Identifying land cover variability distinct from land cover change: Cheatgrass in the Great Basin

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Abstract

An understanding of land use/land cover change at local, regional, and global scales is important in an increasingly human-dominated biosphere. Here, we report on an under-appreciated complexity in the analysis of land cover change important in arid and semi-arid environments. In these environments, some land cover types show a high degree of inter-annual variability in productivity. In this study, we show that ecosystems dominated by non-native cheatgrass (Bromus tectorum) show an inter-annual amplified response to rainfall distinct from native shrub/bunch grass in the Great Basin, US. This response is apparent in time series of Landsat and Advanced Very High Resolution Radiometer (AVHRR) that encompass enough time to include years with high and low rainfall. Based on areas showing a similar amplified response elsewhere in the Great Basin, 20,000 km², or 7% of land cover, are currently dominated by cheatgrass. Inter-annual patterns, like the high variability seen in cheatgrass-dominated areas, should be considered for more accurate land cover classification. Land cover change science should be aware that high inter-annual variability is inherent in annual dominated ecosystems and does not necessarily correspond to active land cover change.

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1. Introduction

A challenge to land cover change science is distinguishing change in land cover from variability within land cover types. Change implies a shift in land cover type, frequently associated with land use, while inter-annual variability in growth is an inherent characteristic of some vegetated communities. In the semi-arid Great Basin, US (Fig. 1), inter-annual variability distinct from land cover change is prominent in land cover types dominated by cheatgrass (Bromus tectorum). Correctly identifying and interpreting change in land cover and/or land use is of great interest in the field of environmental change (Dale, 1997; Lambin et al., 2001; Turner, 2003; Vitousek et al., 1997), so inter-annual patterns caused by communities like cheatgrass should be recognized.

In order to identify change, it is important to have a baseline of land cover at national and international scales. Global assessments of land cover have been performed based on single year phenologies using Normalized Difference Vegetation Index (NDVI) data from Advanced Very High Resolution Radiometer (AVHRR) and the Moderate Resolution Imaging Spectroradiometer (MODIS) (Defries & Townshend, 1994; Defries et al., 1995; Friedl et al., 2002; Loveland et al., 2000, 1999). Multiple phenology-based mapping methods have been employed, including principle component analysis, fourier analysis, and decision tree approaches (Defries & Townshend, 1994; Homer et al., 2002; Loveland et al., 2000, 1999). However, because most land cover algorithms rely on single year or averaged phenologies to differentiate between land cover types, they do not capture inter-annual variability. Land cover with high inter-annual variability could distort the baseline from which change is measured depending on growing conditions during the baseline year (Lambin, 1996).
Landsat-scale land cover change detection relies on an accurate interpretation of baseline conditions and change in surface spectral properties over time. For example, the conversion of vegetated surfaces to man-made materials through urbanization can be readily identified and mapped using remotely sensed tools (Masek et al., 2000). Similarly, land cover dynamics in tropical regions such as cutting of forest for pasture and secondary regrowth have well documented trajectories of spectral properties over time tied to land cover (Adams et al., 1995; Skole & Tucker, 1993). In the Great Basin, baseline conditions from which to measure change are difficult to define. Here, changes in remotely sensed surface properties can be a result of a high degree of species elasticity in response to rainfall, not land cover change. A comparison of NDVI for this land cover type between low and high rainfall periods could suggest a significant increase in vegetation, or the reverse, a dramatic loss. Inter-annual variability makes identification of a baseline increasingly complex.

Regional scale change detection typically involves interpretation of NDVI time series from sensors such as AVHRR and MODIS. Time series analyses have been used to identify changes in the Sahel (Tucker et al., 1991), and to estimate changes to growing season attributed to climate in the northern latitudes (Myneni et al., 1997, 1998; Shabanov et al., 2002; Zhou et al., 2003, 2001) and in China (Young & Wang, 2001). Potter et al. (2003) use AVHRR derived fraction absorbed of photosynthetically active radiation (FPAR) estimates to identify global disturbance events during an 18-year record. With an increasing interest in change detection over large spatial scales, it is important to understand how a range of ecosystems are affected by short-term climate patterns. In the Amazon, AVHRR NDVI time series have been shown to be greatly influenced by precipitation, and thus coupled to the El Niño cycle (Asner et al., 2000). As we will show, an even more pronounced effect exists in cheatgrass-dominated annual grasslands in the Great Basin.

Cheatgrass’ inter-annual variability is distinct in the Great Basin due to its link to rainfall. Precipitation patterns in the Great Basin show a high degree of temporal variability. Twenty six distributed National Climatic Data Center rain gages with continuous records from 1990 to 2002 averaged 18 cm of rainfall per year with an inter-annual variance about that mean of 26 cm. Rainfall during wet years is frequently three to four times higher than during dry years. This pattern of extreme wet and dry years causes a dramatic response in cheatgrass. Rangeland studies have shown that during wet years cheatgrass can be 10 times taller and denser than during dry years (Hull & Pechanec, 1947; Stewart & Hull, 1949; Stewart & Young, 1939). High inter-annual variability is unique to annual grasslands in the Great Basin. Shrub/perennial bunch grass ecosystems are adapted to rainfall patterns. While they show some change in productivity coupled with rainfall, the range of variance is limited (Prince et al., 1998). Elmore et al. (2003) showed that for a 20-cm variance in rainfall, native perennial communities exhibited a 5% variance in live cover, while invasive annuals had an inter-annual variance in live cover up to five times higher. Remote sensing is a good candidate for identifying a similar pattern in the Great Basin because regionally, cheatgrass monocultures have become increasingly prominent in formerly shrub/bunch grass ecosystems (Mack, 1981; Young et al., 1972).

Our goals in this analysis are two-fold. First, we demonstrate that annual grassland in the Great Basin, US...
exhibits inter-annual variability of greenness in response to rainfall that exceeds the range expected for shrub-dominated land cover types. Second, we show that this signal of amplified response to environmental conditions can be used to map a land cover type not previously captured by standard land cover mapping methods. This land cover type is dominated by the invasive annual cheatgrass. It is important to note that the extreme variability in inter-annual NDVI resulting from cheatgrass dominance is not caused by land cover change during the period of record. Rather, the variability is an effect of cheatgrass presence. These goals are accomplished through coordinated analysis of coarse spatial, high temporal resolution AVHRR data and high spatial resolution Landsat data.

2. Great Basin vegetation

Native vegetation in the Great Basin is adapted to the desert’s highly variable precipitation. The Great Basin frequently has years of persistent drought followed by extremely wet years. Native perennial shrubs and grasses have adapted to these conditions by setting deep roots (in some cases up to 30 ft), growing photosynthetically active leaves judiciously, and investing resources in seed production only in years when conditions are optimal (Grayson, 1993; Meyer & Monsen, 1992). Perennial shrub and bunch grass communities typically green up in early to mid-May and remain photosynthetically active through the hot summer months.

Cheatgrass, an invasive annual, germinates in mid-April in the Great Basin (except in rare years when wet conditions permit fall germination), but remains green for only a few weeks (Rice et al., 1992). It invests all of its resources in growing larger to support the production of a maximum number of seeds (Knapp, 1996; Young & Allen, 1997). Cheatgrass growth peaks in mid-May, after which point, it quickly senesces and remains dormant until seeds germinate the following season. The distinct inter-annual response of perennial vs. annual communities presented here is caused by these differences in plant physiology.

3. Datasets

Three types of data were used in this study: field observations of land cover, a time series of Landsat data centred on the lower Humboldt River, Nevada, and a time series of AVHRR weekly and biweekly data. All three were used to assess temporal vegetation patterns in the Great Basin.

Field observations were made in May 2003 in areas surrounding the lower Humboldt River, Nevada (40–41°N, 117.5–119°W). Thirteen sites dominated by either cheatgrass monoculture, or native shadscale (Atriplex spp.) and bunch grass (Poa secunda, Agropyron spicatum) were identified and geolocated. Polygons were then created surrounding the observed areas. Five sites, each spanning ≥4 km², contained cheatgrass monoculture. The remaining eight sites, also spanning ≥4 km², contained native shadscale/bunch grass and no cheatgrass. An additional three sites, each spanning ≥9 km², were selected on non-vegetated salt flats. A location map and pictures of representative land cover types are shown in Fig. 2.

Field observations were repeated in 2004 at 659 distributed localities in order to validate the predicted

![Map of field sites with known land cover types.](image-url)
distribution of high density cheatgrass (Fig. 3). Validation localities span the Landsat scene in areas that are accessible by road. Validation points were selected to include three types of non-cheatgrass-dominated native vegetation: dry desert shrubs, sagebrush steppe, and pinyon-juniper woodland. Cheatgrass-dominated validation points included monoculture and dense understories of cheatgrass in dry desert shrub and sagebrush steppe ecosystems. The incorporation of validation points in the study allows us to assess the accuracy of the distribution maps created with the remotely sensed data.

A series of 10 Landsat TM and ETM+ scenes (Path 42 Row 32) were acquired for the lower Humboldt River, Nevada between 5/15/88 and 5/11/2001 (Table 1). The 30 m resolution of Landsat captures local, landscape-scale variability over time. Dates of the scenes were as close to May 15 as possible. By this time, residual snow has melted from the valleys, and Great Basin vegetation, both shrubs and cheatgrass, is near peak greenness. Landsat data were converted to reflectance based on the spectral signatures of five sites whose reflectance spectra were measured with an ASD FieldSpec spectrometer (Elmore et al., 2000; Hall et al., 1991; Schott et al., 1988). The use of invariant targets rather than Landsat calibration coefficients increases the accuracy of the reflectance conversion by better accounting for atmospheric aerosols for each observation. The sites contained no vegetation, and were therefore assumed to be spectrally invariant over time. The five spectrally invariant targets encompass a range of reflectance values from dark (Pyramid Lake) to bright (salt flat) (Fig. 4). The mean spectral signature of 25 spectra acquired at each of the five sites was used to convert Landsat-measured radiance to reflectance. A linear regression fit to DN vs. reflectance had an $R^2$ value greater than 0.98 in all cases. NDVI values for each scene were then calculated using Landsat bands 3 and 4.

Weekly and biweekly AVHRR NDVI composites for the conterminous US were used for the regional analysis (Eidenshink, 1992; Teillet & Holben, 1994). The 1-km resolution of AVHRR allows for regional detection of prominent processes found at the landscape scale. The dataset spans 1/1/1990–12/31/2001 and was clipped to include only the Great Basin (boundaries in Fig. 1). The visible band for every scene was checked for snow and/or cloud cover. Parts of scenes containing snow or clouds (primarily in winter scenes) were discarded, creating a final NDVI dataset consisting of 394 scenes. Signal variations caused by orbital drift and sensor degradation have previously been recognized (Privette et al., 1995) and removed by subtracting NDVI time series over unvegetated surfaces from vegetation NDVI time series (Myneni et al., 1998). In order to account for long-term sensor bias in the Great Basin, we removed a curve fit to the mean NDVI time series of the unvegetated Bonneville Salt Flat, UT and Black Rock Desert, NV. A smooth curve fit rather than the mean signal is used to prevent any propagation of stochastic error in the data. A linear continuum was fit to the NOAA-11 NDVI data, and a 3rd order polynomial fit to the NOAA-14 NDVI data after (Kastens et al., 2003). This continuum was subtracted from every pixel.

### Table 1

<table>
<thead>
<tr>
<th>Sensor type</th>
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<tr>
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<td>Landsat TM</td>
<td>5/8/1997</td>
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<tr>
<td>Landsat ETM+</td>
<td>5/11/2001</td>
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Fig. 4. Reflectance in Landsat TM bands 3 and 4 of non-vegetated, spectrally invariant targets used to calibrate Landsat scenes to reflectance.
4. Amplified response of cheatgrass-dominated land cover

Previous work has shown that Landsat time series can detect an amplified response to rainfall characteristic of invasive annuals in Owens Valley, CA (Elmore et al., 2003). Cheatgrass has also been observed to have a similar amplified response following years with above average rainfall (Hull & Pechanec, 1947; Stewart & Hull, 1949). Therefore, we predict that time-series of NDVI determined from remotely sensed data will show an inter-annual amplified response to rainfall in cheatgrass-dominated areas. We expect to see this pattern in time series of Landsat as well as AVHRR data.

In order to identify amplified response in the Landsat time series, we determine the ΔNDVI, or the difference in NDVI values between a high rainfall year and a low rainfall year for each pixel. By subtracting the low rainfall NDVI values, we normalize the high rainfall scene across vegetation types to target areas showing an amplified response. Native perennial communities should have low ΔNDVI values because they do not respond strongly to inter-annual rainfall variability (Elmore et al., 2003). However, cheatgrass-dominated areas should have high ΔNDVI values as a result of their amplified response to rainfall. We selected 1995 as the high rainfall scene and 1991 as the low rainfall scene. The 1995 scene was chosen for ΔNDVI calculation because its timing, June 4th, was closer to cheatgrass peak greenness than the June 28, 1998 scene (Table 1). The low rainfall scene was selected due to its seasonal proximity, June 9, 1991, to the high rainfall 1995 scene.

In the case of AVHRR, 2 years are not adequate for identification of regional amplified response because rainfall patterns are heterogeneous throughout the Great Basin. We identified regionally high and low rainfall years based on 26 rain gages with continuous records from 1990 to 2001 distributed through Utah, Nevada, and Oregon (Fig. 5A). To account for differences in rainfall patterns between stations, rainfall is normalized by the decadal mean at individual stations, making mean rainfall equal to 1. The resulting normalized October–May rainfall patterns for all 26 gages were then averaged to identify regionally high rainfall years (Fig. 5B). The 3 years of regionally high rainfall were 1993, 1995, and 1998. Annual rainfall was above the station decadal average at 65%, 96%, and 88% of the rain gages during 1993, 1995, and 1998, respectively. This indicates that these years were regionally wet, rather than affecting only localized areas. The remaining years were below average at between 62% and 92% of the stations, indicating that these years were regionally dry. To identify amplified response, we found the maximum NDVI between April 15 and June 15 for each year. Spring timing was chosen to coincide with peak cheatgrass productivity. ΔNDVI was calculated by subtracting the median of the spring maxima during the 8 low rainfall years from the median of the spring maxima during the 3 high rainfall years. By using medians rather than means, the result is not skewed by anomalously low or high values caused by local rainfall variability, agriculture, or sensor error. The method used to identify regional amplified response with AVHRR assumes that cheatgrass was present during all 3 high rainfall years in the 1990s. Changes in the distribution of cheatgrass during this time period via expansion or decline add uncertainty to the regional estimate.

5. Results

Fig. 6 shows mean Landsat and AVHRR time series for the three land cover type localities identified in Fig. 2: cheatgrass monoculture, native shadscale/bunchgrass, and non-vegetated salt flats. In the Landsat time series, cheatgrass shows a highly amplified response to rainfall compared to the other land cover types following the wet years of 1988, 1995, and 1998. Likewise, in the AVHRR
time series, cheatgrass shows an amplified response following 1995 and 1998. The amplified response of cheatgrass is also apparent when ΔNDVI values are compared (Fig. 7). With Landsat, cheatgrass-dominated areas have a mean ΔNDVI of 0.202±0.091 (1σ), native shadscale/bunch grass ecosystems have a mean ΔNDVI of 0.055±0.032 (1σ), and salt flats have a mean ΔNDVI of 0±0.015 (1σ). Histograms of ΔNDVI values for the three land cover types show that salt flats and native ecosystems are normally distributed. Cheatgrass, however, shows a bimodal distribution of ΔNDVI values with the lower peak covering a similar range of values as native vegetation (Fig. 7C). This suggests that the cheatgrass-dominated field sites contained patches of native vegetation in 1995. These areas may have since been converted to cheatgrass monoculture, accounting for the discrepancy between the remotely sensed data and the field observations.

With AVHRR data, we see a similar separation between land cover types. Cheatgrass-dominated areas have a mean ΔNDVI of 0.12±0.045 (1σ), native shadscale/bunch grass ecosystems have a mean ΔNDVI of 0.049±0.021 (1σ), and salt flats have a mean ΔNDVI of 0.004±0.005 (1σ).

Fig. 7. Box plots and histograms indicate the distribution of ΔNDVI values at three land cover types. Boxes encompass the central 50% of values, lines encompass 95%. Cheatgrass-dominated areas show higher ΔNDVI values, a result of their amplified response to rainfall. (A) Landsat box plots. (B) AVHRR box plots. (C) Landsat histograms.
All three land cover types appear normally distributed, although there are fewer samples because of the 1-km² AVHRR pixel size. The mean ΔNDVI value for cheatgrass land cover calculated from AVHRR is lower than the mean ΔNDVI calculated from Landsat. Mixtures of shrub/bunchgrass and cheatgrass are more likely within the 1-km² spatial resolution of AVHRR, resulting in a lower mean. The AVHRR calculation also combines multiple years to identify ΔNDVI, which may account for the lower values.

5.1. Regional amplified response

Using the distributions of ΔNDVI values at known land cover types, we estimate regional occurrence of amplified response in the Great Basin. We chose to increase the sensitivity, or the likelihood that cheatgrass will be present given a positive detection, by setting a detection level above the 95% confidence interval (C.I.) for the native ΔNDVI distribution. Localities with ΔNDVI values above this detection level are predicted to contain cheatgrass. Predicted cheatgrass-dominated areas are well separated from the native population while still capturing most of the cheatgrass population (Fig. 7). To demonstrate that populations showing an amplified response are distinct despite changes to the threshold level, the distributions of areas with ΔNDVI values above both the 95% and 99% C.I.s are presented in Fig. 8. For Landsat, the 95% C.I. for native shadscale/bunch grass is >0.103 ΔNDVI and the 99% C.I. is >0.124 ΔNDVI. For AVHRR, the 95% C.I. is >0.082 ΔNDVI and the 99% C.I. is >0.102 ΔNDVI.

In the Great Basin, the AVHRR 95% C.I. amplified response map predicts 20,000 km², or 7% of the total land cover to be dominated by cheatgrass. The Landsat 95% C.I. amplified response map predicts 5000 km², or 17% of the total land cover within the Landsat scene to be dominated by cheatgrass. In the Landsat scene, AVHRR predicts 4500 km² to be dominated by cheatgrass. Areas of overlap between the two sensors are shown in Fig. 8C. Both sensors identify similar spatial patterns of cheatgrass presence in valleys of the eastern half of the Landsat scene. The inter-annual variability of cheatgrass is distinct enough that it can be identified over spatial resolutions ranging from 30 m to 1 km. Any discrepancy between Landsat and AVHRR distributions of ΔNDVI values may be due to differences in timing of scene acquisition, differences in band width at the red and infra-red wavelengths, and the difference in sensor resolution mentioned previously.

Fig. 8. Predicted distribution of cheatgrass-dominated areas based on an amplified response to rainfall. (A) Landsat distribution of amplified response higher than the 95th (blue) and 99th (red) percentile for native vegetation. Cultivated areas and peaks above 1800 m are masked. (B) AVHRR distribution of amplified response higher than the 95th (blue) and 99th (red) percentile for native vegetation. Landsat extents are outlined in black. (C) Overlap of Landsat and AVHRR distributions of amplified response.
5.2. Validation

The accuracy of both Landsat and AVHRR cheatgrass distributions was validated through field observations at 659 localities in May 2004 (Fig. 3). These localities are distributed along accessible roadways within the Landsat boundaries. Sites containing no cheatgrass or trace cheatgrass (only along roadides or under shrub canopies) were considered to have no cheatgrass and account for 250 of the 659 observations. Sites containing cheatgrass monoculture or a dense understory of cheatgrass in shrub interspaces were considered to have cheatgrass and account for 409 of the 659 observations. Localities with a sparse understory of cheatgrass in shrub interspaces were not considered.

Receiver operator calibration (ROC) curves for both the Landsat and AVHRR predictions are shown in Fig. 9. Based on the validation results, a threshold of $>0.103$ ΔNDVI for Landsat accurately identifies 72% of cheatgrass cover while misidentifying 17% of other land cover types. A threshold of $>0.082$ ΔNDVI for AVHRR accurately identifies 64% of cheatgrass cover while misidentifying 15% of other land cover types. By combining the two sensors, we identify a higher percentage of cheatgrass occurrence. Sites identified by either Landsat or AVHRR using the previous threshold levels accurately identify 81% of cheatgrass cover while misidentifying 25% of other land cover types. The validation results show a decreased sensitivity compared to the original 13 field sites. The higher estimate derived from the original field sites is likely a result of spatial autocorrelation. By using validation points distributed across the Landsat scene, we can more precisely define the accuracy of the maps.

6. Discussion

This study shows that surfaces with high inter-annual variability, a response linked to cheatgrass presence, are widespread throughout the Great Basin. This pattern is distinct from other land cover types and can be used to identify areas where cheatgrass dominates. Cheatgrass, native shadscale/bunch grass, and salt flats are distinct in both time series (Fig. 6) and ΔNDVI values (Fig. 7). When the spatial pattern of amplified response is mapped (Fig. 8), the areas identified by AVHRR are similar to those identified by Landsat. Changing the detection confidence interval does not affect the contiguous areas of amplified response seen in the eastern half of the Landsat scene. The presence of areas identified as cheatgrass by only one of the two sensors is consistent with the identification rates of 64% and 71% by AVHRR and Landsat, respectively. Additionally, areas identified in AVHRR by the ΔNDVI method almost all show the targeted amplified response to rainfall over time. The only exception being scattered pixels in southwestern Utah. There, time series show an amplitude increase during the late 1990s which may be attributable to slight misregistration along steep mountain gradients of the Fish Lake and Dixie National Forests. Everywhere else, positively identified pixels show an amplified response in 1993, 1995, 1998, or a combination of the three. Because cheatgrass is the primary invasive annual into native perennial communities, amplified response is likely caused by cheatgrass dominance.

The inter-annual pattern caused by cheatgrass' amplified response should not be confused with land cover change. There is some risk of this type of pattern being erroneously labeled change, particularly because several of the cheatgrass-dominated time series show a secondary amplified response the year following a wet year. This is particularly notable in 1996 and 1999, despite the fact that rainfall during these 2 years was below average. This effect may be a result of an increased seed bank the year following wet years (Prince et al., 1998), or, in the case of 1999, an exceptionally wet preceding September/October which allowed for fall germination of cheatgrass. A time series spanning the 1990s could be misinterpreted as land cover change due to this secondary response (Fig. 10). However, the pattern is entirely attributable to cheatgrass variability. Land cover change research, particularly studies at regional scales, should be aware that this type of rainfall-driven pattern is a temporal signature of an unchanging land cover type.

Based on the regional map (Fig. 8B), cheatgrass-dominated ecosystems are widespread in northern Nevada and western Utah. The counties most affected by invasion include Pershing, Humboldt, and northern Lander and Eureka in Nevada. Tooele and Box Elder counties are most affected in Utah, and Harney County.
in Oregon also has a concentrated invasion. In all, 20,000 km² of detected amplified response is apparent in several concentrated localities in the Great Basin. Despite the large extent of cheatgrass dominance, the land cover type is not apparent in single year phenology-based classifications of US land cover, like the North American Land Cover Characteristics Map (Fig. 1B) (Loveland et al., 1999). Inter-annual variability in time series encompassing wet and dry years should be considered for more accurate classification.

The broad spatial extent of cheatgrass invasion allows for easy scaling between field observations, Landsat, and AVHRR resolutions. However, the amplified response of cheatgrass is not apparent without a time series of data encompassing both dry and wet years. Additionally, cheatgrass phenology is short, lasting only 1–2 spring months. As a result, Landsat scenes must be chosen with care to capture peak productivity. Analysis of a single scene is not enough to differentiate cheatgrass from native land cover types. While cheatgrass detection based on its early green-up has been performed using Landsat scenes from 2001 (Peterson, 2003), identification of cheatgrass is optimal during wet years. Time series analysis should be considered for distinguishing between land cover types, particularly when they have different responses to climatic patterns on an inter-annual basis.

Variability over time does not necessarily imply active land cover change. Cheatgrass-dominated areas show changing productivity over time, but the land cover itself is not changing. For example, a cheatgrass time series from northern Nevada may at first suggest a dramatic shift in land cover between 1994 and 1995, particularly in areas exhibiting a second year of rainfall-related amplified response (Fig. 10). Likewise, a comparison of NDVI based productivity for 1998 and 2000 would indicate a marked loss of biomass that could be erroneously attributed to land cover change. In fact, the same land cover has been in place at these localities for at least the past decade. Land Use/Land Cover Change science, particularly regional and global models, must be aware that some responses that look like change are caused by inherent variability within ecosystems. Strong correlation to precipitation may be of particular concern in semi-arid ecosystems; however, different environmental variables may affect inter-annual vegetation patterns in other ecosystems. Variability over time, particularly when it can be correlated to climatic patterns, is likely a response of a particular land cover type rather than an indication of land cover change. Land cover change scientists should use caution when interpreting signals like the one presented here.

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