

# Invasion of the Exotic Grasses: Mapping Their Progression Via Satellite

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**Abstract**—Several exotic annual grass species are invading the Intermountain West. After disturbances including wildfire, these grasses can form dense stands with fine fuels that then shorten fire intervals. Thus invasive annual grasses and wildfire form a positive feedback mechanism that threatens native ecosystems. Chief among these within Nevada are *Bromus tectorum* (cheatgrass), *Bromus rubens* (red brome), and *Schismus barbatus* (Mediterranean grass). These grasses have an early phenology for both green-up and senescence that can be detected from the difference in greenness between two well-timed satellite images, allowing grass cover to be geographically modeled. The Nevada Natural Heritage Program is using imagery from Landsat and MODIS satellites to map annual grass invasion, and has completed a map of annual grass cover for the State of Nevada. The models and final map were developed from 806 training sites, remotely sensed data for two seasons from Landsat 5 TM and MODIS satellite sensors, and accessory geographic data. Accuracy of the final map was analyzed from two independent data sets: Southwest Regional Gap Analysis Project (REGAP) training data (15,318 plots) and California Department of Fish and Game vegetation plots from the Mojave region (939 plots). Root-Mean-Square-Error (RMSE) from the REGAP data was 10.33 percent; 75 percent of predictions for gap plots were off by 5 percent or less; and 95 percent of predictions were off by 21 percent or less. For the Mojave data set, RMSE was 7.48 percent; 75 percent of predictions were off by 9 percent or less; and 95 percent of predictions are off by 15 percent or less. Accuracy assessment on REGAP data suggests that annual grass cover is generally underestimated for sites with high cover, thus the map should be interpreted as an index of cover rather than an estimate of actual cover. Nevertheless, the map reveals the pattern of annual grass invasion across Nevada.

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## Introduction

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Invasive exotic annual grasses are an ecological catastrophe that we must contend with. What has brought on this problem is uncertain, and what the solutions will be are even less known. Herbicides have been successfully used to treat limited areas. However, treating tens to hundreds of

millions of infested acres throughout the West with chemicals is unrealistic. Herbicides might be useful in maintaining fire breaks in the ‘cheatgrass sea,’ or southward in the ‘*Schismus* sea,’ but are not a solution to the invasion. That does not mean that we should give up! California’s Central Valley was almost completely converted to invasive annual grasses nearly a century ago, yet people maintain hope for small pieces of remnant native grasslands. The Intermountain West still retains vast areas of native communities. Furthermore, the region has vast areas maintained by public agencies, providing potential for landscape-level strategies against complete transformation of our ecosystems. There is room for optimism, if regional strategies can be sought, found, and employed.

Regional strategies for dealing with invasive annual grasses will require a geographic understanding of the problem—knowing the pattern of invasion across the landscape. For this reason, the Nevada Natural Heritage Program (NNHP), which monitors biodiversity in the state, has taken an interest in invasive species. The goal of the work presented here is to map the current status of invasive exotic annual grasses in Nevada, through statistical modeling of annual grass cover as detected by satellite sensors. This is one step toward a more comprehensive understanding and monitoring of native ecosystems, their biodiversity, and their biogeography.

## Methods and Materials

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Annual grasses tend to have short life-spans and senesce earlier in the season than perennials. Satellite sensor data (imagery) can detect chlorophyll concentration over the landscape, primarily from its reflectance in the near-infrared (Jensen 1996). Locations with large concentrations of annual grasses show a marked drop-off in chlorophyll as annual grasses senesce. Thus the change in chlorophyll concentrations as measured by satellite can be correlated with the actual ground cover of annual grasses at training sites and can be used to create predictive models of annual grass cover (Peterson 2005).

The methods used here are very similar to those previously used to map *Bromus tectorum* (Peterson 2003, 2005) and further details than are given below were reported online (Peterson 2006). Briefly: training data were collected from the field; satellite sensor data were obtained for appropriate times during the annual grass growing season and senescence season; statistical models were developed and expressed through geographic mapping algorithms for visual evaluation; and independent ground data were

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obtained for post-modeling accuracy assessment. During data processing and analysis, all raster data mosaics and re-projections to match the Landsat data set (below) were calculated in ENVI 4.2 (Research Systems Inc. 2005) with nearest neighbor resampling and a 100 X 100 matrix of triangulation points for re-projections. All statistical analyses were performed with the R statistical package (R Development Core Team 2005).

## Training Data

Ocular estimates of annual grass cover were made at training sites over 0.1 ha plots (see Peterson 2005 and 2006 for details).

## Satellite Data

Satellite sensor data (imagery) for this project needed to provide measures of green vegetation during the growing and the senescence periods for annual grasses. These periods can be short, particularly for the senescence period, as the sensor data must be collected when annual grasses have mostly senesced *yet perennial vegetation and most forbs remain photosynthetically active*. Target dates for growing season were the month of March in the south (roughly the Mojave ecoregion), and mid-April to early May in the north. Dates for senescence were mid-April to early May in the south, and mid- to late-June in the North.

Annual grasses have substantial inter-annual variation in production, particularly between wet and dry years as measured by total precipitation (Bradley and Mustard 2005). Fieldwork on this project in the years 2002–2005 suggested that phenology of annual grasses is more geographically variable in wet years than in dry years, so a dry year with relatively low cloud cover (2004) was targeted for the northern portion of Nevada. However, during dry years in the southern portion of the state, the low annual grass production might be difficult to detect reliably. Thus, a wet year (2005) was targeted for the southern portion of Nevada despite substantial obscuring of the land surface from satellite sensors by clouds.

Landsat 5 TM sensor data were purchased for dates within, or close to, the ideal target dates, from the USGS. EROS data center using UTM zone 11, NAD 83 projection with terrain-correction and a spatial resolution of 28.5 meters. Landsat satellites capture a given path on 16 day intervals, forcing the use of several clouded scenes. To fill in the holes left by clouds (referred to hereafter as ‘cloud-holes’), data composites over 16-day periods were obtained from the MODIS satellite sensor (MOD 13 product; NASA 2005).

The satellite data were analyzed in four sets: (1) the 2004 data in the north where Landsat data exists for both seasons (LL04), (2) the 2004 MODIS data to fill in cloud-holes with the prior (MM04), (3) the 2005 data in the south where Landsat data exists for both seasons (LL05), and (4) the 2005 MODIS data to fill in cloud-holes (MM05). Raw spectral band values were analyzed, along with derived values: NDVI for each season (Normalized Difference Vegetation Index; Jensen 1996),  $\Delta$ NDVI, a Greenness Ratio (for each season), and  $\Delta$ Greenness.  $\Delta$ NDVI was calculated as early season NDVI minus late season NDVI and forms the main measure of

phenology. The Greenness Ratio was constructed to represent a greenness of annual grass infestations visible in false-color maps using Landsat bands 7, 4, 2 for red, green, and blue, respectively. The Greenness Ratio was calculated as:

$$\text{GreennessRatio} = \frac{B4}{(B2 + B7) * 0.5}$$

where Bx refers to the spectral band number within the Landsat 5 TM data (B4 is the same near-infrared band as used in calculating NDVI). The  $\Delta$ Greenness was calculated in similar fashion to  $\Delta$ NDVI using the Greenness Ratios.

## Accessory Data

Statistical modeling of vegetation features from satellite imagery is generally enhanced by the use of accessory data that relate to climate and land features. Data gathered and tested for use in models included simple geographic coordinates, elevation models and derived land features, estimated precipitation pattern, and ecoregional variation.

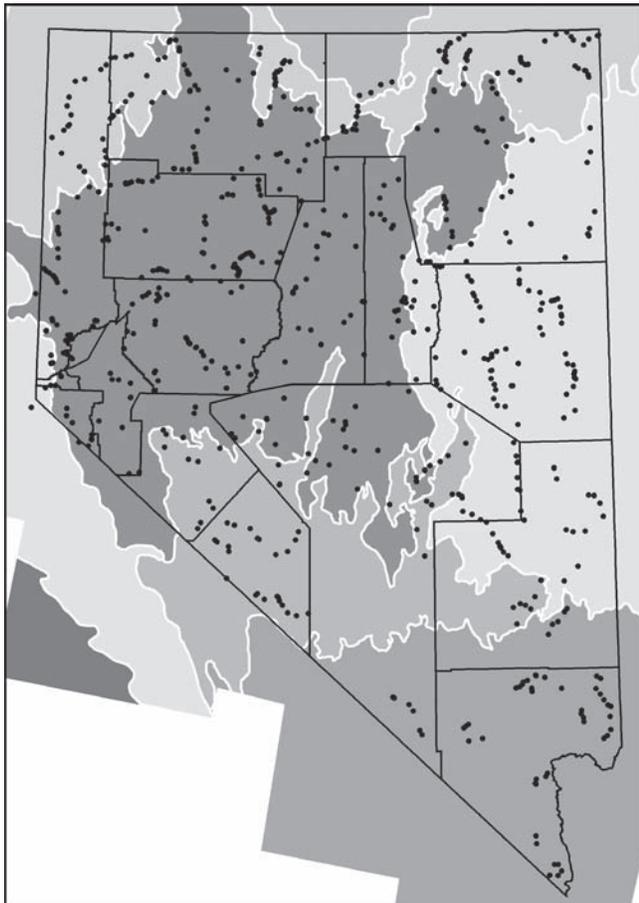
**Elevation and derived land features**—A digital elevation model (DEM) covering the entire extent of all Landsat data scenes with 1 arc-second resolution (ca. 30 m) was extracted from the National Elevation Dataset (USGS, 2005) and reprojected to match the Landsat data. From elevation data, we calculated slope, aspect, heat index, exposure, and aridity indices as described in Peterson (2006).

**Precipitation**—Total annual precipitation corresponds strongly to elevation within the State of Nevada, so total precipitation itself was not analyzed. However, substantial variation exists in the timing of precipitation across the state. Two datasets were constructed to represent normalized seasonality of precipitation, as derived from the PRISM precipitation models (Spatial Climate Analysis Service, Oregon State University 2003). The first contrasted only two months, January versus August (JA), while the second contrasted the total of January to March versus July to September (JFMJAS) (see Peterson 2006 for details).

**Ecoregions**—Maps produced by early models indicated a strong geographic trend in error; most noticeably predicted annual grass values were low on the eastern side of the state. To allow for ecoregional variation, an ecoregion map was constructed (fig. 1). The regions are largely based on agglomerations of sub-regions defined by Bryce and others (2003), but with substantial editing based on field experience and with the intension of mapping boundaries in the behavior of annual grasses. The map construction did not directly utilize a geographic analysis of error from annual grass modeling. Ecoregions were then entered into models as binary factors.

## Modeling Process

The statistical modeling procedure followed Peterson (2005). In short, a form of survival analysis, specifically Tobit regression (Tobin 1958; Austin and others 2000), was used to construct equations that predict ground cover from satellite and accessory data. Separate models were developed for each of the four satellite sensor data sets (LL04, LL05, MM04, and MM05). Once models were chosen, they were



**Figure 1**—State of Nevada, showing county boundaries (black lines), training data plots (black dots), and ecoregions for modeling accessory data (variously gray backgrounds).

used geographically to calculate rough maps of estimated annual grass ground-cover. Maps from LL04 and LL05 were then filtered with spectral algorithms described in Peterson (2006) to reduce error in playas, forests, wetlands and lakes where false positives may result from land reflection characteristics. The maps from separate models were assembled into a final map by first mosaicking models by satellite using cut-lines based on the ecoregion data, then by overlaying MODIS-based mosaic with Landsat-based mosaic. Lastly, a conservative smoothing kernel was applied.

### Map Validation

Independent data sets were utilized for map validation. These were the data collected for the Southwest Regional Gap Analysis Project (REGAP) (Lowry and others 2005) and the Mojave Desert Ecosystem Program (MOJAVE) (Thomas and others 2002, 2004). Although the MOJAVE data lie entirely outside of Nevada, sufficient numbers of plots are covered by our satellite data and are in appropriate ecoregions for assessing map quality. Actual annual grass cover for each plot was summed from the field data. Estimated annual

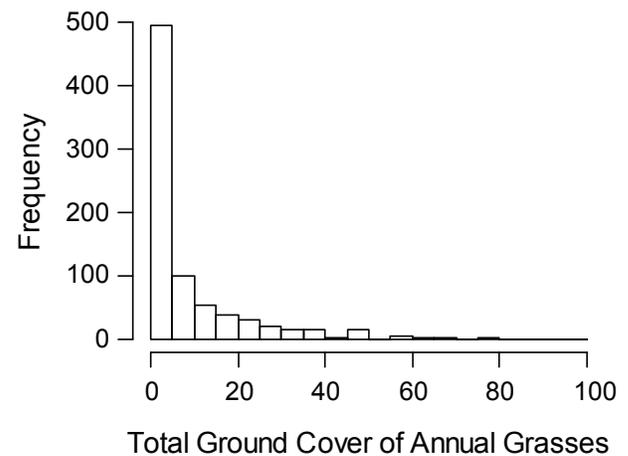
grass cover was extracted for each plot from the final map produced herein. Measures of accuracy were calculated based on these actual and estimated values, using Pearson Correlation, Root-Mean-Squared-Error, and 75<sup>th</sup> and 95<sup>th</sup> percentile errors.

## Results and Discussion

### Field Work

Training data were collected by the Nevada Natural Heritage Program (NNHP) at 806 plots from 2002–2005 (fig. 1). Average ground cover of annual grasses was 9.3 percent, but was skewed (fig. 2) and 64.7 percent of plots had no annual grasses. Predominant annual grasses were *Bromus tectorum* to the north, and *Bromus rubens* and *Schismus barbatus* to the south. *Bromus arvensis*, *Poa bulbosa*, *Taeniatherum caput-medusae*, *Vulpia microstachys*, and *Vulpia octoflora* were observed infrequently. Of the annual grass species encountered, only the *Vulpia* species are native to Nevada, but their abundance is minimal. Thus the map produced herein effectively targets exotic annual grasses.

Field sampling in 2002–2004 followed relatively dry winters, while sampling in 2005 followed a relatively wet winter. Of the 806 plots, 30 plots in northern Nevada were repeats, visited first in 2002 or 2003 then again in 2005, to assess the affect of total seasonal precipitation on annual grass cover. In 2005 mean cover of annual grasses among repeat plots was 8.5 percent lower while mean cover of the native *Poa secunda* was just 0.9 percent lower and biological soil crusts was 1.1 percent lower. Although cover estimates are vulnerable to observer bias, which may change over time, the lack of substantial reduction in the later two measures (both perennial vegetation components) suggests that the reduction in annual grass cover in the 2005 season is real. My personal observation was that although the annual grasses were taller, their cover had not increased. My subsequent



**Figure 2**—Histogram of percent ground-cover for annual grasses in training data plots. Each bar covers a 5 percent range.

personal observations during the 2006 field season, also following a wet winter, were different in that annual grass cover did appear to increase. One might hypothesize that after a prolonged drought, the first year of heavy rains does not increase cover, but instead increases seed production. A second year of heavy rains then allows the seed production to manifest into greater cover of annual grasses. These observations are tentative and limited to northern Nevada. Inter-annual variation in annual grass production has been used as an alternate method for mapping (Bradley and Mustard 2005), but patterns may be more complex than typically presumed. Careful study of these patterns would be welcomed.

## Statistical Modeling

Among the four modeling data sets, hundreds of models were tested with more than fifty expressed geographically for evaluation. The final models are provided in table 1. In

general, models included early season NDVI,  $\Delta$ NDVI, an exponential of  $\Delta$ NDVI, elevation, and ecoregions. The values for  $\Delta$ NDVI were low, including negative values, and covered only a short range, so to calculate an exponential of  $\Delta$ NDVI, the variable was rescaled by adding two and then a power of four was used. Ecoregions were included as binary variables and were frequently retained even when not statistically significant because regional patterns in error were more visually obvious without them. Models for MODIS data were difficult to develop independently of the Landsat based models, possibly due to the low spatial resolution of MODIS data resulting in noisy data. However, when the variables from the Landsat-based models were applied to the MODIS data with newly calculated coefficients, the resultant models performed well despite the loss of statistical significance for some coefficients. Greenness, aridity, and precipitation indices were found to be statistically significant for some models, but were dropped for the final models as elevation and multiple NDVI measures accounted for some of the

**Table 1**—Final models for each dataset. Ecoregion was included as a set of binary variables.

Data Set	Variable	Coefficient	p-value
LL04 (n = 689)	Intercept	-612.9975	0.0203
	NDVlearly	362.2552	0.000000293
	$\Delta$ NDVI + 2	414.7017	0.0177
	$(\Delta$ NDVI + 2) <sup>4</sup>	-11.3159	0.0362
	ELEV	-0.0222	0.000000187
	Region2	-0.3103	0.00143
	Region3	1.5568	0.483
	Region4&5	-4.4817	0.0549
	Region6	-10.5149	0.0107
	NDVlearly*ELEV	-0.1603	0.0000831
LL05 (n = 130)	Intercept	58.4205	0.00000000000787
	NDVlearly	79.7398	0.000230
	$\Delta$ NDVI	-69.0320	0.00165
	ELEV	-0.0163	0.000115
	LateSeasonDate	-0.2737	0.00156
	DaysApart	0.0532	0.390
	Region3&7	12.8757	0.00397
	Region6	4.4046	0.335
MM04 (n = 688)	Intercept	-524.1190	0.107
	NDVlearly	545.6410	0.000000000782
	$\Delta$ NDVI + 2	372.9796	0.0853
	$(\Delta$ NDVI + 2) <sup>4</sup>	-12.0503	0.0764
	ELEV	-0.0193	0.000160
	Region3	3.3588	0.137
	Region4&5	-5.3061	0.0209
	NDVlearly*ELEV	-0.2488	0.00000261
MM05 (n = 118)	Intercept	22.1276	0.182
	NDVlearly	76.2708	0.138
	$\Delta$ NDVI	1.4205	0.988
	ELEV	-0.0230	0.0000000834
	Region6	5.0345	0.409

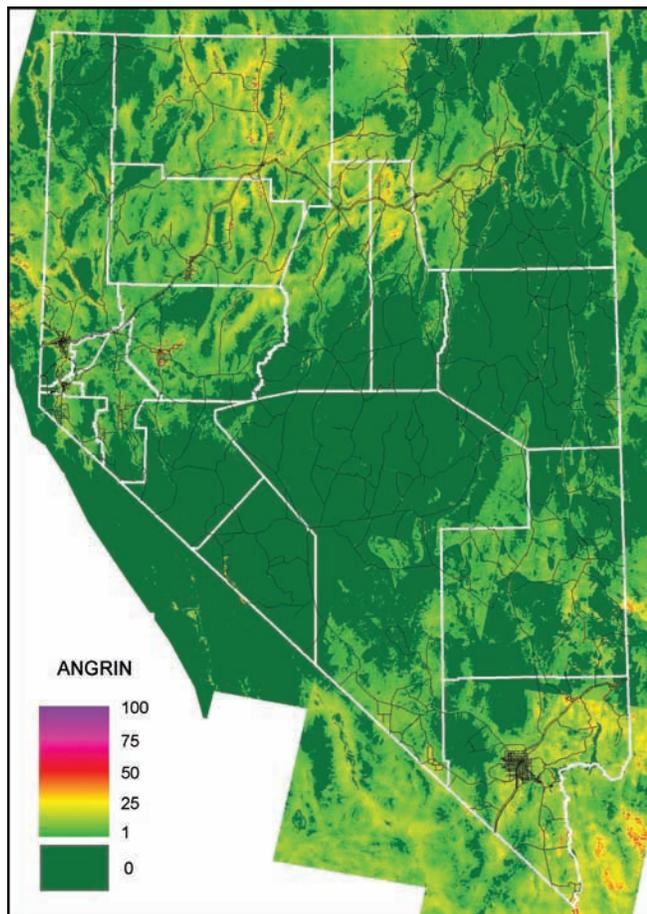
same variation in the data. The individual model maps were assembled and smoothed to form the final Annual Grass Index map (ANGRIN) (fig. 3). Data for this map are available online at <http://heritage.nv.gov/reports>.

### Accuracy Assessment

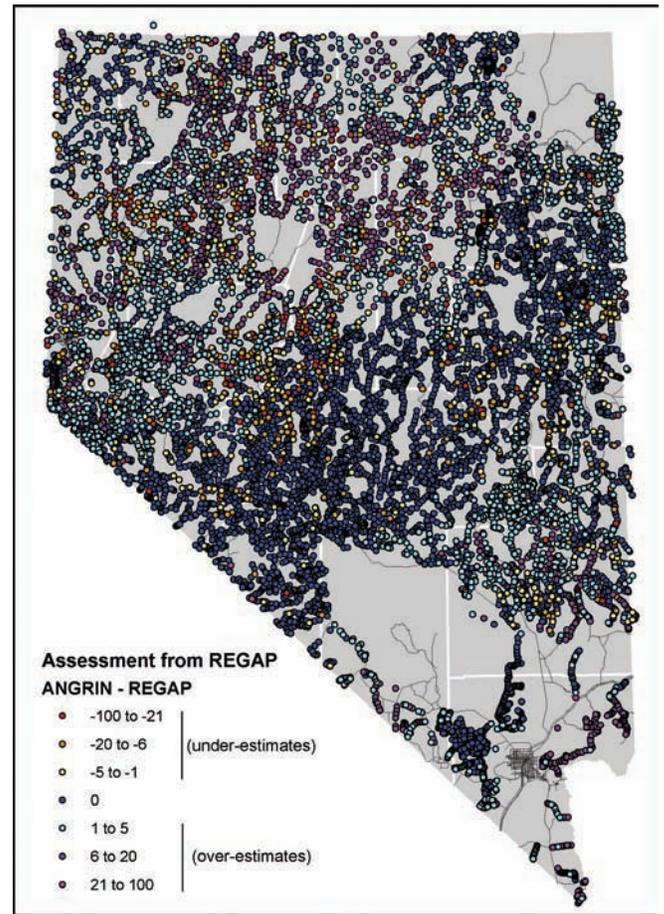
Use of REGAP data for assessment of the ANGRIN map involved 15,318 plots (fig. 4). Actual cover according to REGAP data compared to ANGRIN modeled values show RMSE = 10.33 percent; 75 percent of modeled values differ by 5 percent or less ground cover; and 95 percent of modeled values differ by 21 percent or less. Of the total REGAP dataset, 8,909 plots are identical in value between ANGRIN and measured ground cover, of those 8,848 are zero in both datasets. However, correlation between ANGRIN and REGAP data showed weak correspondence ( $R = 0.24$ ). The discrepancy between the estimated values in ANGRIN and the measured values suggests frequent

underestimation at high cover sites in the ANGRIN map. For this reason, as well as inter-annual variation in annual grass cover (Bradley and Mustard 2005), I suggest that the map be interpreted as an index of cover rather than an estimate of actual cover.

Although REGAP plots were distributed across most of the state, the number of plots from the northern Great Basin region was much greater than in the Mojave region (fig. 4) so assessment by REGAP data applies mainly to the Great Basin. Despite underestimation of high cover sites in the Great Basin, detection accuracy of no infestation or of low cover infestation was strong and modeling performed quite well for annual grasses specifically. This is an improvement over previous mapping (Peterson 2005) with less area inappropriately estimated to have annual grasses. For example, considerable cover of *Bromus tectorum* had been estimated for the shores of Walker Lake in the previous map whereas appropriately little area of annual grasses are mapped there in the present effort.



**Figure 3**—Annual grass index (ANGRIN), as expressed geographically over the satellite sensor dataset. Dark green represents areas with no detectable annual grasses; 1-100 percent ground cover of annual grasses is represented with the color gradient from light green through yellow and red to purple. County boundaries (white lines) and roads (black lines) are provided for reference.



**Figure 4**—Distribution of plots from REGAP data set showing discrepancy between REGAP plots and ANGRIN estimates. Overlapping points are displayed with greater discrepancies on top.

The California Department of Fish and Game collected 939 plots in the MOJAVE dataset that were useful to this project. Comparing the measured annual grass cover at those plots to the ANGRIN estimates shows RMSE = 7.48 percent; 75 percent of predictions are off by 9 percent or less; and 95 percent of predictions are off by 15 percent or less. The discrepancy between measured and estimated values shows that in most cases, the estimated value is higher than the measured value. Two factors likely contributed to this appearance of over-estimation in the Mojave region. First, the MOJAVE dataset was collected in drier years than the 2005 growing season, thus it could be expected that 2005 satellite data would show greater amounts of annual grasses. Second, the phenology of this warmer desert region is much more temporally compressed than in the Great Basin, leading to greater contamination of the satellite measured phenology signal by other annual and deciduous perennial species. Although many of the species contaminating the signal may be other invasives, particularly mustards (Brassicaceae), many native annual wildflowers are probably included.

## Sources of Error

There are countless sources for error in any remote sensing project; any imaginable natural or human-caused variation in the spectral reflectance or accessory modeling can reduce the quality of a map. Lengthy discussions of error with these mapping methods are provided in Peterson (2003, 2006), including observer bias, inter-annual variation in growth and senescence, signal contamination from other early-season species, timing of satellite data, data contamination by clouds or other atmospheric phenomena, and regional variations.

Another source of error can be the modeling method. Tobit regression has a strong advantage over many statistical modeling methods in its handling of censored data (limited to zero and positive values). However, it is a linear modeling method, while responses of ecological variables such as annual grass cover are often non-linear with respect to predictor variables. This source of error was discussed by Peterson (2003) so I will not dwell on it here, but alternative methods do need to be explored. Generalized additive models (Yee and others 1991) and multivariate windowing techniques (Peterson 2000), particularly Nonparametric Multiplicative Regression (McCune 2006), have potential to provide more realistic models of the data. However, software choices for those techniques are limited in the size of geographic data files that they can manipulate within a reasonable amount of time. Considerable effort may need to be devoted to reprogramming their data handling capabilities, or perhaps the continual increase in computing power may overcome this issue.

## Summary of Map

Various authors have attempted to provide statistics on the degree of annual grass invasion in the Intermountain West. West (1999) estimated that half of the sagebrush steppe had been invaded to some degree and that a quarter had been converted to annual grass dominated vegetation systems. The USDI Bureau of Land Management (2002) estimated

that as of 2000 in the Great Basin, 14 million acres of public lands were at risk of conversion and three million acres had already been converted. The politically defined boundaries of Nevada used herein do not match the regions covered by West and Wisdom, so direct comparisons of my models to their estimations cannot be made. However, by clipping the ANGRIN map to the border of Nevada and masking out open water, urban, and cultivated areas using data landcover data from REGAP (Lowry and others 2005), my models suggest that 41 percent of the state has been invaded to a detectable degree (ANGRIN value of 1 or greater). Although ANGRIN does not distinguish converted vegetation from heavily invaded vegetation, a value of 10 or greater might reasonably represent heavy invasion, a value met across 11 percent of the state of Nevada.

High degrees of invasion appear to follow the transportation corridor of Highway 80 and the historic Central Pacific, and northward from that along Highways 95 and 140. High degrees of invasion are also prevalent in many valleys of southern Nevada, though interference from other short-phenology plants inhibits any strong statements about invasion in the Mojave. Perhaps of most interest are the areas that are not strongly invaded. Most obvious is the large swath in the middle of the state running from southwest to northeast. Much of this area is of relatively high elevation with some basins at over 2,000 m (6,500 ft). However, invasion is also low in the Tonopah area where elevation and total annual precipitation is comparable to the Lovelock area, which is highly invaded. Another notable area is the western Owyhee Desert, along the northern edge of the state. This is a region of sagebrush at 1,500–1,700 m (4,900–5,600 ft) elevation and thus within the vulnerable elevation range, though perhaps the poor soils in the area may help impede invasion.

## Management Implications

Peterson (2005) demonstrated that mapping of annual grasses over large areas is possible. This project further demonstrates that annual grasses can be mapped on the scale of states and to some extent across ecoregional boundaries. Any mapping projects with large geographic scope will contain a degree of error and land management proposals should be verified on-site. However, maps of large geographic scope are useful in evaluating and prioritizing management actions. The annual grass index (ANGRIN) map reveals the pattern of invasion and infestation by these grasses across the landscape of Nevada. It thus provides an assessment of a major component of landscape condition, or ecological integrity. The map indicates areas that may warrant restoration or rehabilitation. Areas that do not show much infestation may be important for protective actions. Since, annual grasses form fine, often continuous fuels, the map is also useful for wildfire planning and management.

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