay functions ($e^{\text{(Euclidean distance from feature (km)/-distance parameter)}}$) with the distance parameter set at 0.05, 0.25, 0.5, 1, and 5 km (Nielsen et al. 2009) allowed for nonlinear responses of species to distance from anthropogenic features. Several terrain-derived variables were generated from a 90-m digital elevation model (DEM) including growing season (May to August) global solar radiation (SOLR, Area Solar Radiation Analysis, ESRI 2006), topographic relative moisture index (TRMI, Manis et al. 2001), and topographic ruggedness index (TRI, Riley et al. 1999).

We used the conterminous United States multilayer soil characteristics dataset (Miller and White 1998) to characterize soil information including: soil depth ($SOIL_{cm}$), available water content (AWC), salinity (SALIN), and percentages of sand (SAND) and clay (CLAY). Distance from perennial (pH2Od) water sources were estimated in a GIS from hydrological features and were also transformed into negative exponential decays using the same distance parameters used for the anthropogenic disturbance variables. Finally, mean annual minimum temperature (Tmin) was estimated from Parameter-elevation Regressions on Independent Slopes Model (PRISM) (PRISM Group 2007).

Species Occurrence Modeling

Because plots were nested within survey blocks, we used a random-effects logistic regression model (survey block was used as a random effect to account for non-independence of plots) using the XTLOGIT command in STATA 10.1 (Stata Corporation, College Station, TX) to estimate the probability of occurrence for each of the four non-native invasive plant species. Predictors included local habitat, abiotic, and anthropogenic factors. Because we lacked knowledge about specific responses of species to anthropogenic disturbances, as well as appropriate extents for assessing habitat conditions, we refrained from using an *a priori* model building and assessment approach (Burnham and Anderson 2002). Instead, we modeled species occurrences using a multi-stage hierarchical design reflecting the three major groupings of factors influencing occupancy of our four selected invasive plants: habitat effects (sagebrush and NDVI), abiotic effects (climate, soils, and terrain), and human disturbance effects (roads, railroads, well-pads, etc.). Sub-models were developed individually for each major group and combined into a final composite model by assessing all possible combinations of variables chosen in sub-models and ranking models using Akaike's Information Criterion (AIC) to penalize for complexity.

First, to account for the fact that two habitat variables were originally used for stratification of survey blocks, a single 'base' model was selected using AIC from models containing either sagebrush, NDVI (including a quadratic term), or sagebrush and NDVI variables (note that interaction terms were not assessed due to difficultly in interpretation). The top ranked base model then was carried forward for inclusion in each of the three sub-models and the final composite model. Total number of model variables considered for each species was limited to a ratio of one variable per ten occurrences (e.g., 10 variables if found in 100 plots). To determine which factors to include within each sub-model, univariate models (including hypothesized quadratic terms) were fit for all variables and multicollinearity among variables assessed using Spearman rank (Rho) correlations. The final model was selected from the set of composite models based on all combinations of the sagebrush-NDVI base model and the variables from the AIC-best abiotic and anthropogenic disturbance sub-models. To incorporate model uncertainty, weighted-average coefficients (Burnham and Anderson 2002) were estimated from top-ranked composite models having a cumulative AIC weight (w_i) of just ≥ 0.9. Coefficients were set to zero when a model did not contain a particular variable. Model accuracy was assessed using a receiver operating characteristic (ROC) area under the curve (AUC) estimate (Metz 1978).

Model Predictions

We predicted species occurrence using the final model coefficients in our GIS at a 90-m cell size (0.81 ha) using ArcGIS 9.3 raster calculator (ESRI 2006) and displayed final model predictions in 10% probability classes. When sagebrush was a variable in the final model, the all sagebrush (*Artemisia* spp.; ALLSAGE) spatial dataset (Ch. 4) was used as a substitute for the field-derived sagebrush variable to facilitate spatial extrapolation of the statistical model. To prevent predictions in high-elevation conifer forests or alpine vegetation where we did not sample (study design was focused on sagebrush vegetation) and would not expect similar responses, we masked areas having <3% of the landscape dominated by sagebrush vegetation within a 5-km radius moving window. To examine responses in occurrence to selected anthropogenic disturbances, we calculated the mean predicted species occurrence by distance classes using the Dose Response Calculator for ArcGIS (Hanser et al. 2011) and interpreted this as a dose-response function. We also estimated risk ratios using mean map predictions at or adjacent to an anthropogenic disturbance in comparison to distant locations for exponential decay distance variables (risk ratios = p_{0m}/p_{far}) or a 1-km distance for Euclidean distance variables (risk ratios = p_{0m}/p_{1km}).

TABLE 10.1. Summary of invasive plant detections in the Wyoming Basins Ecoregional Assessment area at the plot sample level within survey blocks stratified to on-road, near-road, or far-road classes. Number of occurrences reported by species and frequency of detection in parentheses. Total plots per stratum reported under stratum name. Refer to Appendix 4.3 for a list of sampled species.

Common name	Scientific name	On-road (n = 590)	Near-road (n = 510)	Far-road (n = 485)	Total (n = 1,585)
Russian knapweed	*Acroptilon repens*	0 (0%)	1 (0.2%)	0 (0%)	1 (0.1%)
Crested wheatgrass	*Agropyron cristatum*	39 (7.6%)	30 (5.1%)	14 (2.9%)	83 (5.2%)
Cheatgrass	*Bromus tectorum*	76 (14.9%)	80 (13.6%)	58 (12%)	214 (13.5%)
Whitetop	*Cardaria draba*	0 (0%)	0 (0%)	1 (0.2%)	1 (0.1%)
Curveseed bitterwort	*Ceratocephala testiculata*	9 (1.8%)	5 (0.8%)	0 (0%)	14 (0.9%)
Canada thistle	*Cirsium arvense*	13 (2.5%)	1 (0.2%)	7 (1.4%)	21 (1.3%)
Halogeton	*Halogeton glomeratus*	51 (10%)	51 (8.6%)	28 (5.8%)	130 (8.2%)
Perennial pepperweed	*Lepidium latifolium*	1 (0.2%)	0 (0%)	0 (0%)	1 (0.1%)
Russian thistle	*Salsola* spp.	40 (7.8%)	37 (6.3%)	8 (1.6%)	85 (5.4%)
Tumble mustard	*Sisymbrium altissimum*	4 (0.8%)	10 (1.7%)	1 (0.2%)	15 (0.9%)
Tamarisk	*Tamarix ramosissima*	1 (0.2%)	0 (0%)	1 (0.2%)	2 (0.1%)

RESULTS

Crested Wheatgrass

Crested wheatgrass was found at 5.2% of sampled plots (n = 83), with frequency of occurrence highest in the on-road stratum at 6.6% of sites (Table 10.1). Of the two top-supported AIC models (ΔAIC $\leq$ 2), crested wheatgrass was explained by one survey design habitat variable, three abiotic factors, and four anthropogenic factors (Table 10.2). For the habitat-based survey design factor, crested wheatgrass was more likely to occur in areas of intermediate vegetation productivity as measured by NDVI (Table 10.2). For abiotic factors, crested wheatgrass occurrence was more likely in areas of less rugged terrain (TRI) and in soils with either moderate amounts of clay (CLAY) or high salinity levels (SALIN) (Table 10.2). Finally, anthropogenic predictors of crested wheatgrass included areas near major roads with a 1-km distance parameter ($MjRD_{1km}$), local areas around energy wells with a 0.05-km distance parameter ($WELL_{50}$), and near populated places (POP_d) or agricultural (AG_d) areas (Table 10.2). Although only two models were most supported (ΔAIC $\leq$ 2), a total of 20 candidate models were used to derive model-averaged coefficients predicting the probability of crested wheatgrass occurrence using summed AIC weights (w_i) of just $\geq$ 0.9 (Table 10.3). The final composite crested wheatgrass occurrence model had a ROC AUC value of 0.88 (SE = 0.01), suggesting very good predictive accuracy.

Crested wheatgrass was predicted to occur along major road corridors and around energy wells throughout the WBEA area (Figure 10.1). Although occurrence of crested wheatgrass was reduced in areas of more rugged terrain, anthropogenic factors were the most important predictor of crested wheatgrass occurrence, with individual roads and energy wells easily observed as hot spots on the distribution map. Based on mean predicted occur-

TABLE 10.2. Log-likelihood (LL), number of parameters (K), Akaike's Information Criterion (AIC), change in AIC value from the top model (ΔAIC), and Akaike weight (w_i) of (A) crested wheatgrass, (B) cheatgrass, (C) halogeton, and (D) Russian thistle random-effects logistic regression models of species occurrence in the Wyoming Basins Ecoregional Assessment area. Only models with ΔAIC ≤ 2 are shown.

Species – Model[a]	LL	K	AIC	ΔAIC	w_i
A. Crested wheatgrass (*Agropyron cristatum*)					
$NDVI + NDVI^2 + TRI + CLAY + CLAY^2 + MjRD_{1km} + WELL_{50} + POP_d$	-203.25	10	426.50	0.00	0.222
$NDVI + NDVI^2 + TRI + SALIN + MjRD_{1km} + WELL_{50} + AG_d + POP_d$	-203.99	10	427.98	1.47	0.106
B. Cheatgrass (*Bromus tectorum*)					
$NDVI + NDVI^2 + SOLR + SOLR^2 + Tmin + Tmin^2 + TRMI + TRMI^2 + MjRD_{50} + WELL_{50}$	-319.79	12	663.57	0.00	0.349
$NDVI + NDVI^2 + SOLR + SOLR^2 + Tmin + Tmin^2 + TRMI + TRMI^2 + MjRD_{50} + WELL_{50} + RAIL_d$	-319.42	13	664.85	1.27	0.185
$NDVI + NDVI^2 + SOLR + SOLR^2 + Tmin + Tmin^2 + TRMI + TRMI^2 + MjRD_{50} + WELL_{50} + POP_{1km}$	-319.62	13	665.25	1.67	0.151
C. Halogeton (*Halogeton glomeratus*)					
$SAGE + NDVI + SOLR + SOLR^2 + Tmin + Tmin^2 + SALIN + SALIN^2 + AWC + AWC^2 + RAIL_d + TOWER_{500} + POWER_{50} + AGd + WELL_{50} + RD_{1km}$	-247.53	15	531.05	0.00	0.068
$SAGE + NDVI + SOLR + SOLR^2 + Tmin + Tmin^2 + SALIN + SALIN^2 + AWC + AWC^2 + RAIL_d + TOWER_{500} + POWER_{50} + WELL_{50} + RD_{1km}$	-248.57	14	531.14	0.09	0.065
$SAGE + NDVI + SOLR + SOLR^2 + Tmin + Tmin^2 + SAND + SAND^2 + SALIN + SALIN^2 + AWC + AWC^2 + SOIL_{cm} + RAIL_d + TOWER_{500} + POWER_{50} + AG_d + WELL_{50} + RD_{1km}$	-244.87	18	531.74	0.69	0.048
$SAGE + NDVI + SOLR + SOLR^2 + Tmin + Tmin^2 + SAND + SAND^2 + SALIN + SALIN^2 + AWC + AWC^2 + RAIL_d + TOWER_{500} + POWER_{50} + AG_d + WELL_{50} + RD_{1km}$	-246.21	17	532.42	1.37	0.034
$SAGE + NDVI + SOLR + SOLR^2 + Tmin + Tmin^2 + SAND + SAND^2 + SALIN + SALIN^2 + AWC + AWC^2 + SOIL_{cm} + RAIL_d + TOWER_{500} + POWER_{50} + WELL_{50} + RD_{1km}$	-246.23	17	532.45	1.40	0.034
$SAGE + NDVI + SOLR + SOLR^2 + Tmin + Tmin^2 + SAND + SAND^2 + SALIN + SALIN^2 + AWC + AWC^2 + SOILc_m + RAIL_d + TOWER_{500} + POWER_{50} + WELL_{50} + RD_{1km}$	-246.23	17	532.45	1.40	0.034
$SAGE + NDVI + SOLR + SOLR^2 + Tmin + Tmin^2 + SAND + SAND^2 + SALIN + SALIN^2 + AWC + AWC^2 + SOIL_{cm} + TOWER_{500} + POWER_{50} + AG_d + WELL_{50} + RD_{1km}$	-246.35	17	532.69	1.64	0.030
$SAGE + NDVI + SOLR + SOLR^2 + Tmin + Tmin^2 + SALIN + SALIN^2 + AWC + AWC^2 + SOIL_{cm} + RAIL_d + TOWER_{500} + POWER_{50} + AG_d + WELL_{50} + RD_{1km}$	-247.36	16	532.71	1.66	0.030
$SAGE + NDVI + SOLR + SOLR^2 + Tmin + Tmin^2 + SAND + SAND^2 + AWC + AWC^2 + SOIL_{cm} + RAIL_d + TOWER_{500} + POWER_{50} + WELL_{50} + RD1km$	-248.40	15	532.81	1.76	0.028

TABLE 10.2. Continued

Species – Model[a]	LL	K	AIC	ΔAIC	w_i
SAGE + NDVI + SOLR + SOLR^2 + Tmin + Tmin^2 + SALIN + SALIN^2 + AWC + AWC^2 + SOIL$_{cm}$ + RAIL$_d$ + TOWER$_{500}$ + POWER$_{50}$ + WELL$_{50}$ + RD$_{1km}$	-248.41	15	532.82	1.77	0.028
SAGE + NDVI + SOLR + SOLR^2 + Tmin + Tmin^2 + SALIN + SALIN^2 + AWC + AWC^2 + TOWER$_{500}$ + POWER$_{50}$ + AG$_d$ + WELL$_{50}$ + RD$_{1km}$	-249.41	14	532.82	1.77	0.028
SAGE + NDVI + SOLR + SOLR^2 + Tmin + Tmin^2 + SAND + SAND^2 + SALIN + SALIN^2 + AWC + AWC^2 + RAIL$_d$ + TOWER$_{500}$ + POWER$_{50}$ + WELL$_{50}$ + RD$_{1km}$	-247.47	16	532.94	1.89	0.026
SAGE + NDVI + SOLR + SOLR2 + Tmin + Tmin^2 + SAND + SAND2 + AWC + AWC2 + SOILcm + RAIL$_d$ + TOWER500 + POWER50 + AG$_d$ + WELL50 + RD1km	-247.50	16	533.00	1.95	0.026
D. Russian thistle (*Salsola* spp.)					
NDVI + NDVI^2 + SOLR + pH2Od$_{1km}$ + POP$_d$ + 2RD$_{250}$ + WELL$_{1km}$ + MjRD$_{500}$	-211.33	10	442.67	0.00	0.462

[a] See Appendix 10.1 for variable definitions

rences of crested wheatgrass by distance classes, crested wheatgrass was predicted to occur, on average (threshold probability predicting occurrence at 0.05), when within 270 m of energy wells, 825 m of major roads, 2.5 km of railroads, 1.6 km of populated places (Figure 10.2), and 100 m of agriculture. Associations of crested wheatgrass were strongest for major roads and energy wells with mean probabilities of occurrence adjacent to major roads at 0.33 and for energy wells at 1.0 (Figure 10.2). Railroads also showed associations with mean probabilities of occurrence adjacent to railroads at 0.23. When comparing mean probabilities of occurrence at sites closest to anthropogenic disturbances to sites furthest from those disturbances, risk ratios were estimated at 79.0 for major roads, 59.0 for energy wells, 19.0 for railroads, and 3.2 for populated places.

Cheatgrass

Cheatgrass occurred at 13.5% of sampled plots (n = 214), with frequency of occurrence highest in the near-road stratum at 15.7% of plots (Table 10.1). Of the three top-supported AIC models (ΔAIC < 2), cheatgrass occurrence was explained by one survey design habitat variable, three abiotic factors, and four anthropogenic factors (Table 10.2). For the habitat-based survey design factor, cheatgrass occurrence was more likely in areas of intermediate vegetation productivity (NDVI) (Table 10.2). For abiotic factors, cheatgrass occurrence was more likely in areas of intermediate summertime solar radiation (SOLR), areas of warmer minimum temperatures (Tmin), and showed non-linear responses to topographic-related moisture (TRMI) (Table 10.2). Anthropogenic predictors of cheatgrass included areas very close to major roads or energy wells with a distance parameter of 50 m for both disturbances (MjRD$_{50}$ and WELL$_{50}$), areas near populated places with a 1-km distance parameter (POP$_{1km}$), and areas near railroads (RAIL$_d$) (Table 10.2). Although three models were most supported (ΔAIC $\leq$ 2), a total of six candidate models were used to derive model-averaged coefficients predicting the probability of cheatgrass occurrence using summed AIC weights (w_i) of just $\geq$ 0.9 (Table 10.4). The final composite cheatgrass occurrence model had a ROC AUC value of 0.91 (SE = 0.01), suggesting excellent predictive accuracy.

Cheatgrass was predicted to be prevalent throughout the Wind River/Bighorn Basin in Wyoming, the far northern parts of the Wyoming Basins in Montana, the area southeast of the Uintas Mountains in eastern Utah and along the Colorado border, and the southwestern and eastern boundaries of the Wyoming Basins (Figure 10.3). Distribution patterns of cheatgrass appear to be driven mainly by abiotic limitations, although anthropogenic disturbances increase local patterns of cheatgrass occupancy (Figure 10.4). Associations of cheatgrass were strongest for major roads and energy wells, with mean probabilities of occurrence adjacent to major roads at 0.71 and for energy wells at 1.0 (Figure 10.4). When comparing mean probabilities of occurrence at sites closest to anthropogenic disturbances to sites furthest from those disturbances, risk ratios for major roads and energy wells were estimated at 3.0 and 4.1 respectively.

Halogeton

Halogeton occurred at 8.2% of sampled plots (n = 130), with frequency of occurrence highest in the near-road stratum at 10.0% of plots (Table 10.1). Support was high (ΔAIC $\leq$ 2) for 13 halogeton models that contained two habitat-based survey design variables, six abiotic factors, and six anthropogenic disturbance factors (Table 10.2). The habitat-based survey design factors included both sagebrush habitat (SAGE) and vegetation productivity (NDVI), with halogeton positively associated with sagebrush and negatively associated with vegetation productivity (NDVI) (Table 10.2). For abiotic factors, halogeton responded in a non-linear manner to summertime solar radiation (SOLR) and positively related to minimum temperatures (Tmin) but negatively related to available soil water content (AWC) (Table 10.2). For anthropogenic effects, halogeton was predicted to occur in areas near railroads ($RAIL_d$), close to agriculture (AG_d), near transmission towers with a distance parameter of 0.5 km ($TOWER_{500}$), very close to power lines with a distance parameter of 0.05 km ($POWER_{50}$), very close to energy wells with a distance decay parameter of 0.05-km ($WELL_{50}$), and near roads with a distance parameter of 1 km (RD_{1km}) (Table 10.2). Although 13 models were most supported (ΔAIC $\leq$ 2), a total of 93 candidate models were used to derive model-averaged coefficients predicting the probability of halogeton occurrence with summed AIC weights (w_i) of just $\geq$ 0.9 (Table 10.5). The final composite halogeton occurrence model had a ROC AUC value of 0.91 (SE = 0.01), suggesting excellent predictive accuracy.

Similar to the distribution of cheatgrass, but at a reduced extent and lower probabilities, halogeton was predicted throughout the Wind River/Bighorn Basin in Wyoming, the far northern parts of the Wyoming Basins in Montana, and in the area southeast of the Uintas Mountains in eastern Utah and along the Colorado border (Figure 10.5). Like cheatgrass, abiotic factors appear to be particularly important in limiting the distribution of halogeton, but with additional anthropogenic effects increasing local occurrences of halogeton. Associations of halogeton with anthropogenic disturbances were strongest for transmission towers and energy wells with mean probabilities of occurrence adjacent to towers at 0.99 and for energy wells at 1.0 (Figure 10.6). When comparing mean probabilities of occurrence at sites closest to anthropogenic disturbances to those sites furthest from those disturbances, risk ratios were estimated at 6.6 for towers and 6.5 for energy wells.

TABLE 10.3. Crested wheatgrass random-effects logistic regression model[a] parameter estimates (beta [SE]), model log-likelihood (LL), number of parameters (K), Akaike's Information Criterion (AIC), change in AIC value from the top model (ΔAIC), and Akaike weight (w_i) for all candidate models in the Wyoming Basins Ecoregional Assessment area where Akaike weights sum to just ≥ 0.9. Superscript numbers reflect quadratic terms, while subscript numbers for anthropogenic and water variables represent the distance parameter value of the exponential distance decay function used to scale distance effects. Anthropogenic terms ending in the subscript letter "d" reflect Euclidian distance variables rather than distance decay functions.

Rank	Intercept	NDVI	$NDVI^2$	TRI	CLAY	$CLAY^2$	$MjRD_{1km}$	$WELL_{50}$
1	-3.68 (1.82)	9.77 (3.77)	-14.35 (6.96)	-0.08 (0.02)	0.16 (0.23)	-0.01 (0.01)	4.53 (0.97)	44.76 (14.66)
2	-4.00 (0.97)	5.59 (3.45)	-8.13 (5.98)	-0.08 (0.02)			4.18 (0.95)	47.82 (15.13)
3	-4.79 (1.00)	6.94 (3.47)	-9.46 (6.19)	-0.08 (0.03)			4.63 (1.00)	45.68 (15.32)
4	-4.53 (0.95)	7.21 (3.41)	-9.64 (6.13)	-0.08 (0.02)			4.41 (0.96)	45.95 (14.83)
5	-4.88 (1.03)	7.50 (3.45)	-9.61 (6.16)	-0.08 (0.02)			4.19 (0.98)	46.43 (14.87)
6	-4.57 (0.95)	7.45 (3.44)	-10.04 (6.20)	-0.08 (0.03)			4.41 (0.97)	45.72 (14.83)
7	-3.63 (0.95)	5.21 (3.57)	-8.38 (6.24)	-0.08 (0.02)			4.03 (1.00)	49.56 (15.85)
8	-3.35 (0.88)	4.60 (3.61)	-8.41 (6.33)	-0.08 (0.03)			4.62 (1.03)	48.35 (16.38)
9	-3.08 (0.84)	4.93 (3.56)	-8.67 (6.26)	-0.08 (0.03)			4.41 (0.99)	48.62 (15.86)
10	-5.47 (0.96)	6.19 (3.53)	-8.13 (6.28)	-0.08 (0.02)			3.84 (0.98)	50.01 (15.42)
11	-6.75 (1.89)	11.57 (3.93)	-15.02 (7.45)	-0.07 (0.03)	0.28 (0.24)	-0.01 (0.01)	4.31 (1.00)	46.39 (14.79)
12	-3.90 (0.86)	6.29 (3.57)	-10.02 (6.47)	-0.08 (0.03)			4.88 (1.06)	46.25 (16.04)
13	-3.64 (0.82)	6.67 (3.52)	-10.35 (6.42)	-0.08 (0.03)			4.67 (1.02)	46.65 (15.58)
14	-4.46 (1.00)	6.71 (3.61)	-9.92 (6.49)	-0.08 (0.03)			4.59 (1.06)	46.83 (16.01)
15	-3.14 (0.85)	5.21 (3.59)	-9.12 (6.33)	-0.08 (0.03)			4.41 (1.00)	48.39 (15.86)
16	-4.17 (0.96)	7.08 (3.56)	-10.26 (6.43)	-0.08 (0.03)			4.38 (1.03)	47.23 (15.55)
17	-5.08 (0.92)	5.29 (3.68)	-8.27 (6.59)	-0.07 (0.03)			4.20 (1.05)	50.60 (16.62)
18	-3.96 (0.87)	6.58 (3.60)	-10.5 (6.55)	-0.08 (0.03)			4.88 (1.06)	45.97 (16.02)
19	-4.79 (0.87)	5.60 (3.63)	-8.53 (6.53)	-0.08 (0.02)			3.98 (1.02)	50.88 (16.09)
20	-3.70 (0.82)	6.95 (3.55)	-10.81 (6.50)	-0.08 (0.03)			4.67 (1.02)	46.39 (15.56)

[a] See Appendix 10.1 for variable definitions
[b] Coefficients and standard errors multiplied by 10^3

TABLE 10.4. Cheatgrass random-effects logistic regression model[a] parameter estimates (beta [SE]), model log-likelihood (LL), number of parameters (K), Akaike's Information Criterion (AIC), change in AIC value from the top model (ΔAIC), and Akaike weight (w_i) for all candidate models in the Wyoming Basins Ecoregional Assessment area where Akaike weights sum to just ≥ 0.9. Superscript numbers reflect quadratic terms, while subscript numbers for anthropogenic and water variables represent the distance parameter value of the exponential distance decay function used to scale distance effects. Anthropogenic terms ending in the subscript letter "d" reflect Euclidian distance variables rather than distance decay functions.

Rank	Intercept	NDVI	$NDVI^2$	SOLR[b]	$SOLR^{2c}$	Tmin	$Tmin^2$	TRMI
1	-221.56 (123.88)	11.70 (2.68)	-12.71 (3.73)	0.59 (0.30)	-0.38 (0.18)	1.94 (0.48)	0.17 (0.07)	-0.27 (0.15)
2	-223.75 (124.01)	11.62 (2.69)	-13.11 (3.85)	0.59 (0.30)	-0.38 (0.18)	1.97 (0.49)	0.18 (0.07)	-0.26 (0.16)
3	-240.86 (125.62)	11.56 (2.69)	-12.77 (3.86)	0.63 (0.31)	-0.41 (0.19)	2.05 (0.50)	0.20 (0.07)	-0.26 (0.16)
4	-236.95 (125.35)	11.66 (2.68)	-12.35 (3.75)	0.62 (0.31)	-0.41 (0.19)	2.00 (0.50)	0.19 (0.07)	-0.27 (0.15)
5	-235.27 (122.90)	11.57 (2.59)	-12.07 (3.56)	0.62 (0.30)	-0.40 (0.18)	1.82 (0.46)	0.16 (0.07)	
6	-250.02 (124.28)	11.54 (2.59)	-11.71 (3.58)	0.65 (0.30)	-0.42 (0.18)	1.88 (0.47)	0.17 (0.07)	

[a] See Appendix 10.1 for variable definitions
[b] Coefficients and standard errors multiplied by 10^3
[c] Coefficients and standard errors multiplied by 10^9

TABLE 10.3. Extended

POP_d[b]	SALIN	2RD_{50}	RAIL_{5km}	AG_d[b]	pH2Od_{50}	LL	K	AIC	ΔAIC	$\sum w_i$
-0.10 (0.04)						-203.25	10	426.78	0.00	0.222
-0.10 (0.04)	0.33 (0.16)			-0.10 (0.10)		-203.99	10	428.26	1.48	0.328
-0.10 (0.04)	0.33 (0.17)	0.84 (0.56)				-204.28	10	428.85	2.06	0.407
-0.10 (0.04)	0.33 (0.16)					-205.33	9	428.88	2.15	0.483
-0.10 (0.04)	0.31 (0.16)		1.50 (1.50)			-204.84	10	429.96	3.17	0.528
-0.10 (0.04)	0.33 (0.16)				-18.66 (32.07)	-204.92	10	430.13	3.34	0.570
-0.10 (0.04)			2.31 (1.53)	-0.10 (0.10)		-204.96	10	430.20	3.41	0.610
-0.10 (0.04)		0.85 (0.56)		-0.10 (0.10)		-205.07	10	430.42	3.64	0.646
-0.10 (0.04)				-0.10 (0.10)		-206.14	9	430.51	3.77	0.680
	0.31 (0.17)		3.14 (1.41)	-0.20 (0.10)		-205.22	10	430.73	3.94	0.711
			3.99 (1.43)			-205.33	10	430.93	4.15	0.739
-0.10 (0.04)		0.88 (0.56)				-206.40	9	431.04	4.30	0.765
-0.10 (0.04)						-207.54	8	431.27	4.58	0.787
-0.10 (0.04)		0.89 (0.56)	2.01 (1.57)			-205.57	10	431.43	4.64	0.809
-0.10 (0.04)				-0.10 (0.10)	-20.41 (32.80)	-205.66	10	431.60	4.82	0.829
-0.10 (0.04)			1.94 (1.54)			-206.74	9	431.71	4.98	0.847
		0.90 (0.56)	3.76 (1.47)	-0.20 (0.10)		-205.84	10	431.96	5.18	0.864
-0.10 (0.04)		0.89 (0.56)			-21.82 (33.76)	-205.90	10	432.09	5.30	0.880
			3.71 (1.44)	-0.20 (0.10)		-207.03	9	432.28	5.55	0.894
-0.10 (0.04)					-20.45 (33.17)	-207.08	9	432.39	5.66	0.907

TABLE 10.4. Extended

TRMI^2	MjRD_{50}	WELL_{50}	POP_{1km}	RAIL_d[b]	LL	K	AIC	ΔAIC	$\sum w_i$
0.01 (0.004)	3.71 (1.03)	15.05 (7.70)			-319.79	12	663.97	0.00	0.349
0.01 (0.004)	3.71 (1.03)	14.96 (7.69)	1.57 (2.71)		-319.42	13	665.31	1.27	0.534
0.01 (0.004)	3.67 (1.03)	15.09 (7.79)	1.85 (2.74)	-0.01 (0.01)	-319.62	13	665.71	1.67	0.685
0.01 (0.004)	3.67 (1.03)	15.19 (7.80)		-0.01 (0.01)	-323.03	10	666.35	2.49	0.785
	3.79 (1.02)	14.59 (7.37)			-319.20	14	666.94	2.83	0.870
	3.75 (1.02)	14.73 (7.46)		-0.01 (0.01)	-322.68	11	667.70	3.79	0.923

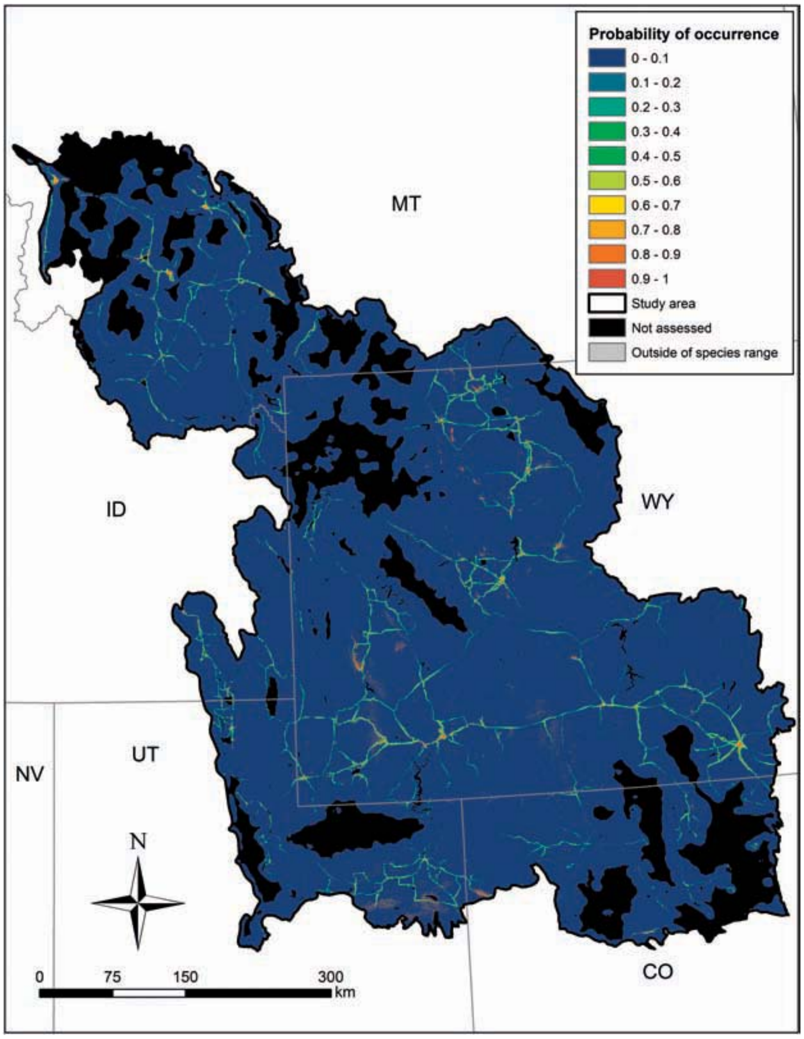

FIG. 10.1. Predicted probability of occurrence for crested wheatgrass in the Wyoming Basins Ecoregional Assessment. Black areas are outside the inference of our models (<3% sagebrush within 5 km or within a body of water).

Russian Thistle

Russian thistle was found at 5.4% of sampled plots (n = 85), with frequency of occurrence highest in the near-road stratum at 7.3% of plots (Table 10.1). Support was high (ΔAIC $\leq$ 2) for a single Russian thistle model that contained one habitat-based survey design variable, two abiotic factors, and three anthropogenic disturbance factors (Table 10.2). For the habitat-based survey design variable, Russian thistle occurrence was predicted to increase in areas associated with intermediate vegetation productivity as measured by NDVI (Table 10.6). For abiotic factors, Russian thistle occurrence was more likely in areas of low summertime solar radiation (SOLR) and in areas further away from perennial sources of water with a distance parameter of 1 km ($pH2Od_{1km}$) (Table 10.6). For anthropogenic factors, Russian thistle occurrence was more likely along secondary

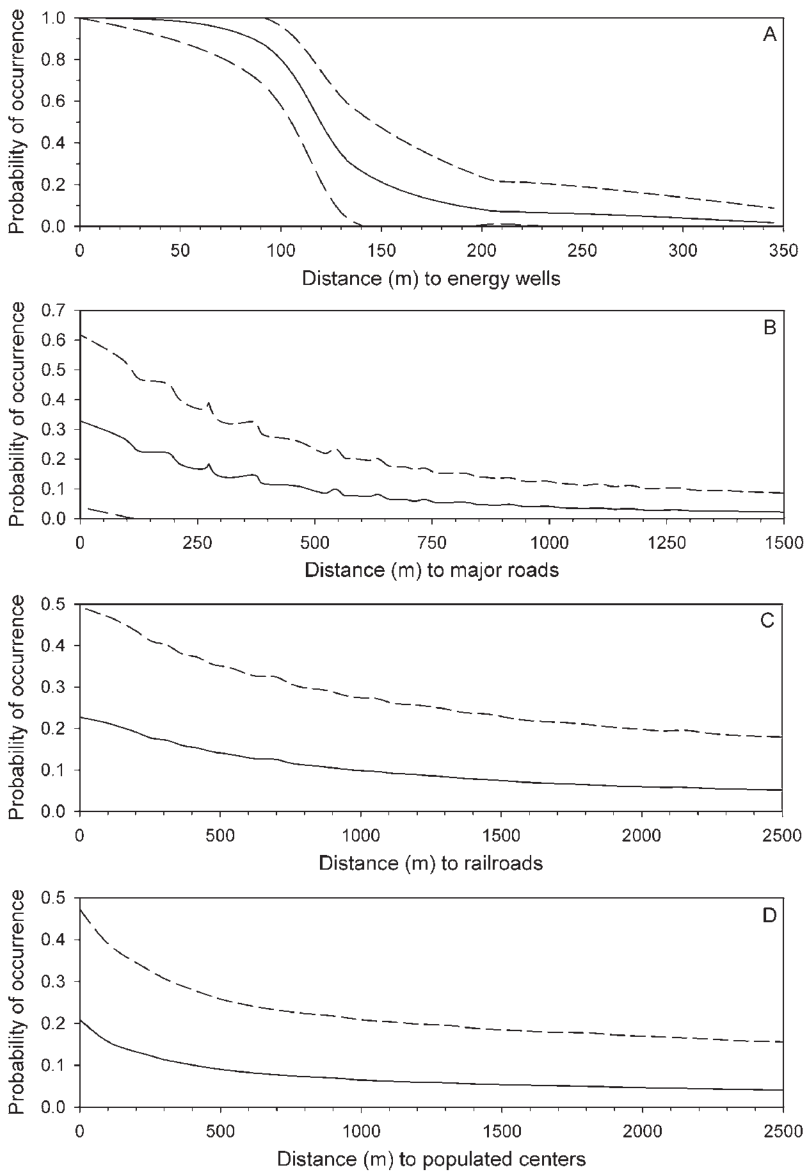

FIG. 10.2. Dose-response curves illustrating mean predicted probability of occurrence (±1 SD) of crested wheatgrass across the Wyoming Basins Ecoregional Assessment area as a function of distance from anthropogenic feature types of energy wells (A), major roads (B), railroads (C), and populated centers (D).

roads with a distance parameter of 0.25 km ($2RD_{250}$), in areas near energy wells with a distance decay parameter of 1 km ($WELL_{1km}$), and in areas near major roads with a distance decay parameter of 0.5 km ($MjRD_{500}$) (Table 10.6). Although a single model was most supported, a total of 13 candidate models were used to derive model-averaged coefficients predicting the probability of Russian thistle occurrence with summed AIC weights (w_i) of just ≥ 0.9 (Table 10.6). The final composite Russian thistle occurrence model had a ROC AUC value of 0.89 (SE = 0.02), suggesting very good predictive accuracy.

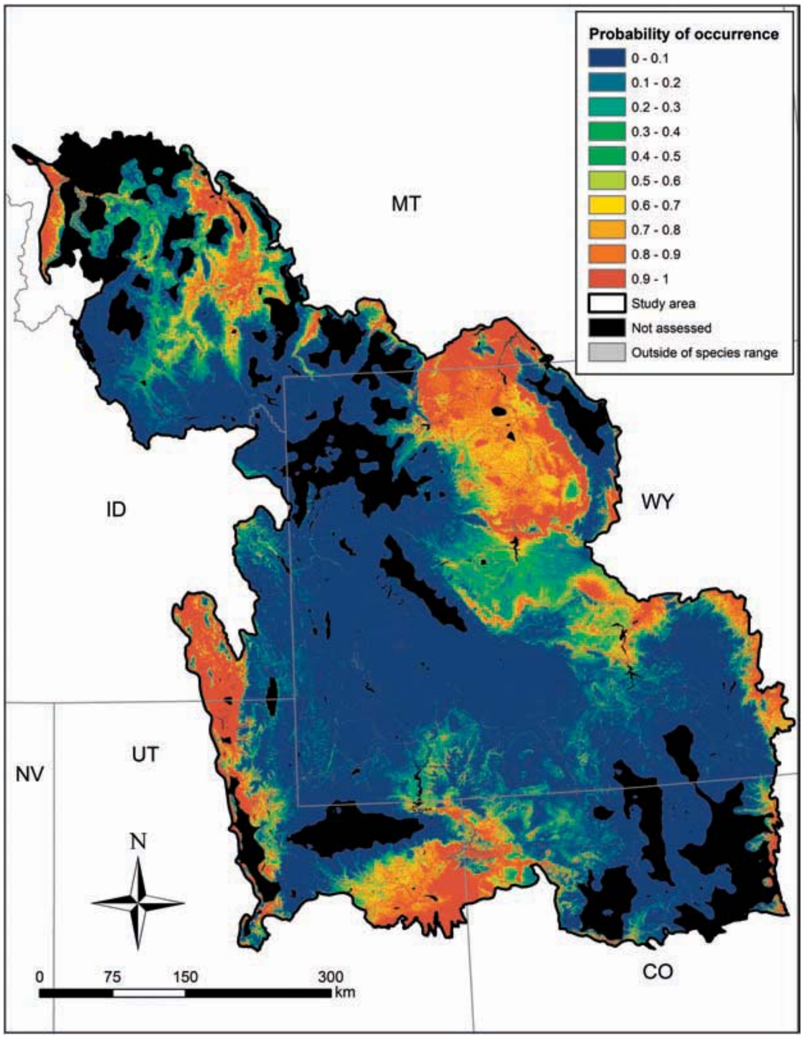

FIG. 10.3. Predicted probability of occurrence for cheatgrass in the Wyoming Basins Ecoregional Assessment area. Black areas are outside the inference of our models (<3% sagebrush within 5 km or within a body of water).

A probability of occurrence map for Russian thistle was generated for the WBEA area using model-averaged coefficients and associated GIS variables. Russian thistle was predicted to occur throughout the Wind River/Bighorn Basin in Wyoming, along the I-80 corridor in Wyoming and associated secondary roads in the area, and finally in the area southeast of the Uintas Mountains in eastern Utah (Figure 10.7). The distribution map for Russian thistle illustrates the importance of anthropogenic factors with individual roads and energy wells easily observed as hot spots. Based on mean predicted occurrences of Russian thistle by distance classes, Russian thistle was predicted to occur, on average (threshold probability > 0.05), within 700 m of populated places, 550 m of major roads, 90 m of secondary roads, 1 km of pipelines, and 1.3 km of energy wells (Figure 10.8). Associations of Russian

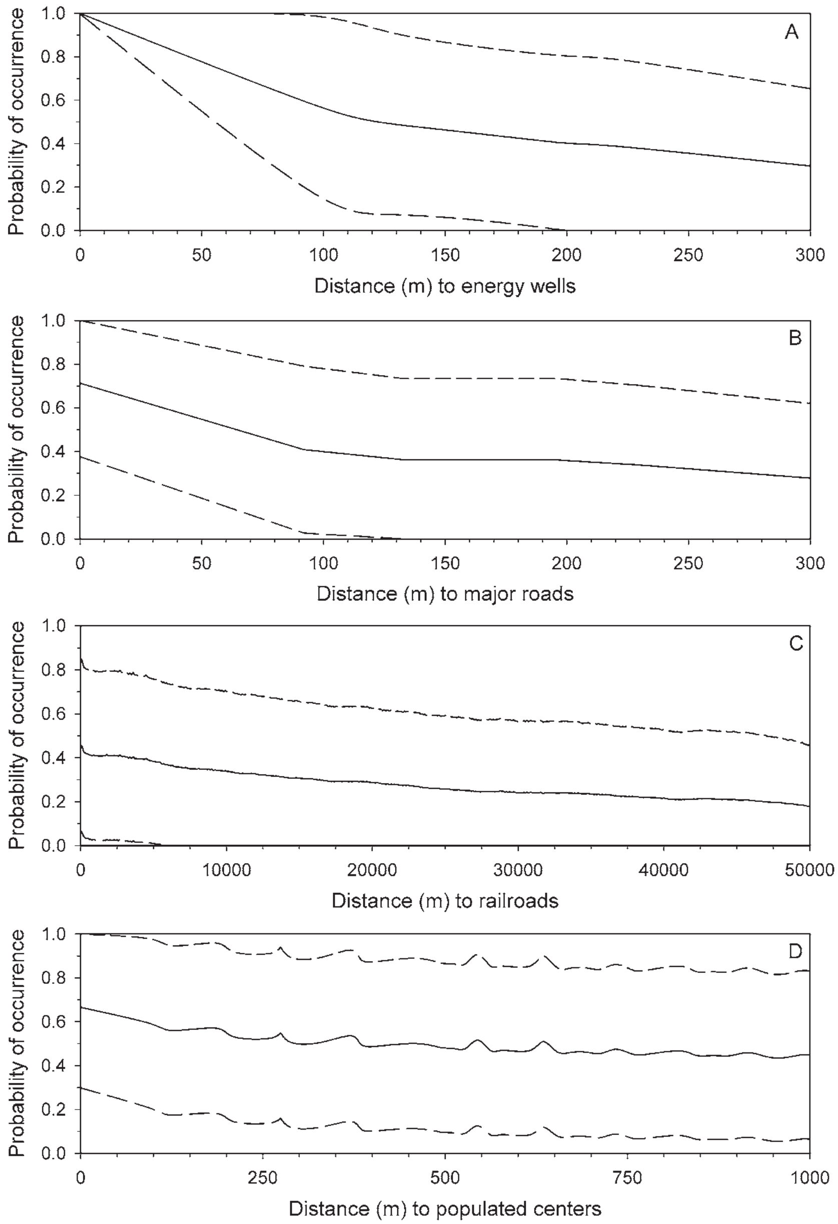

FIG. 10.4. Dose-response curves illustrating mean predicted probability of occurrence (±1 SD) of cheatgrass across the Wyoming Basins Ecoregional Assessment area as a function of distance from anthropogenic feature types of energy wells (A), major roads (B), railroads (C), and populated centers (D).

thistle were strongest for major roads and energy wells with mean probabilities of occurrence adjacent to major roads at 0.23 and for energy wells at 0.36 (Figure 10.8). When comparing mean probabilities of occurrence at sites closest to anthropogenic disturbances to those sites furthest from those disturbances, risk ratios were estimated at 11.4 for major roads and 17.2 for energy wells.

TABLE 10.5. Halogeton random-effects logistic regression model[a] parameter estimates (beta [SE]), model log-likelihood (LL), number of parameters (K), Akaike's Information Criterion (AIC), change in AIC value from the top model (ΔAIC), and Akaike weight (w_i) for all candidate models in the Wyoming Basins Ecoregional Assessment area where Akaike weights sum to just ≥ 0.9. Superscript numbers reflect quadratic terms, while subscript numbers for anthropogenic and water variables represent the distance parameter value of the exponential distance decay function used to scale distance effects. Anthropogenic terms ending in the subscript letter "d" reflect Euclidian distance variables rather than distance decay functions.

Rank	Intercept	SAGE	NDVI	SOLR[b]	SOLR^{2}[c]	Tmin	Tmin^2	SALIN	SALIN^2	AWC	AWC^2	$RAIL_d$[e]
1	377.29 (160.35)	-0.58 (0.38)	-1.83 (2.75)	-0.88 (0.3)	0.51 (0.24)	-0.08 (0.54)	-0.18 (0.12)	1.36 (0.69)	-0.12 (0.08)	-1.99 (0.94)	0.13 (0.08)	-0.32 (0.17)
2	401.08 (156.33)	-0.55 (0.37)	-1.47 (3.07)	-0.93 (0.38)	0.54 (0.23)	-0.03 (0.56)	-0.16 (0.12)	1.20 (0.68)	-0.10 (0.08)	-1.82 (1.00)	0.11 (0.09)	-0.35 (0.18)
3	356.20 (164.07)	-0.59 (0.37)	-2.05 (2.42)	-0.84 (0.40)	0.49 (0.24)	-0.08 (0.59)	-0.21 (0.14)	1.42 (0.62)	-0.17 (0.08)	-1.71 (0.93)	0.07 (0.08)	-0.30 (0.17)
4	352.93 (162.40)	-0.55 (0.40)	-1.51 (2.49)	-0.83 (0.39)	0.48 (0.24)	-0.17 (0.58)	-0.20 (0.13)	1.18 (0.68)	-0.10 (0.08)	-1.67 (0.96)	0.10 (0.08)	-0.31 (0.20)
5	389.36 (159.09)	-0.56 (0.37)	-0.92 (2.12)	-0.92 (0.39)	0.53 (0.23)	-0.01 (0.60)	-0.19 (0.14)	1.38 (0.63)	-0.16 (0.08)	-1.65 (0.87)	0.07 (0.07)	-0.32 (0.16)
6	389.36 (159.09)	-0.56 (0.37)	-0.92 (2.12)	-0.92 (0.39)	0.53 (0.23)	-0.01 (0.60)	-0.19 (0.14)	1.38 (0.63)	-0.16 (0.08)	-1.65 (0.87)	0.07 (0.07)	-0.32 (0.16)
7	392.25 (162.98)	-0.50 (0.37)	-2.17 (2.07)	-0.93 (0.40)	0.54 (0.24)	-0.24 (0.62)	-0.24 (0.16)	1.72 (0.82)	-0.19 (0.10)	-1.92 (0.96)	0.09 (0.08)	
8	398.98 (175.11)	-0.60 (0.36)	-2.14 (2.88)	-0.93 (0.42)	0.54 (0.26)	-0.05 (0.55)	-0.19 (0.12)	1.45 (0.69)	-0.14 (0.09)	-2.19 (0.96)	0.13 (0.08)	-0.34 (0.18)
9	403.69 (162.43)	-0.46 (0.36)	-2.25 (2.33)	-0.95 (0.40)	0.55 (0.24)	0.10 (0.55)	-0.17 (0.13)			-1.39 (0.85)	0.04 (0.07)	-0.32 (0.18)
10	411.66 (160.00)	-0.59 (0.37)	-1.37 (2.72)	-0.96 (0.39)	0.56 (0.24)	-0.01 (0.57)	-0.17 (0.12)	1.35 (0.69)	-0.13 (0.09)	-2.02 (0.99)	0.11 (0.08)	-0.35 (0.17)
11	422.42 (158.42)	-0.51 (0.37)	-1.78 (2.07)	-0.99 (0.39)	0.58 (0.23)	-0.25 (0.55)	-0.22 (0.12)	1.79 (0.71)	-0.17 (0.08)	-2.24 (0.96)	0.15 (0.08)	
12	385.08 (157.40)	-0.51 (0.37)	-0.68 (2.19)	-0.90 (0.38)	0.52 (0.23)	-0.12 (0.56)	-0.18 (0.13)	1.15 (0.60)	-0.10 (0.07)	-1.60 (0.89)	0.09 (0.07)	-0.33 (0.17)
13	402.23 (170.86)	-0.43 (0.37)	-2.46 (2.07)	-0.94 (0.42)	0.54 (0.25)	0.15 (0.53)	-0.17 (0.12)			-1.81 (0.87)	0.09 (0.07)	-0.31 (0.15)
14	451.86 (164.34)	-0.54 (0.36)	-1.08 (2.11)	-1.05 (0.40)	0.61 (0.24)	-0.24 (0.62)	-0.21 (0.13)	1.61 (0.67)	-0.14 (0.08)	-2.04 (0.99)	0.13 (0.08)	
15	390.95 (167.73)	-0.51 (0.36)	-2.61 (1.93)	-0.89 (0.41)	0.51 (0.25)	0.19 (0.63)	-0.12 (0.13)			-1.76 (0.96)	0.09 (0.08)	-0.39 (0.16)
16	415.20 (169.96)	-0.44 (0.37)	-1.97 (2.15)	-0.98 (0.41)	0.57 (0.25)	-0.40 (0.54)	-0.27 (0.15)	1.38 (0.60)	-0.11 (0.07)	-1.90 (1.01)	0.12 (0.08)	
17	372.48 (170.70)	-0.51 (0.36)	-2.50 (2.31)	-0.86 (0.42)	0.50 (0.25)	0.11 (0.60)	-0.14 (0.14)			-1.21 (0.92)	0.05 (0.08)	-0.36 (0.16)
18	422.81 (158.32)	-0.54 (0.38)	-1.81 (2.14)	-0.99 (0.39)	0.58 (0.23)	-0.27 (0.59)	-0.23 (0.13)	1.92 (0.92)	-0.19 (0.12)	-2.32 (0.94)	0.14 (0.08)	
19	346.91 (168.04)	-0.59 (0.39)	-2.65 (7.25)	-0.80 (0.41)	0.46 (0.25)	-0.25 (0.53)	-0.20 (0.12)	1.30 (1.21)	-0.11 (0.16)	-2.11 (1.54)	0.13 (0.15)	-0.39 (0.19)
20	425.14 (158.20)	-0.50 (0.36)	-1.60 (2.15)	-1 (0.38)	0.58 (0.23)	-0.03 (0.61)	-0.18 (0.12)	1.53 (0.69)	-0.18 (0.09)	-1.56 (0.83)	0.06 (0.07)	
21	391.24 (171.88)	-0.50 (0.36)	-3.22 (2.10)	-0.90 (0.42)	0.52 (0.25)	0.20 (0.61)	-0.13 (0.12)			-1.86 (0.93)	0.11 (0.08)	-0.38 (0.15)
22	375.35 (159.61)	-0.55 (0.38)	-1.83 (2.74)	-0.87 (0.39)	0.50 (0.24)	-0.18 (0.56)	-0.18 (0.12)	1.22 (0.65)	-0.11 (0.08)	-2.00 (1.02)	0.12 (0.09)	-0.41 (0.17)
23	333.83 (174.72)	-0.53 (0.38)	-2.68 (2.47)	-0.77 (0.42)	0.44 (0.26)	0.02 (0.61)	-0.16 (0.14)			-1.30 (0.97)	0.06 (0.08)	-0.36 (0.15)
24	391.87 (163.26)	-0.49 (0.37)	-1.91 (2.37)	-0.91 (0.39)	0.53 (0.24)	-0.06 (0.54)	-0.18 (0.12)	1.31 (0.63)	-0.11 (0.07)	-2.10 (0.86)	0.14 (0.08)	-0.34 (0.16)
25	389.66 (160.02)	-0.53 (0.36)	-2.22 (1.90)	-0.89 (0.39)	0.51 (0.23)	0.17 (0.60)	-0.13 (0.13)			-1.88 (0.88)	0.09 (0.07)	-0.42 (0.18)
26	389.40 (160.33)	-0.57 (0.36)	-1.21 (2.34)	-0.90 (0.39)	0.52 (0.23)	0.01 (0.53)	-0.17 (0.12)	1.48 (0.62)	-0.12 (0.07)	-2.19 (0.88)	0.15 (0.07)	-0.36 (0.16)
27	363.44 (163.74)	-0.59 (0.36)	-1.12 (2.18)	-0.84 (0.40)	0.48 (0.24)	0.08 (0.56)	-0.15 (0.12)	1.28 (0.59)	-0.10 (0.07)	-1.67 (0.86)	0.09 (0.08)	-0.37 (0.16)
28	355.75 (159.33)	-0.53 (0.37)	-2.33 (2.26)	-0.84 (0.39)	0.49 (0.23)	0.00 (0.58)	-0.18 (0.13)	1.38 (0.62)	-0.17 (0.08)	-1.72 (0.92)	0.08 (0.08)	-0.31 (0.16)
29	355.75 (159.33)	-0.53 (0.37)	-2.33 (2.26)	-0.84 (0.39)	0.49 (0.23)	0.00 (0.58)	-0.18 (0.13)	1.38 (0.62)	-0.17 (0.08)	-1.72 (0.92)	0.08 (0.08)	-0.31 (0.16)
30	323.35 (161.44)	-0.58 (0.36)	-2.21 (2.41)	-0.76 (0.39)	0.43 (0.24)	-0.29 (0.59)	-0.24 (0.15)	1.40 (0.60)	-0.16 (0.08)	-1.90 (0.90)	0.09 (0.08)	-0.36 (0.17)
31	404.28 (162.20)	-0.48 (0.36)	-1.15 (2.51)	-0.94 (0.39)	0.54 (0.24)	-0.04 (0.54)	-0.17 (0.12)	1.18 (0.60)	-0.10 (0.07)	-1.96 (0.93)	0.13 (0.08)	-0.36 (0.16)

TABLE 10.5. Extended

$TOWER_{500}$	$POWER_{50}$	AG_d^e	$WELL_{50}$	RD_{1km}	SAND	$SAND^{2f}$	$SOIL_{cm}$	LL	K	AIC	ΔAIC	$\sum w_i$
15.79 (8.26)	3.03 (1.30)	-0.78 (0.59)	27.88 (30.16)	2.42 (1.11)				-247.53	15	531.94	0.00	0.068
15.40 (7.70)	3.11 (1.31)		28.08 (29.45)	2.49 (1.10)				-248.57	14	531.93	0.09	0.133
15.15 (7.76)	2.89 (1.30)	-1.00 (0.65)	25.00 (30.03)	2.71 (1.20)	0.23 (0.12)	-0.37 (0.19)	0.03 (0.02)	-244.87	18	532.93	0.69	0.181
15.66 (8.54)	3.05 (1.33)	-0.87 (0.63)	25.72 (30.28)	2.50 (1.18)	0.17 (0.10)	-0.24 (0.16)		-246.21	17	533.50	1.37	0.216
15.08 (7.25)	3.06 (1.34)		26.43 (30.78)	2.71 (1.17)	0.22 (0.13)	-0.35 (0.20)	0.03 (0.02)	-246.23	17	533.54	1.40	0.249
15.08 (7.25)	3.06 (1.34)		26.43 (30.78)	2.71 (1.17)	0.22 (0.13)	-0.35 (0.20)	0.03 (0.02)	-246.23	17	533.54	1.40	0.283
16.14 (7.44)	3.03 (1.33)	-1.21 (0.68)	22.73 (27.16)	2.71 (1.16)	0.25 (0.13)	-0.40 (0.20)	0.04 (0.03)	-246.35	17	533.78	1.64	0.313
16.00 (8.15)	3.02 (1.29)	-0.82 (0.62)	29.18 (30.85)	2.49 (1.12)			0.01 (0.02)	-247.36	16	533.70	1.66	0.343
15.46 (6.94)	2.97 (1.34)		25.27 (30.08)	2.75 (1.13)	0.27 (0.15)	-0.42 (0.23)	0.03 (0.01)	-248.40	15	533.69	1.76	0.371
15.46 (7.47)	3.12 (1.31)		29.14 (29.91)	2.58 (1.10)			0.01 (0.02)	-248.41	15	533.70	1.77	0.399
16.86 (7.13)	3.18 (1.33)	-1.01 (0.65)	25.74 (30.49)	2.54 (1.03)				-249.41	14	533.61	1.77	0.427
15.51 (8.22)	3.15 (1.33)		27.11 (30.24)	2.62 (1.17)	0.16 (0.11)	-0.23 (0.16)		-247.47	16	533.92	1.88	0.453
17.10 (8.41)	2.82 (1.39)	-0.86 (0.60)	25.64 (30.17)	2.69 (1.04)	0.26 (0.15)	-0.41 (0.23)	0.03 (0.01)	-247.50	16	533.99	1.95	0.479
16.99 (6.47)	3.36 (1.30)		25.51 (30.95)	2.64 (1.12)				-250.86	13	534.43	2.68	0.497
15.00 (7.11)	3.08 (1.37)		25.35 (29.56)	2.85 (1.10)				-251.90	12	534.42	2.74	0.514
16.86 (7.92)	3.23 (1.31)	-1.26 (0.71)	26.01 (31.34)	2.74 (1.18)	0.20 (0.11)	-0.30 (0.17)		-247.98	16	534.95	2.91	0.530
14.11 (6.95)	3.17 (1.30)		23.00 (28.77)	2.94 (1.14)	0.19 (0.13)	-0.28 (0.18)		-250.19	14	535.17	3.33	0.543
16.70 (7.07)	3.18 (1.33)	-1.01 (0.65)	25.55 (30.33)	2.58 (1.06)			0.01 (0.02)	-249.21	15	535.31	3.38	0.555
	3.05 (1.29)	-0.87 (0.66)	27.52 (30.60)	2.82 (1.19)				-250.22	14	535.24	3.40	0.568
16.83 (6.64)	3.13 (1.30)		22.20 (28.59)	2.51 (1.14)	0.23 (0.12)	-0.38 (0.19)	0.03 (0.02)	-248.25	16	535.48	3.45	0.580
15.70 (7.65)	2.96 (1.40)	-0.64 (0.54)	25.37 (29.77)	2.72 (1.08)				-251.27	13	535.23	3.48	0.592
	3.11 (1.34)		27.67 (29.75)	2.86 (1.14)				-251.28	13	535.26	3.50	0.604
14.48 (7.61)	3.00 (1.31)	-0.80 (0.62)	22.55 (25.78)	2.85 (1.12)	0.21 (0.13)	-0.31 (0.20)		-249.36	15	535.60	3.67	0.614
16.13 (8.35)		-0.84 (0.56)	27.95 (30.52)	2.20 (1.04)				-250.43	14	535.66	3.82	0.625
15.56 (7.48)	3.03 (1.41)		26.46 (29.57)	2.75 (1.12)			0.01 (0.01)	-251.45	13	535.61	3.86	0.634
19.71 (7.59)	2.75 (1.25)	-0.77 (0.55)	32.98 (30.79)					-250.47	14	535.74	3.90	0.644
19.20 (7.05)	2.96 (1.23)		31.91 (30.12)					-251.48	13	535.65	3.90	0.654
15.06 (7.71)		-1.03 (0.61)	23.35 (28.32)	2.53 (1.17)	0.23 (0.12)	-0.36 (0.18)	0.04 (0.02)	-247.57	17	536.23	4.09	0.663
15.06 (7.71)		-1.03 (0.61)	23.35 (28.32)	2.53 (1.17)	0.23 (0.12)	-0.36 (0.18)	0.04 (0.02)	-247.57	17	536.23	4.09	0.671
	3.03 (1.31)	-1.09 (0.68)	24.50 (28.24)	3.18 (1.24)	0.24 (0.12)	-0.38 (0.19)	0.03 (0.02)	-247.61	17	536.32	4.18	0.68
15.75 (8.02)			28.65 (30.02)	2.26 (1.02)				-251.65	13	536.01	4.26	0.688

TABLE 10.5. Continued

Rank	Intercept	SAGE	NDVI	SOLR[b]	$SOLR^2$[c]	Tmin	$Tmin^2$	SALIN	$SALIN^2$	AWC	AWC^2	$RAIL_d$[e]
32	448.96 (160.81)	-0.55 (0.36)	-1.01 (2.09)	-1.05 (0.39)	0.61 (0.24)	-0.25 (0.63)	-0.21 (0.13)	1.68 (0.72)	-0.16 (0.09)	-2.10 (0.94)	0.13 (0.08)	
33	345.85 (160.81)	-0.57 (0.43)	-0.53 (2.10)	-0.80 (0.39)	0.46 (0.24)	-0.42 (0.62)	-0.23 (0.14)	1.31 (0.66)	-0.12 (0.08)	-1.76 (0.91)	0.10 (0.08)	-0.43 (0.18)
34	314.75 (162.14)	-0.61 (0.39)	-1.83 (3.48)	-0.73 (0.39)	0.42 (0.24)	-0.45 (0.57)	-0.24 (0.13)	1.29 (0.68)	-0.11 (0.09)	-1.84 (0.94)	0.11 (0.08)	-0.40 (0.19)
35	364.71 (162.73)	-0.47 (0.39)	-2.32 (2.34)	-0.85 (0.40)	0.48 (0.24)	-0.08 (0.58)	-0.18 (0.14)			-1.67 (0.90)	0.06 (0.07)	-0.41 (0.18)
36	352.09 (161.40)	-0.57 (0.38)	-0.80 (2.12)	-0.82 (0.39)	0.47 (0.24)	-0.25 (0.60)	-0.22 (0.14)	1.43 (0.61)	-0.17 (0.08)	-1.81 (0.87)	0.08 (0.07)	-0.40 (0.17)
37	458.31 (175.73)	-0.50 (0.36)	-1.60 (2.18)	-1.08 (0.43)	0.63 (0.26)	-0.15 (0.56)	-0.21 (0.13)	1.40 (0.61)	-0.13 (0.07)	-1.46 (0.91)	0.08 (0.07)	
38	400.03 (172.27)	-0.53 (0.37)	-3.47 (2.58)	-0.92 (0.42)	0.53 (0.25)	0.12 (0.58)	-0.15 (0.13)			-2.05 (0.92)	0.10 (0.08)	-0.42 (0.17)
39	385.88 (158.34)	-0.49 (0.38)	-1.25 (2.16)	-0.91 (0.38)	0.53 (0.23)	0.07 (0.57)	-0.16 (0.13)	1.31 (0.62)	-0.16 (0.08)	-1.61 (0.87)	0.07 (0.08)	-0.33 (0.16)
40	331.83 (173.75)	-0.55 (0.39)	-2.75 (2.45)	-0.77 (0.42)	0.44 (0.25)	-0.21 (0.61)	-0.22 (0.16)			-1.75 (0.97)	0.07 (0.08)	-0.42 (0.18)
41	311.60 (160.38)	-0.50 (0.39)	-2.00 (2.43)	-0.71 (0.39)	0.40 (0.24)	-0.13 (0.62)	-0.16 (0.13)			-1.46 (1.06)	0.06 (0.09)	-0.44 (0.18)
42	383.24 (156.10)	-0.38 (0.37)	-2.71 (2.13)	-0.89 (0.38)	0.52 (0.23)	0.21 (0.53)	-0.14 (0.12)			-1.81 (0.84)	0.09 (0.07)	-0.36 (0.15)
43	365.82 (180.57)	-0.58 (0.37)	-2.51 (3.51)	-0.85 (0.44)	0.49 (0.26)	-0.20 (0.54)	-0.20 (0.12)	1.38 (0.74)	-0.13 (0.10)	-2.36 (1.11)	0.15 (0.10)	-0.39 (0.18)
44	406.64 (163.47)	-0.54 (0.36)	-2.26 (2.43)	-0.95 (0.40)	0.55 (0.24)	-0.02 (0.55)	-0.18 (0.12)	1.43 (0.67)	-0.14 (0.09)	-2.27 (0.86)	0.14 (0.07)	-0.35 (0.16)
45	383.86 (162.10)	-0.57 (0.37)	-1.76 (3.04)	-0.89 (0.39)	0.51 (0.24)	-0.16 (0.56)	-0.19 (0.12)	1.31 (0.69)	-0.13 (0.09)	-2.14 (1.14)	0.12 (0.10)	-0.41 (0.17)
46	399.06 (160.77)	-0.39 (0.36)	-2.20 (2.19)	-0.93 (0.39)	0.54 (0.24)	0.23 (0.54)	-0.13 (0.12)			-1.69 (0.85)	0.08 (0.07)	-0.39 (0.18)
47	359.13 (162.19)	-0.48 (0.37)	-1.86 (2.42)	-0.84 (0.39)	0.49 (0.24)	-0.14 (0.56)	-0.19 (0.12)	1.10 (0.62)	-0.09 (0.08)	-1.70 (0.95)	0.11 (0.08)	-0.32 (0.17)
48	363.97 (162.50)	-0.54 (0.36)	-0.75 (2.16)	-0.85 (0.39)	0.49 (0.24)	-0.07 (0.51)	-0.18 (0.12)	1.37 (0.58)	-0.11 (0.06)	-1.89 (0.96)	0.12 (0.08)	-0.34 (0.16)
49	426.70 (166.73)	-0.40 (0.37)	-3.01 (1.83)	-1.01 (0.41)	0.58 (0.25)	-0.10 (0.53)	-0.23 (0.13)			-1.56 (0.97)	0.05 (0.08)	
50	377.15 (165.77)	-0.56 (0.35)	-0.54 (2.02)	-0.88 (0.40)	0.51 (0.24)	0.16 (0.54)	-0.18 (0.13)	1.47 (0.65)	-0.16 (0.08)	-2.04 (1.27)	0.11 (0.11)	-0.32 (0.14)
51	375.29 (149.29)	-0.42 (0.37)	-2.47 (2.06)	-0.89 (0.36)	0.52 (0.22)	-0.09 (0.58)	-0.19 (0.13)	1.64 (0.74)	-0.19 (0.10)	-1.84 (0.91)	0.09 (0.08)	
52	390.21 (160.37)	-0.61 (0.38)	-1.40 (2.31)	-0.90 (0.39)	0.52 (0.23)	0.03 (0.54)	-0.17 (0.13)	1.61 (0.71)	-0.15 (0.09)	-2.27 (0.88)	0.14 (0.07)	-0.36 (0.16)
53	366.37 (173.07)	-0.60 (0.36)	-1.11 (2.26)	-0.84 (0.42)	0.49 (0.25)	0.08 (0.57)	-0.15 (0.12)	1.32 (0.64)	-0.11 (0.08)	-1.74 (1.00)	0.09 (0.09)	-0.36 (0.17)
54	343.62 (159.23)	-0.49 (0.38)	-2.49 (1.98)	-0.77 (0.39)	0.44 (0.23)	0.01 (0.61)	-0.14 (0.12)			-2.10 (1.03)	0.12 (0.08)	-0.46 (0.16)
55	418.08 (165.54)	-0.52 (0.37)	-1.32 (2.29)	-0.97 (0.40)	0.56 (0.24)	0.01 (0.56)	-0.17 (0.12)	1.29 (0.62)	-0.12 (0.08)	-2.12 (0.89)	0.13 (0.08)	-0.37 (0.16)
56	382.79 (170.91)	-0.55 (0.35)	-0.51 (2.18)	-0.89 (0.41)	0.51 (0.25)	0.01 (0.52)	-0.17 (0.12)	1.27 (0.64)	-0.10 (0.06)	-1.76 (0.98)	0.11 (0.09)	-0.37 (0.17)
57	386.46 (166.30)	-0.47 (0.37)	-2.28 (2.12)	-0.91 (0.40)	0.53 (0.25)	-0.47 (0.60)	-0.28 (0.15)	1.83 (0.67)	-0.21 (0.09)	-2.25 (1.04)	0.11 (0.09)	
58	373.87 (192.67)	-0.54 (0.36)	-4.69 (1.97)	-0.91 (0.47)	0.54 (0.28)	0.41 (0.48)	-0.13 (0.13)	1.64 (0.58)	-0.17 (0.07)			-0.30 (0.14)
59	278.78 (155.25)	-0.53 (0.37)	-2.47 (2.48)	-0.63 (0.38)	0.36 (0.23)	-0.21 (0.59)	-0.18 (0.14)			-1.46 (0.99)	0.07 (0.08)	-0.43 (0.17)
60	369.83 (153.82)	-0.58 (0.35)	-1.09 (2.21)	-0.86 (0.37)	0.50 (0.23)	-0.17 (0.55)	-0.21 (0.12)	1.92 (0.73)	-0.17 (0.09)	-2.10 (1.05)	0.13 (0.09)	
61	475.65 (174.33)	-0.49 (0.35)	-2.32 (1.88)	-1.12 (0.43)	0.65 (0.26)	0.04 (0.56)	-0.20 (0.12)			-1.57 (0.85)	0.06 (0.07)	
62	382.30 (158.63)	-0.45 (0.36)	-0.93 (2.23)	-0.89 (0.38)	0.52 (0.23)	-0.11 (0.55)	-0.18 (0.13)	1.09 (0.58)	-0.09 (0.06)	-1.55 (0.88)	0.09 (0.07)	-0.35 (0.16)
63	431.51 (204.29)	-0.49 (0.35)	-4.23 (2.02)	-1.04 (0.50)	0.62 (0.30)	0.49 (0.47)	-0.11 (0.14)	1.57 (0.59)	-0.15 (0.07)			-0.28 (0.13)
64	339.86 (151.87)	-0.55 (0.36)	-1.32 (2.23)	-0.80 (0.37)	0.47 (0.22)	0.01 (0.57)	-0.18 (0.13)	1.74 (0.71)	-0.19 (0.10)	-1.63 (0.92)	0.07 (0.08)	
65	419.48 (155.17)	-0.44 (0.36)	-1.92 (2.17)	-0.98 (0.38)	0.57 (0.23)	-0.28 (0.56)	-0.22 (0.12)	1.71 (0.72)	-0.15 (0.09)	-2.28 (0.93)	0.15 (0.08)	
66	332.12 (167.56)	-0.51 (0.40)	-3.08 (2.16)	-0.75 (0.41)	0.43 (0.25)	-0.04 (0.63)	-0.15 (0.13)			-2.06 (0.99)	0.12 (0.09)	-0.45 (0.17)

TABLE 10.5. Extended

$TOWER_{500}$	$POWER_{50}$	$AG_d^{\,c}$	$WELL_{50}$	RD_{1km}	SAND	$SAND^{2f}$	$SOIL_{cm}$	LL	K	AIC	ΔAIC	$\sum w_i$
17.04 (6.52)	3.33 (1.30)		24.96 (30.50)	2.60 (1.07)			0.01 (0.02)	-250.66	14	536.11	4.27	0.696
	3.24 (1.51)		27.06 (31.29)	3.29 (1.41)	0.19 (0.12)	-0.27 (0.18)		-249.67	15	536.23	4.29	0.704
	3.21 (1.39)	-1.02 (0.82)	25.57 (30.29)	3.13 (1.32)	0.18 (0.10)	-0.27 (0.15)		-248.68	16	536.35	4.32	0.712
	3.04 (1.35)		23.45 (28.58)	3.05 (1.24)	0.26 (0.12)	-0.39 (0.18)	0.02 (0.01)	-250.72	14	536.23	4.39	0.719
	3.16 (1.34)		25.79 (31.21)	3.24 (1.27)	0.24 (0.13)	-0.37 (0.20)	0.03 (0.02)	-248.73	16	536.45	4.41	0.727
16.98 (6.52)	3.43 (1.29)		25.44 (31.25)	2.78 (1.22)	0.15 (0.10)	-0.24 (0.15)		-249.75	15	536.39	4.45	0.734
15.74 (7.95)	2.98 (1.39)	-0.72 (0.62)	26.59 (30.45)	2.76 (1.18)			0.02 (0.01)	-250.84	14	536.48	4.64	0.741
15.21 (7.47)			25.07 (30.29)	2.46 (1.11)	0.21 (0.13)	-0.35 (0.20)	0.03 (0.02)	-249.10	16	537.19	5.16	0.746
	2.99 (1.40)	-0.89 (0.66)	23.54 (23.93)	3.14 (1.20)	0.30 (0.16)	-0.44 (0.22)	0.02 (0.01)	-250.11	15	537.10	5.16	0.751
	3.09 (1.28)		21.41 (24.77)	3.16 (1.21)	0.21 (0.13)	-0.30 (0.18)		-252.11	13	536.92	5.17	0.756
17.00 (9.02)		-0.88 (0.57)	23.52 (27.37)	2.40 (1.00)	0.23 (0.13)	-0.37 (0.19)	0.03 (0.01)	-250.14	15	537.18	5.24	0.761
	3.04 (1.28)	-0.88 (0.67)	28.37 (31.06)	2.83 (1.16)			0.01 (0.01)	-250.15	15	537.18	5.25	0.766
16.04 (8.07)		-0.87 (0.58)	28.83 (30.97)	2.33 (1.08)			0.01 (0.02)	-250.19	15	537.26	5.32	0.771
	3.12 (1.33)		28.44 (30.13)	2.90 (1.12)			0.01 (0.02)	-251.20	14	537.20	5.36	0.776
15.66 (7.64)			23.75 (29.06)	2.40 (1.13)	0.20 (0.12)	-0.32 (0.18)	0.03 (0.01)	-251.22	14	537.23	5.39	0.780
15.42 (8.05)		-0.93 (0.61)	24.99 (30.08)	2.35 (1.12)	0.16 (0.11)	-0.24 (0.16)		-249.22	16	537.43	5.40	0.785
19.88 (7.65)	2.82 (1.21)	-0.86 (0.58)	30.98 (31.03)		0.19 (0.12)	-0.28 (0.17)		-249.27	16	537.53	5.50	0.789
17.73 (6.79)	3.29 (1.26)	-0.95 (0.77)	24.18 (25.91)	3.14 (1.16)	0.39 (0.17)	-0.60 (0.26)	0.03 (0.01)	-250.29	15	537.47	5.54	0.793
21.72 (9.46)	2.73 (1.29)		32.81 (32.58)		0.33 (0.24)	-0.52 (0.36)	0.04 (0.02)	-249.32	16	537.62	5.58	0.798
16.11 (7.61)		-1.18 (0.61)	20.09 (22.28)	2.51 (1.06)	0.24 (0.13)	-0.39 (0.20)	0.04 (0.02)	-249.34	16	537.66	5.63	0.802
19.56 (7.28)	2.74 (1.28)	-0.80 (0.56)	33.50 (31.14)				0.01 (0.02)	-250.36	15	537.61	5.68	0.806
19.08 (7.03)	2.92 (1.26)		32.05 (30.13)				0.00 (0.02)	-251.37	14	537.53	5.69	0.810
	3.05 (1.37)		23.55 (28.71)	3.12 (1.17)				-254.40	11	537.34	5.75	0.813
15.75 (7.74)			29.47 (30.23)	2.34 (1.04)			0.01 (0.02)	-251.42	14	537.63	5.79	0.817
20.18 (7.57)	2.94 (1.18)		31.32 (30.81)		0.19 (0.16)	-0.28 (0.23)		-250.44	15	537.77	5.84	0.821
	3.18 (1.41)	-1.28 (0.64)	23.13 (25.73)	3.18 (1.24)	0.28 (0.14)	-0.44 (0.22)	0.04 (0.03)	-249.50	16	537.99	5.96	0.824
17.92 (7.02)	3.08 (1.52)	-1.08 (0.65)	27.10 (32.39)	2.61 (1.12)	0.23 (0.12)	-0.41 (0.19)		-250.58	15	538.05	6.12	0.827
	3.02 (1.31)	-0.84 (0.64)	21.50 (20.90)	3.17 (1.21)	0.23 (0.13)	-0.33 (0.19)		-251.58	14	537.96	6.12	0.831
20.37 (7.30)	3.04 (1.27)	-1.05 (0.64)	28.68 (30.68)					-252.59	13	537.88	6.12	0.834
19.30 (6.82)	3.41 (1.36)		25.68 (29.95)	3.42 (1.23)	0.30 (0.13)	-0.49 (0.20)	0.03 (0.01)	-251.63	14	538.06	6.22	0.837
15.37 (8.01)			26.86 (30.46)	2.41 (1.07)	0.15 (0.11)	-0.22 (0.16)		-250.64	15	538.16	6.23	0.840
18.32 (6.88)	3.20 (1.80)		28.19 (32.73)	2.87 (1.32)	0.22 (0.13)	-0.39 (0.20)		-251.66	14	538.12	6.28	0.843
19.76 (7.52)	2.78 (1.23)	-1.05 (0.68)	25.03 (29.67)		0.26 (0.14)	-0.43 (0.22)	0.03 (0.02)	-249.71	16	538.40	6.37	0.846
16.97 (7.58)		-1.09 (0.63)	24.94 (30.01)	2.36 (1.05)				-252.75	13	538.21	6.45	0.848
	2.97 (1.35)	-0.65 (0.60)	23.38 (28.24)	2.98 (1.15)				-253.75	12	538.13	6.45	0.851

TABLE 10.5. Continued

Rank	Intercept	SAGE	NDVI	SOLR[b]	$SOLR^{2c}$	Tmin	$Tmin^2$	SALIN	$SALIN^2$	AWC	AWC^2	$RAIL_d^e$
67	390.66 (173.78)	-0.57 (0.36)	-3.77 (2.00)	-0.93 (0.42)	0.55 (0.26)	0.16 (0.50)	-0.16 (0.12)	1.42 (0.55)	-0.11 (0.06)			-0.29 (0.13)
68	391.64 (166.02)	-0.39 (0.37)	-1.91 (2.14)	-0.92 (0.40)	0.53 (0.24)	-0.58 (0.56)	-0.29 (0.14)	1.41 (0.62)	-0.11 (0.07)	-2.40 (1.12)	0.15 (0.09)	
69	439.25 (181.61)	-0.57 (0.36)	-3.40 (2.02)	-1.04 (0.44)	0.61 (0.27)	0.17 (0.49)	-0.16 (0.12)	1.31 (0.55)	-0.09 (0.06)			-0.29 (0.14)
70	416.03 (159.99)	-0.44 (0.38)	-1.80 (2.17)	-0.97 (0.39)	0.56 (0.24)	-0.43 (0.57)	-0.25 (0.12)	1.93 (0.77)	-0.18 (0.09)	-2.73 (1.00)	0.18 (0.08)	
71	465.37 (163.73)	-0.68 (0.35)	-0.84 (1.73)	-1.08 (0.39)	0.62 (0.24)	0.45 (0.43)	-0.18 (0.10)			-1.99 (0.83)	0.09 (0.06)	-0.37 (0.13)
72	381.32 (163.33)	-0.46 (0.36)	-2.73 (1.91)	-0.87 (0.40)	0.50 (0.24)	0.19 (0.60)	-0.11 (0.12)			-1.71 (0.88)	0.10 (0.07)	-0.46 (0.18)
73	384.17 (155.34)	-0.61 (0.35)	-0.11 (2.29)	-0.89 (0.38)	0.51 (0.23)	-0.14 (0.66)	-0.20 (0.13)	1.97 (0.94)	-0.18 (0.12)	-1.97 (1.08)	0.12 (0.09)	
74	393.17 (156.95)	-0.52 (0.35)	-1.39 (2.27)	-0.91 (0.38)	0.53 (0.23)	-0.02 (0.50)	-0.18 (0.11)	1.38 (0.59)	-0.11 (0.07)	-2.14 (0.82)	0.15 (0.07)	-0.39 (0.16)
75	352.85 (162.90)	-0.52 (0.38)	-2.31 (2.60)	-0.81 (0.39)	0.47 (0.24)	-0.23 (0.55)	-0.20 (0.13)	1.32 (0.64)	-0.12 (0.08)	-2.26 (0.94)	0.15 (0.08)	-0.40 (0.16)
76	416.83 (164.94)	-0.64 (0.36)	-1.28 (1.89)	-0.97 (0.40)	0.56 (0.24)	0.45 (0.43)	-0.17 (0.10)			-1.91 (0.82)	0.09 (0.06)	-0.37 (0.13)
77	355.71 (158.71)	-0.52 (0.38)	-2.42 (2.04)	-0.80 (0.38)	0.46 (0.23)	-0.01 (0.60)	-0.15 (0.13)			-2.18 (1.06)	0.12 (0.08)	-0.46 (0.16)
78	385.37 (159.48)	-0.45 (0.36)	-3.52 (2.07)	-0.88 (0.39)	0.51 (0.23)	0.21 (0.59)	-0.12 (0.11)			-1.88 (0.88)	0.11 (0.07)	-0.42 (0.14)
79	413.35 (163.47)	-0.54 (0.35)	-0.92 (2.52)	-0.95 (0.39)	0.55 (0.24)	0.01 (0.54)	-0.17 (0.12)	1.19 (0.61)	-0.09 (0.07)	-2.06 (0.99)	0.14 (0.09)	-0.41 (0.17)
80	450.57 (198.69)	-0.51 (0.36)	-3.44 (2.06)	-1.08 (0.48)	0.64 (0.29)	0.27 (0.51)	-0.16 (0.16)	1.48 (0.57)	-0.12 (0.07)			-0.29 (0.12)
81	349.48 (151)	-0.57 (0.35)	-1.03 (2.25)	-0.82 (0.37)	0.47 (0.22)	-0.24 (0.53)	-0.22 (0.13)	1.67 (0.64)	-0.14 (0.08)	-1.59 (0.94)	0.09 (0.08)	
82	370.37 (176.29)	-0.58 (0.37)	-3.95 (2.05)	-0.89 (0.43)	0.53 (0.26)	0.25 (0.52)	-0.15 (0.14)	1.54 (0.57)	-0.14 (0.07)			-0.29 (0.13)
83	385.24 (169.61)	-0.56 (0.36)	-1.14 (3.60)	-0.88 (0.41)	0.51 (0.25)	-0.02 (0.54)	-0.17 (0.12)	1.22 (0.64)	-0.10 (0.07)	-2.32 (1.87)	0.15 (0.17)	-0.45 (0.18)
84	373.16 (163.09)	-0.47 (0.37)	-1.52 (2.69)	-0.86 (0.39)	0.50 (0.24)	-0.15 (0.56)	-0.17 (0.13)	1.18 (0.63)	-0.10 (0.07)	-2.14 (1.07)	0.14 (0.09)	-0.42 (0.16)
85	430.90 (161.21)	-0.47 (0.37)	-1.04 (2.09)	-1.00 (0.39)	0.58 (0.24)	-0.33 (0.60)	-0.23 (0.12)	1.74 (0.69)	-0.16 (0.08)	-2.56 (1.08)	0.16 (0.09)	
86	382.35 (171.29)	-0.57 (0.36)	-2.99 (2.65)	-0.88 (0.42)	0.51 (0.25)	0.36 (0.65)	-0.10 (0.15)			-1.19 (0.89)	0.05 (0.07)	-0.44 (0.20)
87	356.24 (164.11)	-0.47 (0.36)	-2.41 (2.17)	-0.82 (0.40)	0.47 (0.24)	0.16 (0.58)	-0.11 (0.12)			-1.42 (0.96)	0.08 (0.08)	-0.43 (0.18)
88	327.73 (158.33)	-0.52 (0.36)	-2.39 (2.22)	-0.77 (0.38)	0.44 (0.23)	-0.22 (0.58)	-0.22 (0.13)	1.38 (0.59)	-0.17 (0.08)	-1.90 (0.89)	0.09 (0.08)	-0.36 (0.16)
89	392.72 (158.97)	-0.47 (0.36)	-2.34 (1.94)	-0.90 (0.38)	0.52 (0.23)	0.20 (0.57)	-0.12 (0.12)			-1.95 (0.88)	0.10 (0.07)	-0.46 (0.18)
90	332.14 (159.08)	-0.49 (0.37)	-2.69 (2.49)	-0.76 (0.39)	0.44 (0.23)	0.08 (0.60)	-0.14 (0.13)			-1.57 (0.93)	0.09 (0.08)	-0.41 (0.15)
91	395.74 (153.97)	-0.40 (0.36)	-2.22 (2.19)	-0.93 (0.37)	0.54 (0.23)	-0.33 (0.55)	-0.23 (0.12)	1.42 (0.61)	-0.11 (0.07)	-1.86 (0.99)	0.12 (0.08)	
92	345.55 (152.60)	-0.52 (0.38)	-1.54 (2.22)	-0.81 (0.37)	0.47 (0.22)	0.10 (0.52)	-0.16 (0.12)	1.49 (0.63)	-0.17 (0.09)	-1.77 (0.93)	0.08 (0.08)	-0.32 (0.15)
93	372.30 (154.57)	-0.58 (0.35)	-1.06 (2.22)	-0.86 (0.38)	0.50 (0.23)	-0.16 (0.56)	-0.21 (0.12)	1.95 (0.77)	-0.18 (0.10)	-2.14 (1.03)	0.13 (0.09)	

[a] See Appendix 10.1 for variable definitions
[b] Coefficients and standard errors multiplied by 10^3
[c] Coefficients and standard errors multiplied by 10^9
[e] Coefficients and standard errors multiplied by 10^4
[f] Coefficients and standard errors multiplied by 10^2

TABLE 10.5. Extended

$TOWER_{500}$	$POWER_{50}$	AG_d[e]	$WELL_{50}$	RD_{1km}	SAND	$SAND^2$[f]	$SOIL_{cm}$	LL	K	AIC	ΔAIC	$\sum w_i$
17.75 (7.50)	3.24 (1.43)	-0.72 (0.54)	30.34 (31.66)	2.43 (1.05)			-0.03 (0.01)	-251.75	14	538.30	6.46	0.854
	3.27 (1.37)	-1.26 (0.65)	24.62 (29.71)	3.15 (1.27)	0.20 (0.11)	-0.31 (0.17)		-250.77	15	538.43	6.50	0.856
18.39 (7.32)	3.42 (1.43)		31.45 (31.50)	2.67 (1.15)			-0.03 (0.01)	-252.79	13	538.29	6.54	0.859
	3.29 (1.37)	-1.07 (0.65)	25.78 (30.14)	2.90 (1.16)				-252.80	13	538.30	6.54	0.862
27.26 (8.11)	3.07 (1.23)		36.40 (37.94)		0.35 (0.12)	-0.54 (0.19)	0.03 (0.01)	-251.94	14	538.67	6.83	0.864
14.99 (7.86)			24.54 (29.03)	2.44 (1.07)				-254.98	11	538.50	6.91	0.866
20.92 (7.69)	3.24 (1.34)		27.64 (31.50)					-253.99	12	538.60	6.93	0.868
19.30 (7.49)		-0.84 (0.55)	33.68 (31.68)					-253.02	13	538.74	6.99	0.87
		-0.91 (0.61)	26.93 (30.83)	2.57 (1.11)				-253.11	13	538.92	7.17	0.872
26.39 (8.60)	2.88 (1.24)	-0.53 (0.56)	34.65 (37.52)		0.33 (0.13)	-0.52 (0.20)	0.03 (0.01)	-251.13	15	539.14	7.20	0.874
	3.08 (1.42)		24.99 (29.49)	3.16 (1.27)			0.01 (0.01)	-254.15	12	538.92	7.25	0.876
15.72 (8.18)		-0.76 (0.54)	24.29 (29.19)	2.42 (1.00)				-254.17	12	538.95	7.28	0.877
18.93 (7.24)			33.74 (31.31)					-254.18	12	538.97	7.30	0.879
18.12 (7.03)	3.31 (1.60)		30.72 (33.61)	2.94 (1.18)	0.16 (0.11)	-0.28 (0.18)	-0.02 (0.01)	-251.2	15	539.29	7.36	0.881
20.74 (7.42)	3.12 (1.28)	-1.15 (0.71)	27.69 (31.28)		0.17 (0.11)	-0.27 (0.16)		-251.24	15	539.37	7.44	0.883
17.48 (7.14)	3.21 (1.68)	-0.98 (0.59)	27.98 (32.53)	2.67 (1.06)	0.18 (0.12)	-0.31 (0.19)	-0.01 (0.01)	-250.26	16	539.50	7.46	0.884
	2.81 (1.20)		32.37 (31.20)					-254.33	12	539.27	7.60	0.886
			27.15 (30.24)	2.56 (1.07)				-254.34	12	539.29	7.62	0.887
	3.40 (1.29)		25.82 (30.20)	2.75 (1.26)				-254.34	12	539.31	7.64	0.889
18.25 (7.00)	3.14 (1.29)		25.79 (30.92)		0.22 (0.12)	-0.32 (0.17)		-253.35	13	539.40	7.65	0.890
14.30 (7.61)			21.84 (27.49)	2.52 (1.10)	0.12 (0.10)	-0.19 (0.14)		-253.35	13	539.41	7.65	0.892
		-1.10 (0.63)	23.58 (26.53)	2.97 (1.20)	0.24 (0.12)	-0.39 (0.19)	0.03 (0.02)	-250.36	16	539.70	7.66	0.893
15.72 (7.95)			26.31 (29.32)	2.48 (1.07)			0.01 (0.01)	-254.36	12	539.34	7.67	0.895
15.17 (8.27)		-0.94 (0.64)	22.27 (25.01)	2.58 (1.05)	0.16 (0.12)	-0.25 (0.18)		-252.36	14	539.51	7.67	0.896
16.39 (7.79)		-1.23 (0.64)	22.93 (28.20)	2.60 (1.13)	0.17 (0.11)	-0.27 (0.16)		-251.37	15	539.63	7.69	0.898
18.42 (7.05)		-0.94 (0.59)	27.73 (30.86)		0.24 (0.14)	-0.38 (0.22)	0.04 (0.02)	-250.39	16	539.76	7.73	0.899
20.36 (7.33)	3.01 (1.28)	-1.04 (0.64)	28.81 (30.62)				0 .00 (0.02)	-252.45	14	539.69	7.85	0.900

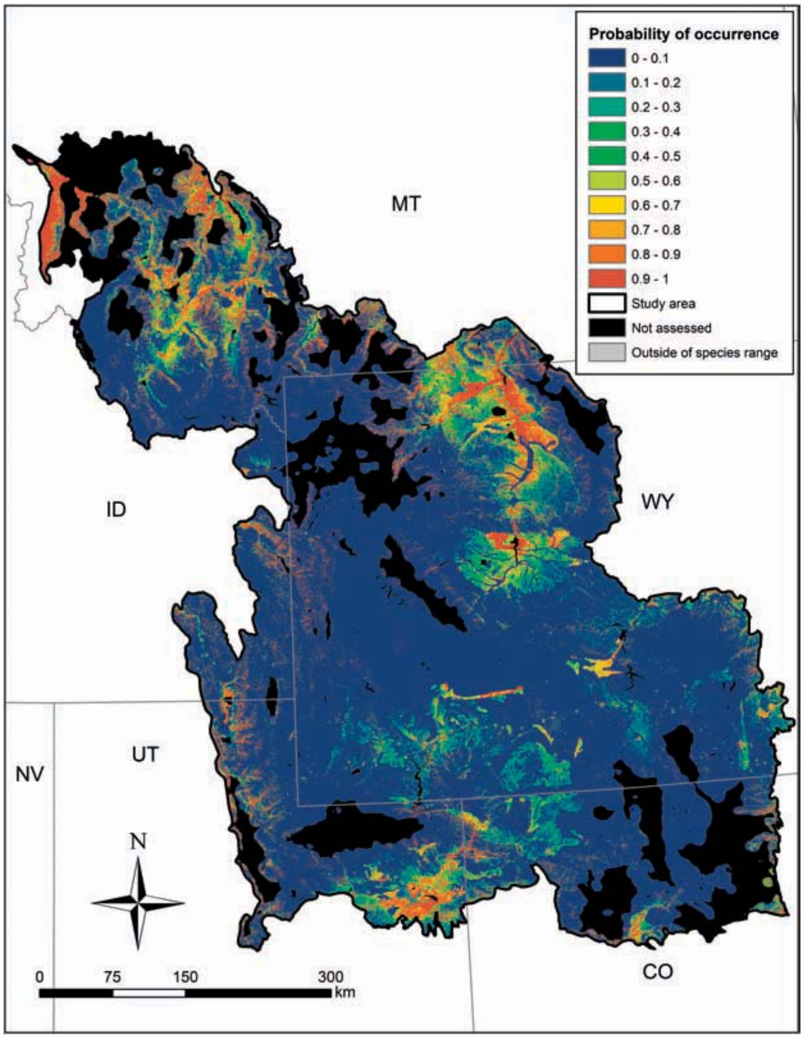

FIG. 10.5. Predicted probability of occurrence for halogeton in the Wyoming Basins Ecoregional Assessment area. Black areas are outside the inference of our models (<3% sagebrush within 5 km or within a body of water).

DISCUSSION

Fragmentation of sagebrush by anthropogenic disturbance, particularly major roads and energy wells, increased the occurrence of the four most common invasive plants in the Wyoming Basins: crested wheatgrass, cheatgrass, halogeton, and Russian thistle. Although the positive association between anthropogenic disturbance and non-native invasive plants was common across all species examined, the shape of the response to individual anthropogenic disturbances (i.e., the dose-response) varied among species. Response shapes were often non-linear and dependent on distance from disturbance type and species and limited by abiotic environments of climate, soils, and terrain. Anthropogenic factors that influenced non-native species occurrence included major roads, secondary roads, all road types, energy wells, railroads, agricultural areas, pipelines, power lines, transmission towers, and populated places. Crested wheatgrass and Russian thistle showed the strongest association with anthropogenic

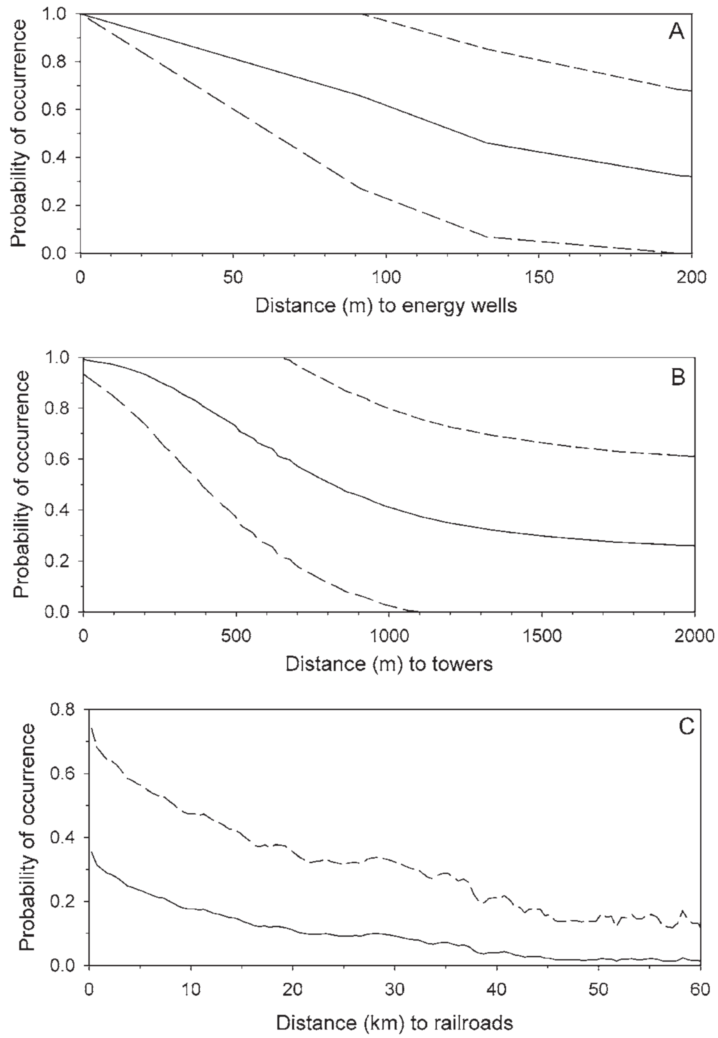

FIG. 10.6. Dose-response curves illustrating mean predicted probability of occurrence (±1 SD) of halogeton across the Wyoming Basins Ecoregional Assessment area as a function of distance from anthropogenic feature types of energy wells (A), towers (B), and railroads (C).

disturbances, particularly major roads and energy wells, which were included and among the strongest anthropogenic factors in all four invasive species models. Crested wheatgrass was often planted by management agencies to reduce erosion (Lorenz 1986, Lesica and DeLuca 1996). Thus, the distribution of this species likely reflects the location of those past activities. Crested wheatgrass has been one of the most commonly planted non-native grasses in western North America occupying between 6 and 10.5 million hectares (Holchek 1981, Rogler and Lorenz 1983). Several million hectares of crested wheatgrass were planted on idle farmland as part of the Conservation Reserve Program (Lesica and DeLuca 1996). The success of crested wheatgrass is due in part to its wide adaptability to different soil types and cold tolerance (Lesica and DeLuca 1996). Unlike the prior two species, cheatgrass and halogeton were predicted to occur across a much wider area of the Wyoming Basins, and thus appear to be limited by either abiotic environments or alternatively, biotic mechanisms associated

TABLE 10.6. Russian thistle random-effects logistic regression model[a] parameter estimates (beta [SE]), model log-likelihood (LL), number of parameters (K), Akaike's Information Criterion (AIC), change in AIC value from the top model (ΔAIC), and Akaike weight (w_i) for all candidate models in the Wyoming Basins Ecoregional Assessment area where Akaike weights sum to just ≥ 0.9. Superscript numbers reflect quadratic terms, while subscript numbers for anthropogenic and water variables represent the distance parameter value of the exponential distance decay function used to scale distance effects. Anthropogenic terms ending in the subscript letter "d" reflect Euclidian distance variables rather than distance decay functions.

Rank	Intercept	NDVI	$NDVI^2$	SOLR[b]	$pH2Od_{1km}$	POP_d[b]	$2RD_{250}$	$WELL_{1km}$	$MjRD_{500}$
1	29.71 (6.45)	3.98 (3.60)	-10.44 (7.25)	-0.04 (0.01)	-3.29 (1.53)	-0.08 (0.03)	2.76 (0.68)	3.47 (1.12)	3.35 (0.98)
2	27.66 (6.43)	1.57 (3.55)	-12.11 (8.31)	-0.04 (0.01)		-0.09 (0.03)	2.74 (0.69)	3.36 (1.15)	3.46 (1.01)
3	26.79 (6.47)	1.81 (3.56)	-11.72 (8.24)	-0.04 (0.01)		-0.09 (0.03)	2.77 (0.69)	3.19 (1.16)	3.07 (1.06)
4	30.71 (6.59)	4.68 (3.59)	-9.70 (7.24)	-0.04 (0.01)	-4.37 (1.60)		2.76 (0.68)	4.23 (1.16)	3.24 (1.00)
5	30.99 (6.62)	3.21 (3.55)	-18.43 (8.21)	-0.04 (0.01)		-0.12 (0.03)	2.64 (0.67)		2.88 (0.97)
6	25.88 (7.91)	0.87 (3.44)	-12.10 (7.53)	-0.04 (0.01)		-0.10 (0.03)	2.92 (0.68)		3.47 (1.00)
7	33.03 (6.56)	6.12 (3.56)	-11.68 (7.54)	-0.05 (0.01)	-3.86 (1.53)		2.75 (0.67)	4.08 (1.14)	3.53 (0.99)
8	27.35 (6.54)	1.37 (3.63)	-11.90 (8.34)	-0.04 (0.01)		-0.09 (0.03)	2.73 (0.69)	3.40 (1.16)	3.43 (1.02)
9	31.98 (6.62)	6.16 (3.57)	-11.42 (7.50)	-0.05 (0.01)	-3.64 (1.54)		2.77 (0.68)	3.90 (1.15)	3.16 (1.04)
10	34.21 (7.75)	6.00 (3.45)	-13.87 (7.06)	-0.05 (0.01)	-3.74 (1.44)		2.92 (0.66)		3.48 (0.96)
11	31.24 (6.53)	3.60 (3.54)	-17.26 (8.08)	-0.04 (0.01)		-0.11 (0.03)	2.24 (0.64)	2.56 (1.07)	
12	28.81 (6.49)	3.98 (3.53)	-18.11 (8.08)	-0.03 (0.01)		-0.11 (0.03)	2.41 (0.65)		
13	22.37 (7.71)	1.34 (3.39)	-10.36 (7.18)	-0.03 (0.01)		-0.09 (0.03)	2.66 (0.65)		

[a] See Appendix 10.1 for variable definitions
[b] Coefficients and standard errors multiplied by 10^3

with dispersal capabilities and competition (thus a much more diffuse distribution from anthropogenic disturbances).

The shape of the response to anthropogenic disturbances (distances) varied substantially among species and disturbance types, showing local (<100 m) to meso-scale (100 m to 1 km) associations, such as energy wells and major roads respectively, to more macro-scale (>1 km) associations, particularly railroads and agricultural disturbances. In general, energy wells illustrated very strong local effects, roads and other linear features showed strong meso-scale effects, and agriculture and railroads displayed weaker macro-scale responses. The more local effects of energy wells may be simply an artifact of being a relatively young disturbance compared to other disturbance types. The zone of influence around energy wells may expand with time.

Similar to the results of our study, Bergquist et al. (2007) found in the Powder River Basin of Wyoming that non-native invasive plant occurrence varied based on the type of disturbance (coal bed methane developments), although they did not examine the zone (distance) of influence around individual disturbance types or make spatially explicit predictions of the overall landscape effect. Comparing the results of our analysis of non-native invasive species in the WBEA area (using much larger-sized quadrats at 1,257 m^2) to the Powder River Basin work (1-m^2 quadrats) by Bergquist et al. (2007), halogeton was much rarer in the Powder River Basin, while the overall occurrence of both crested wheatgrass and Russian thistle were similar among study areas. Cheatgrass was much more common in the Powder River Basin, being found in approximately 60% of sampled 1-m^2 quadrats, while frequency of occurrence in the

TABLE 10.6. Extended

$PIPE_{250}$	CLAY	$CLAY^2$	Tmin	$Tmin^2$	AG_d[b]	LL	K	AIC	ΔAIC	$\sum w_i$
						-211.33	10	442.95	0.00	0.462
						-214.06	9	446.34	3.44	0.545
1.30 (0.97)						-213.18	10	446.63	3.69	0.618
					-0.09 (0.05)	-213.43	10	447.14	4.20	0.675
	-0.45 (0.14)	0.012 (0.004)				-213.59	10	447.46	4.52	0.723
			0.90 (0.45)	0.16 (0.06)		-213.85	10	447.98	5.04	0.760
						-214.87	9	447.96	5.07	0.797
					-0.01 (0.05)	-214.03	10	448.33	5.39	0.828
1.22 (0.95)						-214.06	10	448.40	5.46	0.858
			0.72 (0.43)	0.16 (0.06)		-215.06	10	450.41	7.46	0.869
	-0.43 (0.14)	0.012 (0.004)				-215.09	10	450.46	7.52	0.880
2.15 (0.88)	-0.44 (0.14)	0.012 (0.004)				-215.15	10	450.58	7.63	0.890
2.87 (0.91)			0.96 (0.44)	0.17 (0.06)		-215.15	10	450.59	7.64	0.900

WBEA quadrats was only 13.5%, despite the larger size of our plots. This difference may reflect the study extent of the Powder River Basin work, which at the regional scale occurs in optimal climates for cheatgrass, consistent with our model predictions. Our predictions of cheatgrass occurrence were also similar to those estimated using bioclimatic envelopes by Bradley (2009), even though we used only one climate variable – mean annual minimum temperature. However, in both cases cheatgrass appears to be limited by cold temperatures (winter or annual temporal scale). We also used additional environmental habitat predictors, including remotely-sensed vegetation productivity (found most commonly in intermediate areas of NDVI) and terrain-based solar radiation (found most commonly in sites having intermediate amounts of summertime solar radiation). Both NDVI and solar radiation are likely to be correlated with other climate variables, including those used by Bradley (2009). Without further experiments it is not possible to distinguish which factors are more important or what specific factors (physiological limitations, competition effects, etc.) limit the distribution of cheatgrass.

CONCLUSIONS

Distribution maps and dose-response predictions for four major non-native invasive plants offer an important regional management and planning tool for stakeholders and management agencies interested in controlling invasive plants. Knowledge about the current distribution and potential risk of further developments can help target implementation of management actions and effectiveness monitoring, improve assessments of the long-term spread of invasive species,

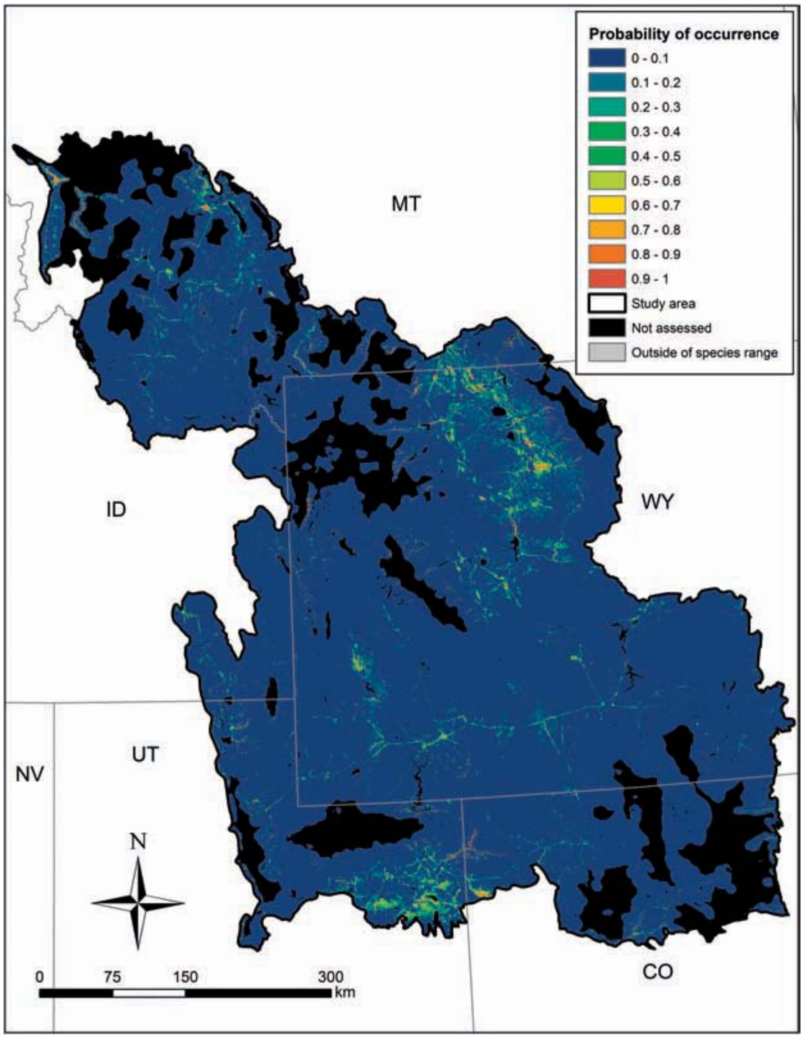

FIG 10.7. Predicted probability of occurrence for Russian thistle in the Wyoming Basins Ecoregional Assessment area. Black areas are outside the inference of our models (<3% sagebrush within 5 km or within a body of water).

and identify areas of sagebrush habitat relatively free from invasive species problems for conservation purposes. Future research should evaluate establishment rates around energy wells and new roads for common invasive plants in the WBEA area, with sites sampled (stratified) by age of disturbance. Such information could be used to predict future threats (growth) associated with energy development within the WBEA area and where invasive species control measures may be most needed.

LITERATURE CITED

Aldridge, C. L., S. E. Nielsen, H. L. Beyer, M. S. Boyce, J. W. Connelly, S. T. Knick, and M. A. Schroeder. 2008. Range-wide patterns of sage-grouse persistence. Diversity and Distributions 14:983–994.

Baker, W.L. 2006. Fire and restoration of sagebrush ecosystems. Wildlife Society Bulletin 34:177–185.

Bergquist, E., P. Evangelista, T. J. Stohlgren, and N. Alley. 2007. Invasive species and coal bed methane development in the Powder

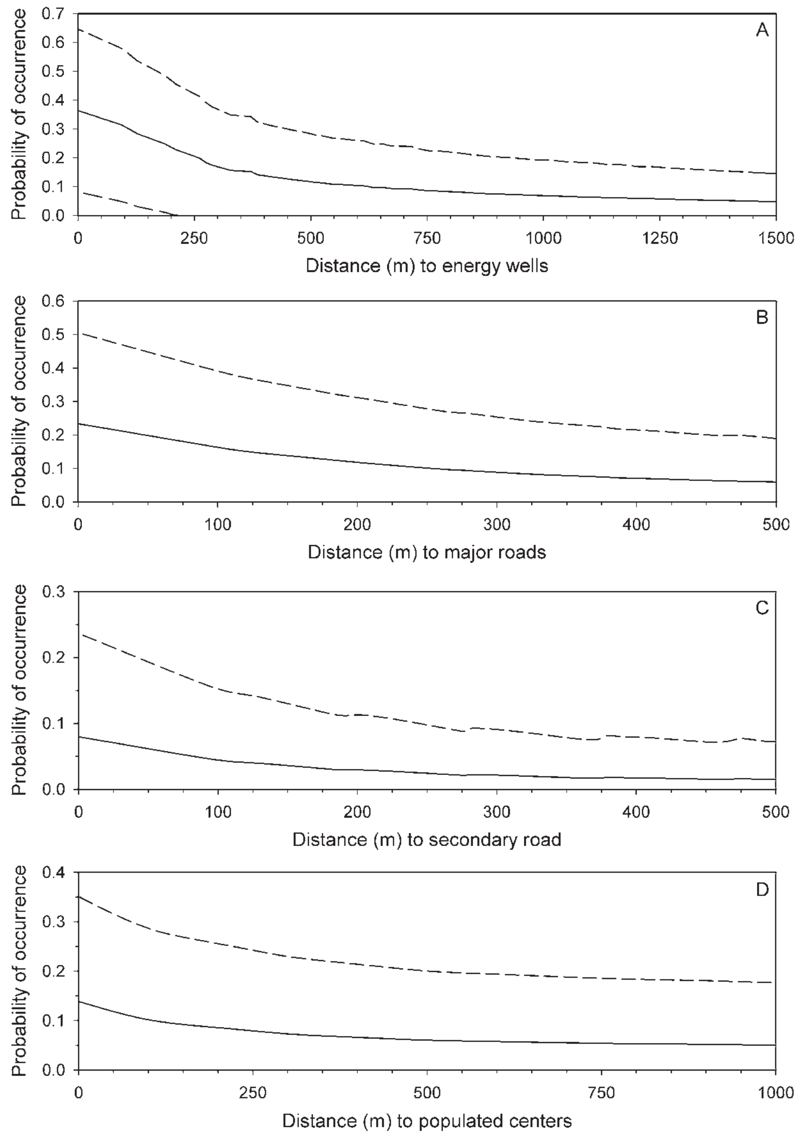

FIG. 10.8. Dose-response curves illustrating mean predicted probability of occurrence of Russian thistle across the Wyoming Basins Ecoregional Assessment area as a function of distance from anthropogenic feature. Dose-response curves illustrating mean predicted probability of occurrence (±1 SD) of Russian thistle across the Wyoming Basins as a function of distance from anthropogenic feature types of energy wells (A), major roads (B), secondary roads (C), and populated centers (D).

River Basin, Wyoming. Environmental Monitoring and Assessment 128:381–394.

Bradley, B. A. 2009. Regional analysis of the impacts of climate change on cheatgrass invasion shows potential risk and opportunity. Global Change Biology 15:196–208.

Brooks, M. L., C. M. D'Antonio, D. M. Richardson, J. B. Grace, J. E. Keeley, J. M. DiTomaso, R. J. Hobbs, M. Pellant, and D. Pyke. 2004. Effects of invasive alien plants on fire regimes. BioScience 54:677–688.

Burnham, K. P., and D. R. Anderson. 2002. Model selection and multimodel inference: a practical information-theoretic approach. Second edition. Springer-Verlag, New York, NY.

CARROLL, M. L., C. M. DIMICELI, R. A. SOHLBERG, AND J. R. G. TOWNSHEND. 2006. 250m MODIS Normalized Difference Vegetation Index. University of Maryland, College Park, MA.

COMER, P., D. FABER-LANGENDOEN, R. EVANS, S. GAWLER, C. JOSSE, G. KITTEL, S. MENARD, M. PYNE, M. REID, K. SCHULZ, K. SNOW, AND J. TEAGUE. 2003. Ecological systems of the United States: A working classification of U.S. terrestrial systems. NatureServe, Arlington, VA.

CONNELLY, J. W., E. T. RINKES, AND C. E. BRAUN. 2011. Characteristics of greater sage-grouse habitats: a landscape species at micro and macro scales. Pages 69–84 *in* S. T. Knick and J. W. Connelly (editors). Greater sage-grouse: ecology and conservation of a landscape species and its habitats. Studies in Avian Biology 38. University of California Press, Berkeley, CA.

CONNELLY, J. W., M. A. SCHROEDER, A. R. SANDS, AND C. E. BRAUN. 2000. Guidelines to manage sage grouse populations and their habitats. Wildlife Society Bulletin 28:967–985.

DAVIES, K. W., AND R. L. SHELEY. 2007. A conceptual framework for preventing the spatial dispersal of invasive plants. Weed Science 55:178–184.

DAUBENMIRE R. A. 1959. Canopy-coverage method of vegetational analysis. Northwest Science 33:43–64.

DOHERTY, K. E., D. E. NAUGLE, B. L. WALKER, AND J. M. GRAHAM. 2008. Greater sage-grouse winter habitat selection and energy development. Journal of Wildlife Management 72:187–195.

ESRI. 2006. ArcMap version 9.2. Environmental Systems Research Institute, Inc., Redlands, CA.

GELBARD, J. L., AND J. BELNAP. 2003. Roads as conduits for exotic plant invasions in a semiarid landscape. Conservation Biology 17:420–432.

GREEN, J. S., AND J. T. FLINDERS. 1980. *Brachylagus idahoensis*. Mammal Species 125:1–4.

HANSER, S. E., AND N. J. HUNTLY. 2006. The biogeography of small mammals of fragmented sagebrush-steppe landscapes. Journal of Mammalogy 87:1165–1174.

HANSER, S. E., C. L. ALDRIDGE, M. LEU, AND S. E. NIELSEN. 2011. Dose Response Calculator for ArcGIS. United States Geological Survey Data Series 631. <http://pubs.usgs.gov/ds/631/> (20 September 2011).

HOLCHEK, J. L. 1981. Crested wheatgrass. Rangelands 3:237–250.

KNICK, S. T., D. S. DOBKIN, J. T. ROTENBERRY, M. A. SCHROEDER, W. M. VANDER HAEGEN, AND C. VAN RIPER. 2003. Teetering on the edge or too late? Conservation and research issues for avifauna of sagebrush habitats. Condor 105:611–634.

KNICK, S. T., J. T. ROTENBERRY, AND M. LEU. 2008. Habitat, topographical, and geographical components structuring shrubsteppe bird communities. Ecography 31:389–400.

LANDFIRE. 2007. LANDFIRE 1.0.0 existing vegetation type layer. U.S. Department of Interior, Geological Survey. <http://landfire.cr.usgs.gov/viewer/> (20 September 2011).

LESICA, P., AND T. H. DELUCA. 1996. Long-term harmful effects of crested wheatgrass on Great Plains grassland ecosystems. Journal of Soil and Water Conservation 51:408–409.

LORENZ, R. J. 1986. Introduction and early use of crested wheatgrass in the northern Great Plains. Pp. 9–19 *in* K. L. Johnson (editor). Crested wheatgrass: Its values, problems and myths; Symposium proceedings. Utah State University, Logan, Utah. 3–7 October 1983.

MACK, R. N. 1981. Invasions of *Bromus tectorum* L. into western North America: an ecological chronicle. Agro-Ecosystems 7:145–165.

MANIS, G., J. LOWRY, AND R. D. RAMSEY. 2001. Preclassification: An ecologically predictive landform model. Gap Analysis Program Bulletin No. 10, December 2001. USGS GAP Analysis Program. Moscow, ID.

METZ, C. E. 1978. Basic principles of ROC analysis. Seminars in Nuclear Medicine 8:283–298.

MILLER, D. A., AND R. A. WHITE. 1998. A conterminous United States multilayer soil characteristics dataset for regional climate and hydrology modeling. Earth Interactions 2:1–26.

NIELSEN, S. E., J. CRANSTON, AND G. B. STENHOUSE. 2009. Identification of priority areas for grizzly bear conservation and recovery in Alberta, Canada. Journal of Conservation Planning 5:38–60.

PYKE, D. A. 2000. Invasive exotic plants in sagebrush ecosystems of the Intermountain West. Pp. 43–54 *in* P. G., Entwistle, A. M. DeBolt, J. H. Kaltenecker, and K. Steenhof (compilers). Proceedings: sagebrush steppe ecosystems symposium. U.S. Bureau of Land Management Publication No. BLM/ID/PT-001001+1150, Boise, ID.

PARENDES, L. A., AND J. A. JONES. 2000. Role of light availability and dispersal in exotic plant invasion along roads and streams in the H. J. Andrews Experimental Forest, Oregon. Conservation Biology 14:64–75.

PIMENTEL, D., R. ZUNIGA, AND D., MORRISON. 2005. Update on the environmental and economic costs associated with alien-invasive species in the United States. Ecological Economics 52:273–288.

PRISM GROUP. 2007. United States minimum annual temperature, 1971 – 2000. Oregon State University. <http://www.prismclimate.org> (20 September 2011).

RIITTERS, K. H., AND J. D. WICKHAM. 2003. How far to the nearest road? Frontiers in Ecology and the Environment 1:125–129.

RILEY, S. J., S. D. DEGLORIA AND R. ELLIOT. 1999. A terrain ruggedness index that quantifies topographic heterogeneity. Intermountain Journal of Sciences 5:1–4.

ROGLER, G. A., AND R. J. LORENZ. 1983. Crested wheatgrass-early history in the United States. Journal of Range Management 36:91–93.

VON DER LIPPE, M., AND I. KOWARIK. 2007. Long-distance dispersal of plants by vehicles as a driver of plant invasions. Conservation Biology 21:986–996.

WALKER, B. L., D. E. NAUGLE, AND K. E. DOHERTY. 2007. Greater sage-grouse population response to energy development and habitat loss. Journal of Wildlife Management 71:2644–2654.

WHISENANT, S. G. 1990. Changing fire frequencies on Idaho's Snake River Plains: ecological and management implications. Pp. 4–10 *in* E. D. McArthur, E. M. Romney, S. D. Smith, and P. T. Tueller (compilers). Proceedings - Cheatgrass invasion, shrub die-off, and other aspects of shrub biology and management. USDA Forest Service General Technical Report INT-GTR-276. USDA Forest Service Intermountain Research Station, Ogden, UT.

U.S. GOVERNMENT ACCOUNTABILITY OFFICE. 2005. Invasive species. Cooperation and coordination are important for effective management of invasive species. Report to the Chairman, Committee on Resources, House of Representatives. GAO-05-185. U.S. Government Accountability Office, Washington, D.C.

APPENDIX 10.1. Variable descriptions and summary statistics from field plots in the Wyoming Basins Ecoregional Assessment area.

Variable			*Summary statistics*			
Group	Code	Description	$\bar{x}$	SD	Min	Max
A. Habitat and survey design factors						
	NDVI	Maximum Natural Difference Vegetation Index (vegetation productivity) from MODIS sensor (Carroll et al. 2006)	0.13	0.22	-0.26	1.10
	SAGE	Sagebrush presence/absence	0.79	0.41	0.0	1.0
B. Abiotic factors						
	TRI	Terrain Ruggedness Index (Riley et al. 1999)	20.7	21.1	0.0	154.0

APPENDIX 10.1 Continued

Variable			*Summary statistics*			
Group	Code	Description	$\bar{x}$	SD	Min	Max
	TRMI	Topographic Relative Moisture Index (Manis et al. 2001)	15.1	5.6	1.0	27.0
	SOLR[a]	Solar radiation (WH/m^2, May - August) estimated from a DEM	849.2	30.5	733.6	950.7
	Tmin	Mean minimum temperature (°C) of coldest month	-2.9	1.9	-7.4	0.9
	SAND	Percent sand in soils (Miller and White 1998)	39.2	14.7	0.0	88.3
	CLAY	Percent clay in soils (Miller and White 1998)	16.6	7.1	0.0	47.0
	AWC	Available water content (Miller and White 1998)	5.2	1.7	1.5	9.2
	SALIN	Salinity of soils (Miller and White 1998)	2.3	1.6	0.0	9.5
	$SOIL_{cm}$	Soil depth (cm) (Miller and White 1998)	101	29	38	152
	pH2Od	Distance (m) to perennial water source	3,913	3,683	0	20,390
C. Anthropogenic factors						
	RD	Any road type (distance in meters)	481	529	0	3,711
	MjRD	Major roads (distance in meters)	9,048	9,862	0	43,926
	2RD	Secondary roads (distance in meters)	521	546	0	3,711
	RAIL	Railroad (distance in meters)	38,944	24,850	485	107,281
	WELL	Energy well (distance in meters)	10,591	8,647	0	41,180
	TOWER	Tower (distance in meters)	16,124	9,654	371	46,584
	POWER	Power line (distance in meters)	11,316	14,466	0	70,495
	PIPE	Pipeline (distance in meters)	10,856	11,682	0	53,224
	POP	Populated place (distance in meters)	17,320	10,293	180	50,766
	AG	Agriculture (distance in meters)	6,337	6,091	90	29,158

[a] Units are multiplied by 10^{-2}