Assessing the short-term impacts of changing grazing regime at the landscape scale with remote sensing

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Assessing the short-term impacts of changing grazing regime at the landscape scale with remote sensing

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Livestock grazing is an important form of land use, affecting ecosystems worldwide. In ecoregions that evolved with low densities of large ungulates, such as those in the western United States, there is ongoing debate as to the appropriate concentrations of livestock that can be sustained. Limited landscape-scale monitoring makes it difficult to pinpoint the landscape-scale impacts of livestock on ecosystems. In this study, we use remote sensing to identify landscape-scale changes in Landsat Thematic Mapper (TM)-derived normalized difference vegetation index (NDVI), a proxy for community greenness, following changes in land use in south-central Idaho, United States. Grazing allotments in the study area have been managed by Lava Lake Land & Livestock (Lava Lake) since 2001, and recent landscape-scale changes include reduced grazing intensity, longer rest periods and reduced grazing in riparian zones. Additionally, sheep bands owned by Lava Lake were collared with Global Positioning System (GPS) receivers to track their daily locations during the 2004–2005 summer grazing seasons. We found that increased NDVI was more likely to occur adjacent to riparian channels, which have been a focus for ecological recovery by land managers at Lava Lake. Decreased NDVI was most likely within 500 m of sheep grazing. However, the extent of impact differed depending on land use and elevation. Decreased NDVI on allotments with a large reduction in total number of sheep was most likely within only 60–150 m. Grazing on lands at elevations above 2300 m had no relationship to decreased NDVI. Our results suggest that grazing impacts are heterogeneous across the landscape and depend strongly on stocking rates and elevation (which is correlated to precipitation). Spatial analysis of NDVI can identify landscape-scale changes resulting from livestock grazing that may not be apparent from local monitoring. Patterns of change identified with remote sensing can guide ecosystem monitoring across extensive public and private lands.

1. Introduction

Identifying short- and long-term changes in vegetation abundance, structure and function is an important component of understanding regional and global environmental change. Landscape-scale change in vegetation affects plant and animal habitat, often reducing biodiversity (Vitousek 1994, Feddema et al. 2005, Foley...
Vegetation change may also affect biogeochemical cycling (e.g. carbon storage, erosion, nitrogen deposition), often to the detriment of future recovery and regional ecosystem function. Additionally, vegetation change affects the potential for anthropogenic land use. A degraded landscape may be less useful, whereas a restored landscape may enhance economic value and lower the ecological impact of land use (Foley et al. 2005). One goal of investigating vegetation change at a landscape scale is to understand better how land use contributes to change, thereby promoting sustainable land use.

Livestock grazing has a complex relationship with ecosystems. Intensive grazing can lead to decreased biomass, soil disturbance and changes in species assemblages (Harniss and Wright 1982, Belsky 1987, O’Connor and Pickett 1992, Milchunas and Lauenroth 1993, Biondini et al. 1998, Bork et al. 1998, Weber et al. 1998, Belsky et al. 1999, Schuman et al. 1999, Adler et al. 2005). However, grazing has also been shown to have no significant effect on ecosystem structure and function (Manier and Hobbs 2006, 2007), and the long-term ecosystem impacts of moderate and light grazing are poorly understood.

In south-central Idaho, Lava Lake Land & Livestock (Lava Lake) has been managing livestock with a goal of ecological sustainability. Beginning in 2002, Lava Lake began reducing stocking rates of cattle and sheep on deeded lands and public allotments and building in rest periods. As a result, the total time that a given parcel of land is being grazed and repeated use of the same locations in the same season has been reduced. Additionally, a global positioning system (GPS) collar was attached to one ewe in each sheep band to record the daily locations of grazing throughout the grazing season.

GPS collars provide accurate information on the spatial distributions of animals across the landscape (Hulbert and French 2001). GPS collars have been used for monitoring wildlife (Bowman et al. 2000, Johnson et al. 2002, Poole and Heard 2003, Nelson et al. 2004, Sand et al. 2005) and livestock (Rutter et al. 1997, Turner et al. 2000, Schlecht et al. 2004). Precise locations of livestock within rangelands can aid ecosystem monitoring and present an opportunity to measure directly the short-term landscape-scale impacts of recent grazing.

GPS point locations of recent grazing are a critical advance beyond other available grazing data sets. In the western United States, the effect of more than a century of poorly regulated and documented grazing makes it difficult to distinguish short-term responses to changes in grazing management from long-term change associated with a legacy of disturbance. Data on grazing locations and stocking rates on public lands are of uncertain accuracy, and the spatial extents of grazing allotments are too broad to assess spatially explicit impacts of grazing. Landscape-scale analyses of the impacts of grazing on land cover are needed to inform monitoring efforts and improve land management across public and private lands.

Remote sensing provides this important landscape-scale analysis; spatial relationships between grazing locations and detected land-cover change can be used to plan productive monitoring efforts designed to assess the local responses of vegetation to grazing (Washington-Allen et al. 2006). In this analysis, we compare the spatial patterns of sheep grazing with the changes in normalized difference vegetation index (NDVI) as measured by Landsat 5 Thematic Mapper (TM) satellite imagery. The precise locations of sheep grazing on the landscape create an opportunity to measure directly the impacts of grazing using remotely sensed data. Remote sensing has many strengths for studies on land-cover change. Analyses are at the landscape scale, and results are in the form of a spatially extensive data set. Using a time series of images,
ecosystem change can be detected based on the trends or differences in NDVI, which relates to community-scale cover of photosynthetic vegetation. The resulting spatially explicit data set allows for a geographic comparison between locations of change and other spatially explicit data sets relating to land use, such as grazing intensity and location (Coughenour 1991, Pickup and Chewings 1994, Todd and Hoffman 1999, Washington-Allen et al. 2004, 2006, Röder et al. 2008).

NDVI can be used to measure change in community greenness over time. To detect change, a minimum of two Landsat images are required. However, because ecosystems fluctuate inter-annually, change detection optimally utilizes a time series (Bradley and Mustard 2005). Time series of Landsat NDVI have been used to identify land-cover change in a variety of locations (Steininger 1996, Lyon et al. 1998, Hayes and Sader 2001, Wilson and Sader 2002, Nordberg and Everton 2003, 2005, Bradley and Fleishman 2008). Ideally, images should be acquired at the same time of year and during years with similar climate patterns. Using a time series, we increase our ability to confidently distinguish land-cover change from inter-annual variability.

In this study, we analyse the spatial patterns of NDVI increase ($\Delta$NDVI$^{inc}$) and NDVI decrease ($\Delta$NDVI$^{dec}$) observed in a July 2005 Landsat image of grazing allotments utilized by Lava Lake. First, we compare the probabilities of NDVI change for six distinct management practices adopted between 2001 and 2003: reduction of cattle, transition from cattle to sheep, small reduction of sheep, large reduction of sheep, exclusion of all grazing and no change from previous management (table 1). Second, we assess the relationship between NDVI change and physical features of the landscape, including elevation and distance to channels. Finally, we evaluate the spatial relationships between sheep grazing (based on the GPS collar locations) and NDVI change. We further identify how the sheep-grazing relationship differs between allotments with different management scenarios, through time and across a range of elevations. The comparison of remotely sensed data for different changes in grazing practice gives us insight into landscape-scale ecosystem responses to grazing.

2. Methods

2.1 Study area

The Lava Lake grazing allotments in the study area are located in the foothills of the Rocky Mountains in south-central Idaho, just north of the Snake River plain (table 1). The grazing allotments in the study area encompass over 100,000 ha. Elevations range from 1500 to 3500 m a.s.l. However, grazing rarely occurs above 3000 m a.s.l.

<table>
<thead>
<tr>
<th>Management change</th>
<th>Allotments</th>
<th>Land area (ha)</th>
<th>Elevation range (m)</th>
<th>Average elevation (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cattle reduction</td>
<td>3</td>
<td>10,800</td>
<td>1570–2810</td>
<td>1930</td>
</tr>
<tr>
<td>Cattle change to sheep</td>
<td>2</td>
<td>4,500</td>
<td>1620–2210</td>
<td>1840</td>
</tr>
<tr>
<td>Small sheep reduction</td>
<td>5</td>
<td>14,200</td>
<td>1710–3270</td>
<td>2370</td>
</tr>
<tr>
<td>Large sheep reduction</td>
<td>7</td>
<td>23,500</td>
<td>1680–3260</td>
<td>2290</td>
</tr>
<tr>
<td>Sheep exclusion</td>
<td>1</td>
<td>4,400</td>
<td>2060–3560</td>
<td>2730</td>
</tr>
<tr>
<td>No change</td>
<td>17</td>
<td>64,800</td>
<td>1550–3550</td>
<td>2330</td>
</tr>
</tbody>
</table>
Vegetation in grazed lands is primarily sagebrush (*Artemisia* spp.) dominated shrubland, often with abundant bunchgrasses and forbs. Riparian areas are characterized by deciduous trees, primarily willow (*Salix* spp.), aspen (*Populus tremuloides*) and alder (*Alnus incana*). Higher elevations and north-facing slopes are typically woodlands dominated by conifers, primarily Douglas-fir (*Pseudotsuga menziesii*). The grazing allotments are a mixture of privately owned and public land (both Bureau of Land Management and US Forest Service). Prior to the transition to Lava Lake management in 2001, lands were used for either sheep or cattle grazing, although the magnitude and durations of this land use are not formally documented. In 2004–2005, approximately 7000 ewes were grazing on Lava Lake allotments.

The climate within the study area is characterized by warm, dry summers and cold winters. Annual precipitation generally increases from south to north as elevation increases. Most precipitation occurs during the winter (in the form of snow) and spring. Summers tend to be dry, particularly at low elevations. The driest regions within the grazed allotments receive <35 cm of annual precipitation, whereas the wettest receive >60 cm. At the higher elevations, the growing season starts later and is shorter. As a result, livestock access higher elevation allotments for a shorter period of time than lower elevation allotments.

### 2.2 Image acquisition and processing

Images acquired by Landsat are commonly used for studies of vegetation change (e.g. Green *et al.* 1994, Vogelmann *et al.* 1998, Loveland *et al.* 2002). This analysis uses three Landsat TM images acquired on 18 July 1993, 16 July 1998 and 19 July 2005. Although peak vegetation greenness occurs in mid-June in south-central Idaho, the closest cloud-free time series available was in mid-July. The first two images are representative of land-cover conditions prior to the change in grazing regime. Two pre-change images rather than a single one were used to reduce the likelihood that identified vegetation change was due to a change during the 1990s rather than a change observed in 2005. The final image represents land-cover conditions 2–4 years following grazing changes implemented by Lava Lake. The three images were acquired at the same time of year to reduce phenological (i.e. seasonal) variability. All 3 years received above-average precipitation during the preceding 4 months, making growing conditions as similar as possible during the three time periods (table 2). Wet years were selected to reduce the likelihood that small differences in water would have large impacts on plant growth, which is often the case in drought years.

The three images were georeferenced to less than 1 pixel (30 m) average accuracy using the Tiger/Census road maps. Many road intersections in both the valleys and

<table>
<thead>
<tr>
<th>Landsat acquisition date</th>
<th>March*</th>
<th>April*</th>
<th>May*</th>
<th>June*</th>
</tr>
</thead>
<tbody>
<tr>
<td>18 July 1993</td>
<td>142</td>
<td>111</td>
<td>63</td>
<td>272</td>
</tr>
<tr>
<td>16 July 1998</td>
<td>98</td>
<td>113</td>
<td>259</td>
<td>198</td>
</tr>
<tr>
<td>19 July 2005</td>
<td>169</td>
<td>136</td>
<td>300</td>
<td>138</td>
</tr>
</tbody>
</table>

Notes: *Average of rain gauges from Craters of the Moon, Grouse, Ketchum Ranger Station, Mackay Ranger Station and Picabo. Average rainfall (1960–2009) for March–June was 29.5, 25.8, 37.0 and 32.5 mm, respectively.*
mountains are distinct in the Landsat imagery because they are brighter or darker than the surrounding rocks and soil and have been cleared of vegetation. Using 12–15 tie points at spatially distributed road intersections, the three Landsat images were spatially aligned and georeferenced.

Differences in atmospheric properties (e.g. dust, haze) can lead to variation in how bright features appear in different images. Images were converted to reflectance using a dark pixel subtraction methodology (Chavez 1975), which accounts for scattering in the atmosphere (atmospheric scattering is most pronounced at shorter wavelengths and a different value must be subtracted for every visible and near-infrared band). The remainder of the conversion to reflectance uses gain and offset values based on sensor characteristics available in Landsat look-up tables.

Spectral alignment is an additional processing step whereby images in a time series are converted to the same spectral space using an additional gain and offset correction. Sensor degradation and changes in atmospheric properties through time must be accounted for. To do this, we selected ten 3 × 3 pixel areas within the scene that appeared to be unchanging over time (e.g. rocky outcrops with low vegetation content). We then plotted reflectance values in 1993 and 1998 versus reflectance values in 2005 and converted the earlier images to 2005 spectral space based on the gain and offset values of a regression line fit to the points. The $R^2$ values of the regression lines were >0.99 in all cases.

Clouds were present in portions of the 2005 image, and snow was present at the highest elevations in all 3 years. Clouds and snow were excluded using a threshold mask of reflectance values $>0.08$ in Landsat band 1 (blue light). Cloud shadows in 2005 were digitized manually and excluded from the analysis.

### 2.3 Conversion to vegetation index

NDVI is a ratio of the near-infrared to red wavelengths and is used to approximate green vegetation content (Tucker and Sellers 1986). The three Landsat TM images were converted to NDVI using the following formula:

$$\text{NDVI} = \frac{(\text{NIR} - \text{R})}{(\text{NIR} + \text{R})} \quad (1)$$

where NIR is near-infrared corresponding to Landsat band 4 and R is red corresponding to Landsat band 3. NDVI values for soils and vegetated material range from 0 to 1. NDVI is a proxy for ecosystem greenness, so areas with higher cover of green, photosynthetic material will have NDVI values closer to 1.

The study area encompasses a range of vegetation densities from low cover in low-elevation semi-arid shrubland to high cover in high-elevation montane shrub-steppe. Due to the prevalence of high soil cover, we also tested the soil-adjusted vegetation index (SAVI) where

$$\text{SAVI} = \left[ \frac{(\text{NIR} - \text{R})}{(\text{NIR} + \text{R} + L)} \right] \times (1 + L) \quad (2)$$

$L$ is an adjustment factor that was set to 0.5, a value appropriate for intermediate vegetation densities (Huete 1988).
2.4 Identification and modelling of change

To identify change in land cover that might have resulted from the change in land use following new ownership and management practices beginning between 2001 and 2003, we compared NDVI values in 2005 to NDVI values in 1993 and 1998 on a pixel-by-pixel basis. We measured the difference in NDVI values between 1993 and 2005 and between 1998 and 2005. Based on the histograms of \( \Delta \text{NDVI} \) values, we identified all pixels within the top 25% of change for 1993–2005 and 1998–2005 (i.e. pixels with an NDVI increase in 2005). These two maps were combined to identify all pixels within the top 25% in both time period comparisons. The same methodology was used to identify pixels in the bottom 25% (NDVI decrease). Twenty-five percent is an arbitrary threshold that was used to identify locations where some change had taken place while providing sufficient pixels for subsequent spatial analysis.

The same process was also performed on the SAVI values. However, overlap between NDVI and SAVI was 99% for pixels identified as having decreased and 96% for pixels identified as having increased. Because the two maps are nearly identical, we only report results and analysis of NDVI.

The identification of subsets of \( \Delta \text{NDVI} \) increase and decrease to classify change follows the recommendation of Singh (1989). He argues that threshold representing significant differences from the mean \( \Delta \text{NDVI} \) value should be used to exclude NDVI differences stemming from misregistration errors. The use of a threshold for identifying change also reduces error stemming from differences in green cover due to precipitation conditions (Washington-Allen et al. 1998, Bradley and Fleishman 2008). Although a 25% quantile could be considered an overly generous threshold, it was chosen because the subsequent combination of \( \Delta \text{NDVI} \) identified in both 1998–2005 and 1993–2005 substantially reduced the number of change pixels identified. The use of other statistical thresholds such as standard deviation would also be appropriate (e.g. Volcani et al. 2005) and would likely produce similar results.

Identifying overlapping \( \Delta \text{NDVI} \) values for 1998–2005 and 1993–2005 ensures that any difference results from change observed in 2005 rather than in one of the earlier time periods (e.g. a value in the top 25% for both time periods is more likely due to higher NDVI in 2005 rather than lower NDVI in both 1993 and 1998). Combined \( \Delta \text{NDVI} \) values are from here on referred to as \( \Delta \text{NDVI}_{\text{inc}} \) for those that fell within the top 25% in both time periods and \( \Delta \text{NDVI}_{\text{dec}} \) for those that fell within the bottom 25% in both time periods.

The relative probability of \( \Delta \text{NDVI}_{\text{inc}} \) and \( \Delta \text{NDVI}_{\text{dec}} \) were calculated as the number of \( \Delta \text{NDVI} \) pixels divided by the total number of pixels. Relative probabilities of \( \Delta \text{NDVI} \) were calculated for the entire study area and for subsets of the study area stratified by land use, elevation, distance to channel and distance to 2004–2005 sheep grazing. Continuous spatial variables (elevation, distance to grazing and distance to channel) were divided into discrete threshold bands (e.g. 1990–2060 m elevation; 0–30, 30–60 m from a sheep-grazing location). Relative probabilities of \( \Delta \text{NDVI} \) (increase and decrease) were measured for each threshold band. If the spatial variable has no influence on the likelihood of \( \Delta \text{NDVI} \) occurring, then relative probability will not vary across threshold bands and will be equal to the probability of the total study area. However, if the spatial variable does influence the likelihood of \( \Delta \text{NDVI} \), then the probability relationship will vary by land use or land cover, potentially revealing drivers of vegetation cover change in this region. This methodology follows Bradley and Mustard (2006) and Bradley and Fleishman (2008).
In addition to calculating probabilistic relationships between ΔNDVI and individual spatial variables, we also calculated probability relative to distance to sheep grazing for different categories of land use and ranges of elevation. Finally, we conducted a multiple linear regression of land use and topography to test whether they were independently related to ΔNDVI.

### 3. Results

The overall rate of top 25% ΔNDVI_{inc} occurring in both 1993–2005 and 1998–2005 time periods for the total study area was 15.9%. The rate of bottom 25% ΔNDVI_{dec} for the total study area was 9.5%. The median values for pixels with ΔNDVI_{inc}, ΔNDVI_{dec} and the total study area for the three time periods are shown in figure 1. The median NDVI value for the total study area varies by <0.01. The median values for ΔNDVI_{inc} pixels are 0.12 NDVI greater in 2005 than in 1993 or 1998. The median values for ΔNDVI_{dec} pixels are 0.11 NDVI lesser in 2005 than in 1993 or 1998.

The study area was divided into allotments with grossly similar land-use change beginning between 2001 and 2003 (table 1). Allotments where no change occurred had similar rates of ΔNDVI_{inc} (16.2%) and ΔNDVI_{dec} (9.6%) compared with the average for the total study area. Relative to the study area mean, allotments that experienced cattle reduction or cattle transition to sheep, which also occur at the lowest elevations, were the least likely to have had a ΔNDVI_{inc} (4.6% and 2.6% of land area, respectively) and the most likely to have had a ΔNDVI_{dec} (14.9% and 11.8% of land area, respectively; figure 2). Allotments with small reductions of sheep were slightly less likely to have had a ΔNDVI_{inc} (13.3%) and equally likely to have had a ΔNDVI_{dec} (9.8%). Lands on allotments with a large reduction in sheep grazing and on the allotment with grazing exclusion since 2002 were the most likely to have had a ΔNDVI_{inc} (18.4% and 24.4% of land area, respectively) and the least likely to have had a ΔNDVI_{dec} (6.3% and 3.5% of land area, respectively).

![Figure 1. Median values for all pixels in the study area (total population), pixels with ΔNDVI_{inc} and pixels with ΔNDVI_{dec} in 1993, 1998 and 2005.](image-url)
Figure 2. The percentage of land area showing a ΔNDVI\textsubscript{inc} and a ΔNDVI\textsubscript{dec} by land use. Relative to allotments with no change in grazing regime (black bars), allotments with a large sheep reduction or exclusion were more likely to have a ΔNDVI\textsubscript{inc} and less likely to have a ΔNDVI\textsubscript{dec}. Allotments with a cattle reduction and transition from cattle to sheep were less likely to have a ΔNDVI\textsubscript{inc} and more likely to have a ΔNDVI\textsubscript{dec}.

Figure 3. Probability of ΔNDVI\textsubscript{dec} (black squares) and ΔNDVI\textsubscript{inc} (grey squares) with changing elevation across all allotments. Grey bars indicate the percentage of total land area within that elevation range.

There was a strong relationship between probability of ΔNDVI and elevation (figure 3). Low elevations were more likely to have had a ΔNDVI\textsubscript{dec} and less likely to have had a ΔNDVI\textsubscript{inc}. Conversely, high elevations above 2280 m were increasingly likely to have had a ΔNDVI\textsubscript{inc} and less likely to have had a ΔNDVI\textsubscript{dec}.

Although the different land uses occur across a range of elevations, elevation differences alone cannot explain the distribution of ΔNDVI (increases and decreases)
between land uses. A multiple linear regression of topography and land use versus average ∆NDVI value shows that allotments with cattle reduction and cattle transition to sheep have a significantly different response than those with no change (table 3). Similarly, the ∆NDVI values on the allotment with sheep exclusion are significantly different from all other allotments independent of elevation.

Lands within 60 m of stream channels were up to 6% more likely to have had a ∆NDVI_{inc} than the mean for the study area (figure 4). This relationship was observed across all land uses, not only in allotments with reduced grazing. There was no relationship between ∆NDVI_{dec} and distance to channel.

Sheep grazing affects the probability of ∆NDVI_{inc} and ∆NDVI_{dec} in the study area (figure 5) up to an average of 1000 m from recorded GPS collar locations. The probability of a ∆NDVI_{inc} increases with distance from grazing up to 1000 m, whereas the probability of a ∆NDVI_{dec} decreases with distance from grazing up to 660 m for the average of all allotments.

The influence of sheep grazing on probability of ∆NDVI_{dec} changes over time and with land use (figure 6). Allotments with no change in land use and the average across

### Table 3. Multiple regression coefficients for topography \times land use versus ∆NDVI show that land use causes significant changes independent of topography.

<table>
<thead>
<tr>
<th>Land use</th>
<th>Parameter value</th>
<th>95% CI</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cattle reduction</td>
<td>−1.278</td>
<td>[−1.388; −1.169]</td>
<td>p = 0.002*</td>
</tr>
<tr>
<td>Cattle to sheep</td>
<td>−1.257</td>
<td>[−1.339; −1.175]</td>
<td>p = 0.001*</td>
</tr>
<tr>
<td>Small sheep reduction</td>
<td>−1.103</td>
<td>[−1.215; −0.992]</td>
<td>p = 0.098</td>
</tr>
<tr>
<td>No change</td>
<td>−0.962</td>
<td>[−1.064; −0.861]</td>
<td></td>
</tr>
<tr>
<td>Large sheep reduction</td>
<td>−0.791</td>
<td>[−0.895; −0.687]</td>
<td>p = 0.052</td>
</tr>
<tr>
<td>Grazing exclusion</td>
<td>−0.602</td>
<td>[−0.727; −0.477]</td>
<td>p = 0.001*</td>
</tr>
</tbody>
</table>

Notes: *Significant difference at the 95% confidence interval. Significance is in terms of difference from the ‘no change’ land use.

Figure 4. Probability of ∆NDVI_{dec} (black squares) and ∆NDVI_{inc} (grey squares) with distance to channel. ∆NDVI_{inc} is more likely within 60 m of a channel.
all allotments have high probabilities of $\Delta \text{NDVI}_{\text{dec}}$ adjacent to grazing. This relationship extends to a distance of 660 m. A similar relationship exists relative to grazing that occurred in 2005 (figure 6(a)) and grazing that occurred in 2004 (figure 6(b)). However, grazing that occurred in 2005 was more likely to result in a $\Delta \text{NDVI}_{\text{dec}}$ than grazing that occurred in 2004 (differences in maximum probabilities of $\Delta \text{NDVI}_{\text{dec}}$ of 6% and 4% for the no change and average allotments, respectively).

The relationship between distance to sheep grazing and $\Delta \text{NDVI}_{\text{dec}}$ changes considerably between the two time periods for allotments with a large sheep reduction. Grazing that occurred in 2005 related to $\Delta \text{NDVI}_{\text{dec}}$ up to a distance of 150 m (figure 6(a)). However, grazing from the previous year (2004) only relates to $\Delta \text{NDVI}_{\text{dec}}$ up to a distance of 60 m (figure 6(b)). In both cases, the probability of $\Delta \text{NDVI}_{\text{dec}}$ on large sheep reduction allotments is elevated for a much lesser distance from sheep grazing than in allotments with no change.

Finally, a relationship exists between the impacts of sheep grazing and elevation (figure 7). At high elevations between 2300–2500 m and 2500–3000 m, $\Delta \text{NDVI}_{\text{dec}}$ does not show a significant relationship to distance to sheep grazing. At elevations below 2300 m, $\Delta \text{NDVI}_{\text{dec}}$ is more likely adjacent to sheep grazing.

4. Discussion

An understanding of how vegetation-cover change relates to grazing is important for developing sustainable management strategies. The use of satellite data allows for landscape-scale observations of land cover, which can be used to identify the spatial relationships between land-use and land-cover change. Identified spatial relationships between land-use and land-cover change can be used to develop restoration strategies and target locations for ecological monitoring. Spatial analysis of remotely sensed data is complementary to long-term ecological studies and provides a landscape-scale analysis of land-use/land-cover trends.
Figure 6. Probability of $\Delta$NDVI$_{inc}$ with distance to daily sheep band locations in 2004 and 2005 for different land uses. (a) Probability of $\Delta$NDVI$_{inc}$ for different land uses related to grazing during the same year (2005). (b) Probability of $\Delta$NDVI$_{inc}$ for different land uses related to grazing during the previous year (2004).

The Lava Lake grazing allotments show a strong relationship between land use and probability of change. The plots historically dominated by cattle grazing were less likely to have had a $\Delta$NDVI$_{inc}$ and more likely to have had a $\Delta$NDVI$_{dec}$ (figure 2). This relationship is significant even accounting for elevation (table 3). These allotments are drier overall and are characterized by a low percentage cover of sagebrush shrubs, bunch grasses and forbs. It is possible that the prevalence of $\Delta$NDVI$_{dec}$ in this area results from management practices designed to shift livestock use away from more productive riparian areas and into adjacent less productive uplands. This may result in an overall reduction in upland vegetation cover due to lesser available forage.
The sheep exclusion allotment, which occurs in a high-elevation area dominated by heterogeneous communities of sagebrush steppe (shrubs, grasses and forbs), aspen stands and coniferous forest, showed a high probability of $\Delta NDVI_{inc}$ (figure 2). Land-cover change on this allotment was significantly different from all other allotments while accounting for elevation (table 3). The mixed-vegetation cover characteristic of the sheep exclusion allotment showed a strong tendency towards increased greenness following the removal of grazing pressure. As sheep grazing typically favours grasses and forbs over shrubs (Harniss and Wright 1982, Adler et al. 2005), it is likely that this change in greenness represents increased growth of grass and forbs in this area.

Across the study area, higher elevations were more likely to have a $\Delta NDVI_{inc}$ and less likely to have a $\Delta NDVI_{dec}$ than lower elevations (figure 3). This relationship is suggestive of ecosystem ability to recover from grazing pressure. Higher elevations in this area receive more rainfall than lower elevations. This leads to increased productivity in montane sagebrush ecosystems and the high resource availability may create potential for fast regrowth following cessation or decrease of grazing pressure. Additionally, ecosystems at higher elevations are generally free of invasive plants, which may result in higher resilience to disturbance. Also, over time the higher elevations have received more limited grazing due to the shorter growing season, which may have also helped maintain resilience of the native community.

A change in management practices of riparian areas has had a strong influence on increased greenness within and adjacent to channels across all allotments (figure 4). $\Delta NDVI_{inc}$ in riparian corridors is independent of $\Delta NDVI_{inc}$ occurring in upland vegetation. Increases in green cover in riparian areas are likely a direct result of a management strategy by Lava Lake to promote recovery in riparian zones by reducing grazing use through selective herding and, in some cases, total exclusion from riparian areas. Since the beginning of the management approach in 2002, managers have observed increased regeneration of woody riparian species (e.g. willow, aspen, alder) and herbaceous cover. This recovery is consistent with previous observations.
Landscape-scale ecosystem change from grazing

of stream-bank vegetation declines due to livestock trampling and selective grazing (Belsky et al. 1999). It is likely that the combination of increased woody and herbaceous greenness caused the $\Delta\text{NDVI}_{\text{inc}}$ signal observed with remote sensing.

The GPS collar locations of the grazing sheep allow for a measurement of the spatial and temporal extents of their impact. In the study area, sheep grazing related to higher probability of $\Delta\text{NDVI}_{\text{dec}}$ up to a distance of 660 m (figure 5). This distance likely represents the radius of impacts of clipping of green grasses and leaves due to typical dispersal of the sheep band. However, the relationship between grazing and land-cover change differs by land use. On allotments with large sheep reduction, grazing in 2005 only related to $\Delta\text{NDVI}_{\text{dec}}$ to a distance of 150 m (figure 6(a)). This suggests that lower grazing intensity directly influences the radius of impact of that grazing by several hundred metres.

Furthermore, land use influences ecosystem recovery a year after grazing. On allotments with large sheep reduction, $\Delta\text{NDVI}_{\text{dec}}$ in 2005 occurred within only 60 m of grazing that occurred in 2004 (figure 6(b)). Allotments with no change, conversely, showed no change in the relationship between grazing that occurred in either 2004 or 2005 and $\Delta\text{NDVI}_{\text{dec}}$. In both cases, lands within 500 m of grazing were more likely to have had a $\Delta\text{NDVI}_{\text{dec}}$. The difference in spatial relationships to grazing over time suggests that not only does reduced grazing intensity lead to a smaller radius of grazing impact, but it may also lead to a faster recovery in subsequent years. To test this, monitoring efforts could compare recovery of grazed vegetation on allotments with no change to recovery on allotments with a large sheep reduction.

The influence of grazing on the probability of $\Delta\text{NDVI}_{\text{dec}}$ also relates to elevation. Lower elevations are more likely to have had a $\Delta\text{NDVI}_{\text{dec}}$ in areas adjacent to grazing. However, land at high elevations between 2300 and 3000 m showed no relationship between grazing and $\Delta\text{NDVI}_{\text{dec}}$. At high elevation, regardless of land use, sheep grazing does not have a strong impact on ecosystem greenness (figure 7). The relationship between grazing impact and elevation has implications for the types of ecosystem change we should expect in these ecosystems.

In a long-term study at the US Sheep Experiment Station in Dubois, ID, just east of Lava Lake, Harniss and Wright (1982) observed change in vegetation community associated with grazing on both wet and dry sites. Moderate grazing was found to have no long-term impact on vegetation community or cover. Heavy grazing, however, led to a reduction of total vegetation cover on dry sites but a shift in vegetation community in favour of shrubs on wetter sites. Generally, the more palatable grasses and forbs saw the largest reduction in cover, whereas less palatable shrubs and Sandberg bluegrass (Poa secunda) maintained or increased cover. Based on our spatial analysis (figure 7), the transition from ecosystems where grazing causes a loss of cover to ecosystems where grazing causes a shift in composition likely occurs near 2300 m in this area. Monitoring efforts to identify the effects of current grazing should look for reduced vegetation cover below 2300 m but a shift in cover type above 2300 m.

It is important to note that, in general, $\Delta\text{NDVI}_{\text{inc}}$ is not necessarily good, and likewise $\Delta\text{NDVI}_{\text{dec}}$ is not necessarily bad. Grazing may also, in some instances, have a counter-intuitive effect on community greenness. For example, ungrazed grasses may appear less green in subsequent years due to standing dry biomass. NDVI changes in most locations are likely due to a change in percentage cover of some combination of grasses, shrubs and forbs. However, the exact cause of these changes and the implications of change for biodiversity and ecosystem function can only be assessed through field studies.
Similarly, a lack of change in ecosystem greenness does not imply that shifts in community composition and structure are not occurring. Several studies have linked sheep grazing with reduction of grasses and accompanying increases in shrub cover (Harniss and Wright 1982, Bork et al. 1998, Seefeldt and McCoy 2003, Adler et al. 2005). Spring and early summer grazing, in particular, has been found to be detrimental to native grasses and forbs and to increase the probability of invasion by non-native species (Bork et al. 1998, Seefeldt and McCoy 2003).

To understand better the short-term impacts of livestock grazing on ecosystem structure and function, landscape monitoring would ideally include intensive monitoring across extensive sites. However, the time commitment required by this level of effort often makes this type of monitoring impractical. The addition of remote-sensing analysis complements monitoring of vegetation-cover change at landscape scales. Particularly when vegetation-cover change is analysed spatially, remote sensing can identify patterns of change across broad areas to test whether local processes are consistent with the larger landscape. Furthermore, spatial patterns identified with remote sensing can be used to inform monitoring efforts by highlighting areas most likely to change. Remote sensing and spatial analysis are important tools for landscape-scale studies that can help land managers to improve monitoring and restoration of ecosystems across extensive public and private lands.

5. Conclusions

Measuring and understanding the effects of livestock grazing on ecosystems is an extremely challenging task. Historical data on stocking rates and ecological responses are often non-existent, monitoring is rarely sufficiently long term and rangeland extents make landscape-scale analyses prohibitively expensive and time-consuming. The addition of remote sensing and accompanying spatial analysis provides important information to complement monitoring efforts. Spatial relationships between grazing and changing NDVI such as those presented here can inform the location of monitoring and experiments and can be used to scale up local processes to landscape levels. Ultimately, by combining remote sensing with targeted experiments and monitoring, we can improve our understanding of the long-term ecological effects and sustainability of moderate and light grazing.

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