Mapping Percent-Cover of the Invasive Species *Bromus tectorum* (Cheatgrass) over a Large Portion of Nevada from Satellite Imagery.

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Summary: *Bromus tectorum* (cheatgrass) is an annual grass from Eurasia that has invaded western rangelands. It frequently invades landscapes after wildfire, forming dense stands with fine fuels that shorten typical fire intervals. Thus *B. tectorum* and wildfire form a positive feedback mechanism that threatens native ecosystems and often impact the rare and endangered species those ecosystems host. It is not an understatement to say that *B. tectorum* is among the greatest threats to conservation in the intermountain west.

Elimination of *B. tectorum* from the landscape is unrealistic with current technology. Instead, we must learn to manage rangelands so as to minimize the dispersal and establishment of *B. tectorum*, and to promote the reestablishment of native vegetation after disturbances such as wildfire. Key to such management is a strong understanding of where *B. tectorum* has invaded the landscape and how dense it has become. With this need in mind, the Nevada Natural Heritage Program set out to map *B. tectorum* over a large portion of the state of Nevada. A portion of this area was used to test how well the mapping method could be extended to areas beyond the training area.

The mapping method involved developing a statistical model for the estimation of *B. tectorum* cover at training plots with variables derived from satellite imagery and matching topographic data. The model was then applied to each 28.5 X 28.5 meter pixel in the satellite images. Map accuracy was then determined as Root-Mean-Square Error (RMSE) at additional accuracy assessment plots.

Sample plots involved an ocular estimation of percent ground-cover of *B. tectorum* over a circular area of 0.1 hectares. Training data included 262 sampled plots scattered throughout an original (northern 2/3) mapping area. These plots were located arbitrarily to include a broad variety of landscape conditions. For accuracy assessment, an additional 75 plots were sampled. These assessment plots were located throughout the entire mapping area with a constrained-random distribution: random within public lands and within 1 kilometer of a significant road.

Landsat 7 ETM+ satellite data were obtained for two time periods in order to use the unusual early phenology (green-up and senescence) of *B. tectorum* as the primary component of the mapping method. The Normalized Differential Vegetation Index (NDVI) was calculated for each time period and the difference in NDVI between the time periods was then used as the measure of phenology across the landscape. This measure of phenology corresponded well to the cover of *B. tectorum* at the training plots and formed the most important factor in the mapping model. Additional factors that were found statistically significant and decreased error were elevation and the green spectrum band of the satellite image from the senescence-period. Additionally the average pixel brightness was used to bound maximum estimations, reducing error for particularly bright areas of the imagery such as playas and dark areas such as lakes. Post-modeling edits included cultivated fields, urban areas, clouds and their shadows, and a few shallow water bodies where the estimated cover was greater than zero.

The resulting map covers of 32.8 million acres within Nevada, or 46.4 % of the state, plus an additional 2.5 million adjacent acres in neighboring states for potential edge-matching with future mapping projects. The 75 accuracy assessment plots indicate a map-wide RMSE of 9.14 %. To examine how well the model extended to the area beyond the area sampled for training data, accuracy assessment plots were split into two groups: those from the trained portion of the map and those from the untrained portion. Accuracy assessment plots from the trained portion indicate an RMSE of 12.0 %, while plots from the untrained portion indicate an RMSE of 2.8 %. These results are surprising, however the untrained portion of the map includes a great deal of land without *B. tectorum*, so these results are largely indicating that there is greater accuracy in the prediction of absence or low cover of *B. tectorum*, than in the prediction of the precise cover amount where it is abundant. These results at least do not indicate any problem with extending the model to areas within 100 km of the training area, where *B. tectorum* invasion is low.

Introduction

Bromus tectorum L. (cheatgrass) is an annual grass from Eurasia that has been invading western rangelands for at least a century (Young & Allen 1997). It frequently invades landscapes after wildfire, forming dense stands. *B. tectorum* has an earlier phenology than most native vegetation, senescing early in the year and leaving fine fuels that shorten fire intervals (Whisenant 1990; Billings 1994). Thus *B. tectorum* and wildfire form a positive feedback mechanism that threatens native ecosystems and often impacts the rare and endangered species those ecosystems host. Estimates suggest that half or more of the sagebrush steppe (sagebrush with significant grass understories) has been invaded to some degree and that about a quarter has been converted to *B. tectorum* dominated grasslands (West 1999). In Nevada, the sagebrush steppe occurs at higher elevations plus mid elevations toward the north of the state. Non-steppe sagebrush shrublands, mainly at lower elevations and to the south, are likely in similar, condition. *B. tectorum* invasion and dominance after fire can be viewed as a new successional pathway leading to a non-native state, which is very stable except for potential invasion of other non-native weeds (Hann et al. 1997; West 1999; West & Young 2000). It is not an understatement to say that *B. tectorum* is among the greatest challenges for conservation in the Intermountain West.

Although episodic die-offs of *B. tectorum* suggest that reduction of its density on a landscape level may be possible, elimination of *B. tectorum* from the landscape is unrealistic with current or foreseeable future technology. Instead, we must learn to manage rangelands to minimize the dispersal and establishment of *B. tectorum*, and to promote the reestablishment of native vegetation after disturbances such as wildfire. And conservation of native species must acknowledge and understand the presence and affects of *B. tectorum* over the landscape (Anonymous 2001; Rowland & Wisdom 2002). Key to conservation and land management is a map of where *B. tectorum* has invaded the landscape and how dense it has become.

With this need in mind, the Nevada Natural Heritage Program set out to map cover density of *B. tectorum* over a large portion of the state of Nevada. I hypothesized that the early phenology of *B. tectorum* can be used to distinguish it from other vegetation, using satellite imagery from two separate dates. A fortuitous change in the pricing of the satellite data enabled expansion of the mapping area after most of the training data collection but before the assessment data collection. Thus I added an additional hypothesis that the method can be extended to areas neighboring the training data collection up to a distance of about 100 km.

Methods

Overview. Ground data were collected for developing the mapping model (training data) and for assessing the accuracy of the model (assessment data). Satellite images were obtained over the area for early- and late-season dates. The training data were attributed with corresponding data available across the entire geographic area (satellite imagery spectrum bands, elevation, and derived variables). The mapping model was developed from the training data with Tobit Regression, a statistical procedure similar to Multiple Linear Regression, and with estimation limits based on visual interpretation of data graphs. The model was applied to estimate *B. tectorum* cover for each pixel in the satellite images, resulting in the map of estimated *B. tectorum* cover. Post-modeling edits included cultivated fields, urban areas, clouds and their shadows, and a few shallow water bodies where the estimated cover was greater than zero. Error for the final map was calculated from the independent assessment data.

Satellite Imagery. Landsat 7 ETM+ images were purchased from the U. S. Geologial Survey EROS Data Center. Images covered rows 31 to 33 for paths 41 and 42 (Figure 1) for two different dates. Date selection criteria included nearly cloud-free images within the same year targeting the early green-up season of *Bromus tectorum* in late April and senescence season of *B. tectorum* (while other grasses are still green) in late June.

Images were acquired in UTM zone 11 projection with the North American 1927 Datum and with 28.5 m pixels. The rows within a path for a given date were provided as a single image with the "systematic" level of correction. The correction is described as "Radiometrically and geometrically corrected using the satellite model and platform/ephemeris information. Rotated and aligned to the user defined map projection" (U.S.G.S. 2002). Geographic positional accuracy of these images was low so they were further geometrically corrected in Imagine (ERDAS 2002), by registering a minimum of 50 points per scene, to UTM projections of the summer-season images being used for the Southwest Regional Gap Analysis Program landcover map (REGAP; U.S.G.S. 2003). This will maximize use of the *B. tectorum* map in conjunction with the REGAP mapped vegetation. Geometric correction also involved the Landsat 7 geometric model (ERDAS 2002) and the National Elevation Dataset (NED; U.S.G.S. 1999 – downloaded February, 2003) in a matching projection with 30 m pixels. Due to the use of the geometric model, each set of 3 continuous scenes needed to be subset to the individual scene areas.

Geometrically corrected scenes for a given season were mosaicked in Imagine with the overlap order set to minimize cloud presence in the final image. The 28.5 m resolution of the original satellite images was retained throughout all processing. Finally, the images were clipped to the area of interest for vegetation mapping by the Nevada Natural Heritage Program. This area includes the state of Nevada plus a 25 km buffer and an additional buffer to include the entire Lake Tahoe watershed (Figure 2).

Training Data. A total of 262 plots were sampled within the mapping area for training data (Figure 3A). Plots were located arbitrarily in order to incorporate a broad variety of landscape forms and vegetation types into the training dataset. Locations were found by driving through different portions of the mapping area and watching for areas of uniform vegetation of approximately 1 hectare or more. For efficiency sake, most plots were located within 0.5 km of drivable roads. Due to preliminary expectations that only 4 Landsat scenes would be used, training data was confined to the northern 2/3 of the mapping area.

The sampling plots were circular areas of 0.1 hectares (17.8 m radius). Geographic position of plot centers was measured with a 12 channel GPS receiver with Root-Mean-Square Error (RMSE) < 15 meters (a Garmin GPS12 or a Garmin eTrex Legend). Within the sampling plot, I determined percent cover of *B. tectorum* by ocular estimation. Additional data were also collected including slope, aspect, and cover of other vegetation components including cover for each specie of perennially above-ground vascular plant, and cover of biological soil crusts. All data were entered directly into a Geographic Information Systems (GIS) point coverage with ArcPad 6 (ESRI 1995-2003) in order to eliminate transcription error.

Assessment Data. A total of 75 plots were sampled within the mapping area for accuracy assessment (Figure 3B). Plots were located *a priori* by a randomization algorithm in GIS software. Randomization was limited to accessible public lands (U.S. Department of

Defense and Department of Energy administered lands were excluded) and within 1 km of a significant road. Due to these limits, the resulting locations are no longer random within the entire mapping area and will hereafter be referred to as 'pseudorandom'. Methodology for sampling the plots was otherwise identical to the training data sampling plots.

Landscape Data. Several additional variables that are available geographically for the entire mapping area were used or tested for the mapping model. Elevation data were obtained from the NED (USGS 1999; Figure 4). The elevation data were downloaded, mosaicked, then projected to match the satellite images in Imagine (ERDAS 2002) with 30 meter pixels. A Heat Index (Beers et al. 1966; Peterson 2000; Figure 5) was calculated from slope and aspect which were derived from the NED:

$$HeatIndex = \left(\left(\frac{1-\cos(A-45)}{2} \right) - 0.5 \right) \left(\frac{1-\cos(4S)}{2} \right) + 0.5$$

where A is the slope in degrees from level and S is aspect in degrees east of north. The Heat index ranges from 0 on 45° north-east slopes to 1 on 45° south-west slopes and also used 30 meter pixels.

Data from Satellite Imagery. Satellite data actually contains brightness values for several portions of the spectrum. The Landsat 7 ETM+ images are composed of values for 8 bands of the spectrum (Table 1; NASA 2003). For each season, the 6 bands available with ca. 30 m pixel size were tested for use in the mapping model.

Several additional variables were derived from the 6 bands and tested for use in the mapping model. Chlorophyll in green plants is highly reflective in the near infra-red, band 4, making it quite useful for quantifying vegetation. This is used in the Normalized Difference Vegetation Index (NDVI; Jensen 1996), which was used to quantify vegetation for each season (Figures 6A & 6B):

$$NDVI = \frac{IR - R}{IR + R}$$

where IR is the infra-red band 4 and R is the red band 3.

Phenological variables were also calculated from the two NDVI maps. The first was calculated by subtracting the early season NDVI from the late season NDVI resulting in negative values for areas with early phenology and positive values for areas with later phenology (Figure 6C. The second was calculated as a ratio of the relativized NDVI from each season (Figure 6D):

$$relNDVI1 = \frac{NDVI1 - \min NDVI1}{\max NDVI1 - \min NDVI1}$$

$$relNDVI2 = \frac{NDVI2 - \min NDVI2}{\max NDVI2 - \min NDVI2}$$

$$NDVIratio = \frac{relNDVI2 - relNDVI1}{relNDVI2 + relNDVI1}$$

The satellite images for each season were also transformed by the Tasseled Cap method (Jensen 1996; Huang et al. s.d.), which extracts 6 new variables representing 'greenness', 'wetness', 'brightness', and 3 additional variables with less distinct meaning.

Model Development. The values of these geographic variables were extracted for all training plots to develop the mapping model. These data were loaded into the R statistical package (R Development Core Team 2002). Since exceptionally poor sites for *B. tectorum* cannot have percent cover values below zero, the cover data are zero-truncated. This presents a severe problem for classical linear regression, which can be overcome with Tobit Regression (Tobin 1958), or Survival Analysis. Tobit Regression is a parametric method based on a combination of Multiple Linear Regression and Probit Analysis. This method is widely used in econometrics but is just beginning to be used in biological sciences, where it is being used mainly for medical studies measuring a parameter of health that can be truncated at death (Austin et al. 2000). Tobit Regression was used to develop the mapping model with the R 'survival' add-in package, (see sample log in Appendix A).

The model was further developed by plotting percent cover over individual bands in the original satellite images to visually search for cut-off levels that might reduce error.

Map production. Imagine's Model Builder was used to recreate the mapping model within the geographic image analysis software. The model was then run on all relevant geographic data, resulting in estimations of percent cover for each 28.5 X 28.5 meter pixel in the satellite imagery.

Post-modeling alterations were made to the map to eliminate some errors. First, a smoothing kernel was used to filter some of the noise in the map (Nelson 1998; Figure 7). The kernel used replaces the value of each pixel with a weighted average of the pixel and the four adjacent pixels in cardinal directions, where the focal pixel's value is given a weight of 4 while the adjacent pixels are each weighted at one. Then clouds and cloud shadows were removed and replaced with the 'no-data' value; the cloud replacement was partially automated with an algorithm described in Appendix B, then edited by hand. Finally obvious cultivated fields were manually replaced with the value 101 and areas of human habitation ('urban') were manually replaced with the value 102.

Results

Nearly cloud-free images for target seasons were obtained from the year 2001. Imagery available from appropriate seasons of 2002 or 2003 was severely obscured by clouds. Dates found to match the season criteria were May 4, 2001 and June 21, 2001 for path 41, and April 25, 2001 and June 28, 2001 for path 42. The positional Root-Mean-Square Error (RMSE) was less than 30 m for all scenes during geometric correction. These images allowed mapping of 32.8 million acres within Nevada, or 46.4 % of the state, plus an additional 2.5 million adjacent acres in neighboring states for potential edge-matching with future mapping projects.

Summaries for training and assessment data sampling plots are given in Appendix C. Of the 262 training data sampling plots, 80 plots completely lacked *Bromus tectorum*, 17 had a trace (computed as 0.1 percent), and 165 had one or more percent cover of *B. tectorum* (Figure 8a). Of the 75 assessment data sampling plots, 34 completely lacked *B. tectorum,* 4 had a trace, and 37 had one or more percent cover (Figure 8b). Assessment plots that included a road but also included vegetation were not moved. However, one assessment plot was moved 200 meters due north otherwise it would have been completely occupied by pavement and gravel road embankment of Interstate 80. Data files for all plots are stored on the included computer disk (see Appendix D).

Of the four NDVI variables (each season independently, their difference, and their ratio), Tobit Regression revealed the NDVI difference to be the most informative. In order to incorporate a quadratic form of the NDVI difference, the variable was rescaled by taking its negative and adding one. A summary of the statistically most informative model from Tobit Regression is given in Table 2. To produce the final mapping model, the Tobit Regression model (equation A below) was supplemented by cutoff values based on the average pixel brightness across the 6 spectrum bands for the late season imagery (Figure 9; equation B below). The final mapping model algorithm is as follows:

$$\begin{aligned} A = {} & 128.2068 \\ & + (-276.9399)(-\text{NDVIDIFF} + 1) \\ & + (213.3715)(-\text{NDVIDIFF} + 1)^2 \\ & + (-0.0271)\text{ELEV} \\ & + (-0.2391)\text{LSB2} \end{aligned}$$

B = if (LSA < 110) then (-130 + (2.3)LSA) else (250 + (-1.3)LSA)

C = if (A < B) then A else B

D = if (C ≥ 0) then C else 0

E = if (D ≤ 100) then D else 100

PercentCoverEstimate = round-off (E)

The resulting map is provided at a small scale in Figure 10, at a mid-scale on the accompanying poster, and at the full resolution as a GRID file on an accompanying computer disk (see appendix D). Post-modeling alterations to eliminate: (A) cultivated fields covered 532,879 acres (1.51 % of the mapping area), (B) urban areas covered 92,879 acres (0.26 % of the mapping area), and (C) clouds or their shadows obscured 734,102 acres (2.08 % of the mapping area). The remaining area where *B. tectorum* cover was estimated spanned 33,993,806 acres (96.15 % of the mapping area)

A summary of errors of omission and commission for predicting thresholds of *B. tectorum* is given in Table 3. RMSE in predicted percent cover at accuracy assessment sampling plots is 9.14 % and the estimated values correlate well with sampled values ($R^2 = 0.51$; Figure 11). Within the northern 2/3 of the map where training data sampling plots were taken, the RMSE is 12.0 (42 plots) while in the southern 1/3 the RMSE is 2.8 (33 plots).

Discussion

Little published research is available for evaluating what constitutes a 'good' error rate. However, I believe the error rates reported for this map are quite good. Most remote sensing of vegetation components involve classification into categories. Reported accuracy for classification maps generally range ca. 70 - 90 % (or 10 - 30 % error). The GAP landcover map for Nevada reports 64 % correctly classified pixels (Homer 1998). The GAP landcover map for Utah has a substantially higher reported accuracy of 83 % (Edwards et al. 1998). The map of *Bromus tectorum* estimated percent cover is fundamentally different from those classified maps in that percent cover is a continuous variable rather than a categorical one. Comparison to categorical maps requires categorizing the *B. tectorum* map by setting arbitrary break-points in percent cover. Viewing only the presence versus absence of *B. tectorum* in the map presented here, 64 % of the accuracy assessment sites were properly classified (Table 3). However only a one percent error (from 0 to 1 percent or 1 to 0 percent) could cause miss-classification and one might expect such low quantities would be difficult to detect by satellite. Considering a more detectable break-point, below 10 % cover versus 10 % and above, the number of accuracy assessment sites correctly classified jumps to 85 % even though a one percent error (i.e. 9 % versus 10 %) could still cause misclassification.

Very few cases of deriving continuous biological variables from remote sensing imagery are discussed in the literature. Most cases involve estimations of Leaf Area Index (LAI) or forest volume characters. White et al. (1997) estimated total vegetation LAI from Landsat-5 TM (an earlier version of the satellite I used) imagery for Glacier National Park (within a single satellite image) with R^2 = 0.97 and no RMSE figure was given. Hyyppä et al. (2000) compared various sensors, including Landsat TM for estimating forest mean height, basal area, and stem volume with R^2 values ranging from 0.03 – 0.77 across all sensors and 0.26, 0.31, and 0.31 respectively for the Landsat TM values. Those performing better than Landsat were higher in resolution, including the Spot satellite and 3 airplane mounted sensors. Stem volume has also been estimated in small areas by Lidar, an exceptionally precise laser scanning system, with R^2 = 0.90 but that corresponded to RMSE = 22 % (Holmgren et al. 2003). Perhaps most relevant to the *B. tectorum* map, Cohen et al. (2002) measured total canopy cover at agricultural sites within a 25 km^2 area with R^2 = 0.67 and RMSE = 10.41 %.

The 9.14 % RMSE of the *B. tectorum* map also seems good in light of the potential error sources. One major source of error is the ocular estimation method used for determining *B. tectorum* cover in both training and accuracy assessment plots. While many experienced plant ecologists can distinguish between 0, 5, or 10 % cover, consistently distinguishing, say 6 % versus 8 % is near impossible. Such error may be even greater at higher covers, such as in distinguishing 30 % versus 35 %. Where estimations in this work were above 20 % cover, the estimations tended to be rounded to the nearest 5 or 10 %. Thus some error is inherent to the data. It should also be noted that ocular estimations are open to bias through consistently over or underestimating cover. Since the accuracy assessment plots were performed in the same way, I have no measure of such bias. However, since the ocular estimations were always performed by me, any bias in the ocular estimations should at least be fairly uniform. While this potential error and bias could be controlled by using different cover estimation methods for the sampled plots, such methods would be significantly more time consuming. In the trade-off between fewer, more accurate plots versus numerous, less accurate plots, the latter is preferable for this project as it allows for capturing more of the variation present in a large landscape.

Another major source of error is from temporal variation in *B. tectorum* cover. The satellite imagery was from the year 2001, most training plots were examined in 2002 with a few more in 2003, and all accuracy assessment plots were examined in 2003. Many of the high-density *B. tectorum* stands were initiated after the 1999 summer fire season and may be still increasing in density each year. Other recently invaded areas are also probably still increasing in density. For areas where *B. tectorum* density has maximized, annual variation in rainfall or other environmental factors will still cause year-to-year variation. In the creation of this map, training and accuracy data were all from locations that had not been significantly disturbed since 2001. The model fitted the training data to the phenology signal from the 2001 imagery. Then the model was separately run on the 2001 imagery. Thus, the map is effectively an estimation of the *B. tectorum* cover in the year 2001. Accuracy assessment plots were from 2003 so the error measure includes any further invasion over 2 additional growth seasons.

Locations where this map is most clearly dated to 2001 is in failed greenstrips that were initiated during the previous year (barren of *B. tectorum* in the 2001 imagery and mapped as such). Several of these greenstrips were observed during the fieldwork, where the land had been disk plowed then seeded. The planted seeds had largely failed to germinate or establish, allowing dense stands of *B. tectorum* to form by the summer of 2003, even though adjacent recently-burned areas seeded without disking had great establishment of native grasses and crested wheat with near-exclusion of *B. tectorum*. The frequency of these failed greenstrips on the landscape is quite discouraging. There seems to remain a leaning in land management agencies to solve revegetation problems with industrial agriculture techniques such as disk plowing even to the acknowledged detriment of other ecosystem components. This is demonstrated in a discussion of advantages of mechanical treatment in a recent sagebrush management guideline publication (U.S.D.I. 2002):

> "The potential to damage biological crusts, however, must be weighed against the potential consequences of a failure to act. Irreversible dominance by annual species such as cheatgrass can prevent the return of even well-developed biological crusts."

Soil crust communities in sagebrush ecosystems require decades to establish and more to mature (Belnap et al. 2001). They are valuable for erosion control and soil quality (Belnap & Gillette 1998; Eldridge & Greene 1994), and may even inhibit *B. tectorum* germination (Kaltenecker et al. 1999; Larsen 1995). Given the failure of many greenstrips, I suggest that the potential damage to biological soil crusts combined with the risk of failure outweighs any advantages on land with moderate to high cover of soil crusts and, following adaptive management philosophy, suggest that greenstripping with disk plowing should be reexamined and continued only with caution. Perhaps drill seeding could be favored over disking as a less soil-disturbing method that still plants the seed (Hilty et al. 2003).

A third major source of error is that phenology is not a perfect predictor of *B. tectorum* cover. The phenology as detected by the satellite is integrated over all vegetation within the 30 m X 30 m pixel. Plants other than *B. tectorum* within the pixel with different phenologies will alter the phenology measurement. But what appears to be most relevant is that certain plants have similar phenology to *B. tectorum*, causing over-estimates of *B. tectorum* where they are abundant. From field experience, two plants cause such error at scales that are visually noticeable: *Lepidium perfoliatum* L. and *Poa secunda* J. Presl. *L. perfoliatum* is an annual non-native weed that is often abundant in highly disturbed areas. It is known to have caused over estimations of *B. tectorum* in the map in the Reese River Valley on the lower alluvial fans from Battle Mountain peak, just southwest of the town of Battle Mountain and in Buena Vista Valley on the lower alluvial fans from the Stillwater Range. *P. secunda* is a widespread perennial native grass with tremendous genetic and ecotypic variation, which has been considered to include multiple species in the recent past. *P. secunda* appears to have only inflated estimations of *B. tectorum* cover in a few portions of the map suggesting that only a portion of the variants have early enough phenology to cause noticeable error in the *B. tectorum* estimations. Over estimations caused by *P. secunda* are in a small area at the north end of Jersey Valley, and over much of the eastern Owyhee Plateau. The latter is by far the most extensive noticeable error in the map.

The final major source of error is in the limitations of the statistical model. Although Tobit Regression overcomes the zero-truncation problem, it is still a linear modeling method. The plot of predicted versus measured cover of *B. tectorum* (Figure 11) indicates overestimation of low cover values and underestimation of high values, suggesting that the true relationship between phenology and *B. tectorum* cover is non-linear. The inclusion of phenology in the model in a quadratic form reduces this problem (the discrepancy shown in Figure 11 is even greater without the quadratic term), but the problem cannot be eliminated while using Tobit Regression. A non-linear modeling method which has potential to solve this problem, Nonparametric Multiplicitive Regression, a multivariate kernel technique (Peterson 2000; McCune et al. 2003), is currently under development but was not available for geographic mapping in time for this report.

Potential sources of minor error are numerous and cannot be discussed exhaustively. Notable sources include any agricultural cultivation and human habitation areas not masked as ‘urban’ or ‘cultivated’. Such areas often include vegetation removal, crop irrigation, landscaping, and other alterations to the plant-life on the land that result in changes to phenology and thus affect estimations of *B. tectorum* cover. Another potential source of error are thin clouds and haze that are not distinct enough to have been masked out of the map, or clouds and cloud shadows erroneously not masked. Positional error resulting in improper alignment of the sampling plots with the imagery may have resulted from both the quality of GPS receiver used, and from the geometric correction of the images.

Given that RMSE = 9.14 % and that the parameters used in the model, particularly the measure of phenology from the satellite data, were statistically significant (p-values < 0.05), I do not reject my first hypothesis, “that the early phenology of *B. tectorum* can be used to distinguish it from other vegetation, using satellite imagery from two separate dates”. There may be some issues of reliability for distinguishing *B. tectorum* from *Lepidium perfoliatum* and *Poa secunda*, and I would recommend land managers do some reconnaissance prior to making decisions based on this map. But errors from those species appear to be localized. There is little doubt that this map provides a strong overview of the invasion of *B. tectorum*.

My second hypothesis, “the method can be extended to areas neighboring the training data collection up to a distance of about 100 km”, is more problematic to test. The results imply that mapping was ***more*** accurate in the extended area than in the area where the training data collection was conducted (Table 3)! But much of this region appears to have had relatively little invasion of *B. tectorum*. Possible reasons for this will be discussed below. Apparently the model works well for detecting the absence or low abundance of *B. tectorum* for this region. So to some extent, comparing RMSE for the core versus the extended regions is invalid. I cannot say for certain that the model will extend well to other neighboring, unsampled areas with greater invasion of *B. tectorum*. However, I can report that the model worked well for this lightly invaded, neighboring area.

Management Implications

The implications of this map for land managers are too broad and varied to be completely addressed here. Instead, I would like to point out just a few of the implications that I consider to be of high significance.

As pointed out in the introduction, West (1999) estimated that half or more of the sagebrush steppe has been invaded by *B. tectorum* and about a quarter has been converted to *B. tectorum* dominance. The *B. tectorum* map only partially overlaps with the sagebrush steppe, and also covers many other vegetation types. For the area mapped, 51.1 % of the pixels have an estimated *B. tectorum* cover of 1 % (rounded, representing values as low as 0.5 %) or more. Thus this map corresponds well to the estimation of West for sagebrush steppe. The present map does not distinguish *B. tectorum* dominance from subdominance, so a direct comparison to West's estimation of dominance is not possible. However, I can note that 25 % of the map has an estimated cover of 9 % or more, a cover value that is typical of heavily invaded sagebrush vegetation but lower than of typical *B. tectorum* dominated vegetation. So it is likely that less than a quarter of the mapped area has been converted to *B. tectorum* dominance.

Invasion of *B. tectorum* seems to be most heavy in the Interstate-80 corridor and Highways 95 and 140 to the north of Winnemucca. These are areas of historic high traffic and heavy land-use. However, the same is true of Highway 50, which is much more lightly invaded, so causes of *B. tectorum* invasion are probably more complicated than seed transportation and land-use. The heavily invaded areas also correspond well to fire and weather patterns. It is not surprising that wildfire patterns would have a close relation to *B. tectorum* invasion (Figure 12). What is quite interesting is how weather patterns may relate, both directly through making water available, and indirectly by causing the fires. The heavily invaded (and frequently burned) areas may correspond to frequent dry lightning storms in the summer. Unfortunately, the Interstate-80 corridor also presents a significant management challenge due to the checkerboard pattern of land ownership – alternating private and public lands.

What I find to be most notable about this map are the areas with little or no invasion. In particular, the southern portion of the map, the Owyhee Plateau, and area to the north and west of the Trinity Range including Granite Springs Valley. There are other areas with little to no invasion, but they are mainly playas or higher mountains where one would not expect *B. tectorum* invasion.

The southern portion of the map includes the higher central mountains portion of the state where even basin bottoms may exceed 1800 m elevation. In this region, heavy invasion may be inhibited by some effect of the high elevation such as temperature regimes. However, the southern portion of the map does include substantially lower elevation areas, such as Fallon, Hawthorn, and Yerington, which also lack the heavy invasions comparable to those that are common between Lovelock and Elko. This could be due to a separate affect of less annual precipitation than the northern portions of the map. Alternatively, perhaps specifically the greater precipitation specifically in the summer is a controlling factor, as summer rains tend to move up in the state from the southeast. Or broad latitudinal temperature gradients may play a role.

The low invasion of Owyhee Plateau and Granite Springs Valley areas is more difficult to speculate on. Perhaps these areas remain less invaded simply due to historically less disturbance. The Owyhee plateau in particular is quite remote and has few water sources available.

These areas of relatively low invasion represent some of the most ecologically intact land in the state. They are valuable for many plants and animals of conservation concern, including the Greater Sage Grouse (*Centrocercus urophasianus*) and the pygmy rabbit (*Brachylagus idahoensis*). The Owyhee Plateau may be particularly vulnerable. Prevailing winds blowing from the southwest to the northeast have a great potential for both fanning wildfires and blowing *B. tectorum* seed from the intensely invaded Winnemucca area up onto the plateau. Significant land management resources should be devoted to preventing further *B. tectorum* invasion in these areas due to wildfire and other causes.

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