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Comparison of phenology trends by land cover class: a case study in the Great Basin, USA

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Abstract

Direct impacts of human land use and indirect impacts of anthropogenic climate change may alter land cover and associated ecosystem function, affecting ecological goods and services. Considerable work has been done to identify long-term global trends in vegetation greenness, which is associated with primary productivity, using remote sensing. Trend analysis of satellite observations is subject to error, and ecosystem change can be confused with interannual variability. However, the relative trends of land cover classes may hold clues about differential ecosystem response to environmental forcing. Our aim was to identify phenological variability and 10-year trends for the major land cover classes in the Great Basin. This case study involved two steps: a regional, phenology-based land cover classification and an identification of phenological variability and 10-year trends stratified by land cover class. The analysis used a 10-year time series of Advanced Very High Resolution Radiometer satellite data to assess regional scale land cover variability and identify change. The phenology-based regional classification was more detailed and accurate than national or global products. Phenological variability over the 10-year period was high, with substantial shifts in timing of start of season of up to 9 weeks. The mean long-term trends of montane land cover classes were significantly different from valley land cover classes due to a poor response of montane shrubland and pinyon-juniper woodland to the early 1990s drought. The differential response during the 1990s suggests that valley ecosystems may be more resilient and montane ecosystems more susceptible to prolonged drought. This type of regional-scale land cover analysis is necessary to characterize current patterns of land cover phenology, distinguish between anthropogenically driven land cover change and interannual variability, and identify ecosystems potentially susceptible to regional and global change.

Keywords: AVHRR, classification, interannual variability, land use land cover change, NDVI, phenology, regional ecosystems, remote sensing, time series

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Introduction

The amount of land cover influenced by anthropogenic activity has grown along with human population and living standards. Land cover change may result directly from human land use, or it may result from indirect effects of anthropogenic activity such as climate change (see, e.g. Vitousek *et al*., 1997; Foley *et al*., 2005). Land cover provides critical goods (e.g. food, fiber, and other raw materials) and services (e.g. carbon storage and water cycling) to humans and other species (see Costanza *et al*., 1997; Daily *et al*., 2000). Accordingly, it is useful to characterize land cover and understand how land cover responds to interannual variability, climate, and land use. Further, identifying current land cover trends and variability creates a baseline of current ecosystem properties against which future change can be measured.

Land cover may respond in a variety of ways to changes in climate and land use. Long-term increases or decreases in primary productivity may occur (greening or browning trends). Phenology, or the timing of recurring natural phenomena, may shift, leading to changes in events such as germination, reproduction, and senescence (see Schwartz, 1998; Hughes, 2000; Walther *et al*., 2002). The dominant species in an

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ecosystem may also change because of direct land use, invasion of nonnative species, or a shift in competitive interactions among species. Any of these land cover changes could affect ecosystem function and lead to a reduction of goods and services.

A challenge to land cover research is differentiating between anthropogenically driven, long-term change and interannual ecosystem variability. Particularly in the context of global climate change, it is important to characterize current land surface phenology and interannual variability in order to identify future land cover change if and when it occurs.

Long-term trends in land cover phenology

Several studies have looked at greening trends across large areas of land cover. Regional trends in vegetation greenness have been identified using time series of remotely sensed data. For example, Myneni *et al*. (1997, 1998) used time series of Advanced Very High Resolution Radiometer (AVHRR) Normalized Difference Vegetation Index (NDVI) data to quantify increasing greenness in high-latitude boreal forests based on linear fits to the time series. NDVI measures relative photosynthetic activity and has been widely used to estimate vegetation greenness (Tucker & Sellers, 1986). Similar studies and observations were later repeated across more extensive regions of northern forest (Tucker *et al*., 2001; Zhou *et al*., 2001; Shabanov *et al*., 2002; Zhou *et al*., 2003) and temperate forests in China (Young & Wang, 2001). Goetz *et al*. (2005) noted both greening and browning trends across the northern boreal forests. Reed (2006) found trends in seasonality and integrated NDVI across North America. Asner *et al*. (2000) linked productivity in Amazonia to alternating El Niño and La Niña events. Working at the global scale, Potter *et al*. (2003) identified anomalous land cover trends based on changes in fraction of photosynthetically active radiation values. While an assessment of regional and global trends in land cover is important, of equal importance is an understanding of how those trends differ among land cover types within a region.

An important component of assessing trends in land cover that has occasionally been overlooked is interannual variability. The response of some land cover classes is strongly coupled to climate, reducing the certainty of long-term 'trends' if climate conditions at either end of a time series were anomalous. For example, Bradley & Mustard (2005) showed that in the western United States, invasive, nonnative annual grasses were highly responsive to rainfall. Thus, a regional assessment of greenness trends during the 1990s was influenced strongly by annual grasses because of their amplified response to heavy precipitation during the 1998 El Niño. High sensitivity to climatic variability of a particular land cover type may mask anthropogenically driven greenness trends in other land cover types. Merging all land cover classes to assess average trends in decadal greenness or seasonality risks skewing the result based on the response of a single class, or missing trends occurring at small spatial scales. An understanding of greenness trends specific to individual land cover classes could lead to improved identification of land cover change.

A potential problem with identification of long-term greening trends via remote sensing is the confounding effect of sensor error. Long-term trends in AVHRR data have been observed in time series taken from nonvegetated deserts (Gutman, 1999; Kogan & Zhu, 2001; Kastens *et al*., 2003). These data often show positive, increasing NDVI trends that have been associated with sensor drift and calibration problems between instruments (Gutman, 1999). Although these trends are less obvious in areas with dense vegetation or variable interannual phenology, it is difficult to determine the relative proportions of observed greening trends attributable to change vs. sensor error. This problem has been dealt with previously by identifying change as trends that are significant using regression (Fuller, 1998; Slayback *et al*., 2003) and other statistical techniques (de Beurs & Henebry, 2005). However, as mentioned previously, significant trends do not always imply change and can result from climate responses of specific land cover classes (Bradley & Mustard, 2005). Rather than focusing on detection of change, an alternate approach is to compare the mean trends of regional land cover classes. This way, differences in phenology trends between ecosystems can be used to assess responsiveness to climate and potentially identify susceptibility to future change.

Phenological parameters

Several parameters associated with vegetation phenology can be measured with remotely sensed time series. One is start of season (SOS). Different measures of SOS can be derived from time series, including the time at which NDVI values increase beyond a certain threshold (Lloyd, 1990; White *et al*., 1997), inflection points, or the time at which the curve starts to increase (Moulin *et al*., 1997), and maximum growing season slope, or the time at which greenness is increasing the fastest (Zhang *et al*., 2003). Although the relationship between satellite and ground measures is uncertain (Schwartz & Reed, 1999), a SOS measurement is internally consistent within remotely sensed time series and can be used to assess seasonal variability and long-term trends within and between land cover classes. Other phenological parameters measured by time series include end of season (EOS) and the date of maximum NDVI. Length of growing season can be calculated as the difference between EOS and SOS. Relative annual productivity has been calculated using average annual or integrated annual NDVI. Trends and interannual variability over the time series are dependent upon these measures of seasonality.

In this work, we take a two-step approach to analyzing regional land cover. First, we create a refined regional land cover classification. This step is critical because national and global land cover products do not effectively map regional land cover classes, and stratifying phenological characteristics by land cover class is necessary to evaluate their susceptibility to global climate change. Second, we consider long-term trends in greenness (NDVI) and timing of phenology for Great Basin land cover classes. This step helps us to identify typical ecosystem response to climate variability, which may be indicative of adaptability to future global change. In addition, by comparing the mean trends of the individual land cover classes, we get a sense of how different ecosystems respond under similar climate conditions. By focusing on times of drought and on strong El Niño events, we assess relative greenness and growth patterns under extreme conditions for the major regional land cover classes.

Methods

Study area

The Great Basin ecoregion encompasses the majority of Nevada, western Utah, and parts of California, Idaho, and Oregon (USA). Land cover types are diverse because of topographic and local climatic heterogeneity. The most extensive land cover class in the Great Basin is basin big sagebrush (*Artemesia tridentata*), located in valleys where mean annual precipitation is typically >20 cm (Houghton *et al*., 1975). Sagebrush shrubland often contains perennial bunch grasses and forbs in addition to the shrubs.

Salt desert shrubland occurs under slightly drier conditions than sagebrush shrubland, although the two often occur together in broad transition zones. Common species include shadscale and saltbush (*Atriplex* spp.), both C4 woody shrubs, as well as hopsage (*Grayia spinos*), winterfat (*Krascheninnikovia lanata*), and occasional perennial bunch grasses.

Wetlands with groundwater dependent grasses and sedges, often in standing water, are present in several valleys particularly in eastern Nevada (Taylor, 1992). Surrounding these meadows are groundwater-dependent shrublands dominated by greasewood (*Sarcobatus vermiculatus*) and rabbitbrush (*Crysothamnus* spp.). Meadows and associated shrubland are typically found on alkaline soils in the centers of valleys and we collectively refer to them as alkali meadows.

Also present in valleys are invasive species, the most pervasive of which is cheatgrass (*Bromus tectorum*). Cheatgrass is an annual brome originating in Eurasia. It has invaded both sagebrush and salt desert shrubland, including forming monocultures in many areas that formerly were dominated by shrubs (Mack, 1981).

Two other land cover classes are present in valleys. Nonvegetated areas, typically alkaline playas, are common in some of the driest locations. Cultivated agriculture may be isolated or may occur in large contiguous patches like along the Snake River plain in Idaho. Alfalfa is the dominant crop in the region.

In addition to valley land cover classes, the Great Basin also hosts two major montane ecosystems in its prevalent mountain ranges. In the foothills, sagebrush grades into conifer woodland dominated by pinyon pine (*Pinus monophylla*) and juniper (*Juniperus occidentalis*, *Juniperus osteosperma*). At high elevations, woodland grades into mixed shrubs dominated by mountain sagebrush (*A. tridentata* ssp. *vaseyana*, *Artemesia arbuscula*) and perennial bunch grasses.

Many of the land cover classes in the Great Basin may be susceptible to future changes in climate or land use, particularly under future scenarios where there is decreased water availability. An analysis of current land cover, trends, and variability is an important step toward understanding Great Basin ecosystems and assessing current and future change.

Dataset

We used a time series of AVHRR Pathfinder 1 km data from 1991 to 2000 (Eidenshink, 1992). This time series included data from two satellite sources: NOAA-11 from 1991 to 1994, and NOAA-14 from 1995 to 2000. A satellite failure in 1994 resulted in a data gap between September 1994 and January 1995. The dataset is weekly, and was clipped to include only the Great Basin. In order to better define the annual and interannual phenology, we used a curve fitting algorithm developed for time series of AVHRR data (Bradley *et al*., 2007; Hermance *et al*., 2007). This algorithm uses a high-order spline to model interannual phenology. Upweighting of higher data values minimizes the influence of missing data caused by clouds or snow and fits the upper envelope of the data. The smooth, continuous result is better suited than the raw data to evaluating phenological parameters. The output of the curve fit is an average annual product, which we used for land cover classification, and an interannual product, which we used for both land cover classification and evaluation of interannual land cover response. The use of an interannual curve fit is important for consistently identifying SOS without spatial or temporal averaging (Bradley *et al.*, 2007; Hermance *et al.*, 2007). Further, the curve fit reduces cloud and sensor error, thereby creating more distinct separation of land cover types based on annual phenology.

Land cover classification

To create a regional land cover map of the Great Basin, we used a decision tree approach based on annual (Fig. 1) and interannual phenology. A decision tree was created by comparing phenological characteristics of pixels representative of the major Great Basin land cover types. These training pixels were far from transition zones and as close to pure land cover classes as possible at the 1 km resolution. Locations of representative pixels were based on surveys conducted in central Nevada in 2004–2005 (Fig. 2). Phenological characteristics, based on the average year's phenology (Bradley *et al.*, 2007), that achieved the best separation between representative pixels were used to create the map. Thresholds separating the representative pixels were significant at the 95% confidence interval (CI). For example, cultivated agricultural fields reach high NDVI values earlier in the year than other land cover types; as a result,

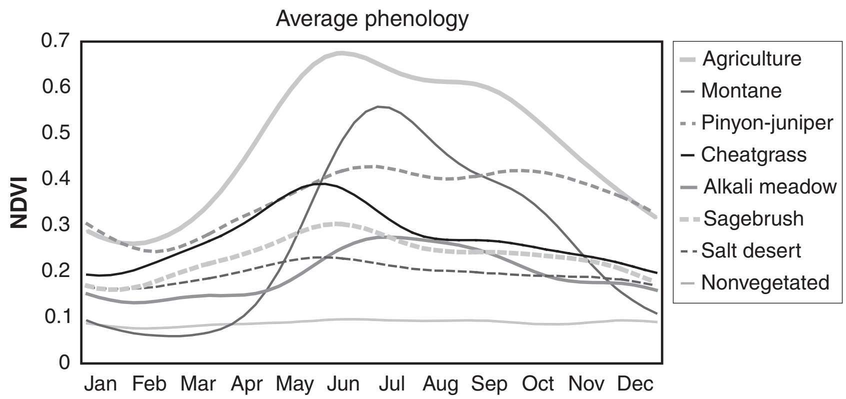

Fig. 1 Average annual phenologies of Great Basin land cover classes used to construct the land cover classification.

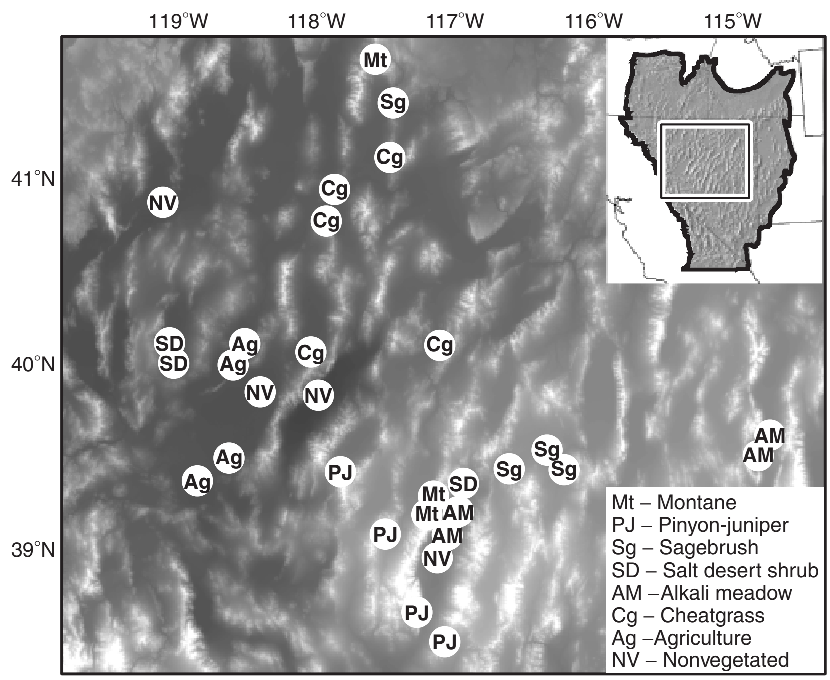

Fig. 2 Locations of representative land cover classes used to create a phenology-based land cover classification.

choosing a springtime NDVI threshold distinguishes the agriculture training data at a 95% CI. The order of operations in the decision tree is important, as some land cover classes can only be distinguished after other classes are characterized and removed from consideration (e.g. late SOS is characteristic of both alkali meadows and montane shrubland, so montane shrubland must be classified first based on phenological amplitude) (Fig. 3).

Although NDVI thresholds and measures of phenological amplitude have often been used in land cover classifications (DeFries *et al*., 1995; Loveland & Belward, 1997; Loveland *et al*., 2000), measures of interannual variability and SOS are also necessary to distinguish cheatgrass grassland and alkali meadows, respectively. Interannual variability requires a time series, and is a useful metric when land cover types have amplified responses to differences in precipitation or temperature. We defined SOS as the timing of NDVI half maximum as described by White *et al*. (1997). This is the point at which the NDVI value first exceeds the midpoint between the minimum and maximum NDVI values during an average growing season. SOS readily identifies meadows that green up later than surrounding shrublands.

In addition to phenological characteristics, elevation thresholds were used to refine the land cover classification in locations where agriculture could not be correctly distinguished from montane shrubland. We established geographically dependent elevation thresholds because mean elevations in the central Great Basin are higher than mean elevations in the northern and eastern Great Basin. We assumed that agriculture could not exist above 1950 m in the central Great Basin, above 1400 m in the northwest Great Basin, and above 1700 m elsewhere in the Great Basin. These elevation thresholds were defined by comparing an initial phenology-based land cover classification with Landsat TM imagery for the region. With Landsat, agriculture in the Great Basin is readily distinguished from other land cover types based on its recognizable pattern of rectilinear and circular plots.

A final refinement of the classification was necessary to redefine pinyon-juniper woodlands and montane shrublands that continued to be misclassified as agriculture. Because phenology of agriculture is driven primarily by irrigation patterns rather than climate, SOS within a given agricultural plot has low interannual variability. Thus, pixels initially classified as agriculture that have a high degree of interannual variability are likely instead to be highly productive montane shrublands or pinyon-juniper woodlands. All land cover initially classified as agriculture that fell above the 85% CI of interannual SOS variability during the 10-year record was reclassified as nonagricultural. This threshold was most appropriate for identifying nonagricultural land cover based on the training data and the Landsat comparison. The nonagriculture class was then reclassified as either montane shrubland or pinyon-juniper woodland using the amplitude threshold to define montane shrubland (Fig. 3).

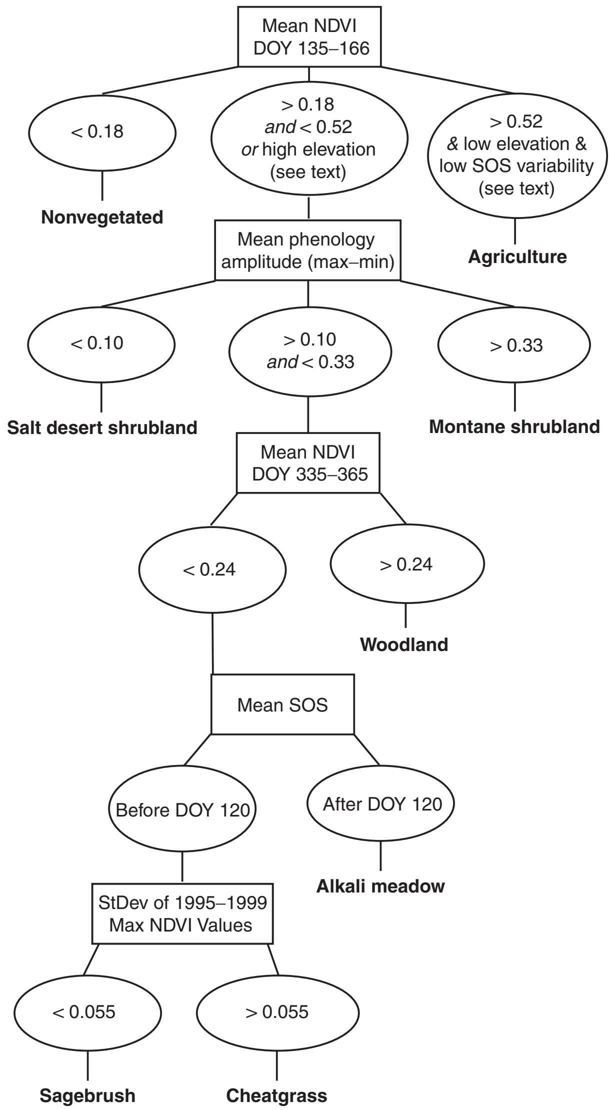

Fig. 3 Decision tree used to classify Great Basin land cover classes.

Validation

In order to test the overall accuracy of the land cover classification, we used 30 m plot data collected by the EPA southwest re-GAP in the state of Nevada (USGS, 2004). Although comparing 30 m plot data with a 1 km classification leads to inaccuracies in heterogeneous

Table 1 Land cover classes from southwest re-GAP (USGS, 2004) used to assess map accuracy

Land cover type	Re-GAP land cover (alliance)	Dominant species
Cultivated agriculture	Agriculture herbaceous	n/a
Nonvegetated	Bare soil sparse vegetation Playa sparse vegetation	n/a
Salt desert shrubland	Mixed salt desert scrub	*Atriplex confertifolia* *Atriplex canescens* *Krascheninnikovia lanata* *Ephedra nevadensis* *Grayia spinosa* *Picrothamnus desertorum*
Sagebrush shrubland	Big sagebrush steppe Big sagebrush shrubland Xeric mixed sagebrush shrubland	*Artemesia tridentata* ssp. *tridentate* *Artemesia tridentata* ssp. *wyomingensis*
Alkali meadow	Arid west emergent marsh	*Typha species* *Juncus balticus* *Schoenoplectus species*
Cheatgrass grassland	Invasive annual grassland	*Bromus tectorum*
Pinyon-juniper woodland	Pinyon-juniper woodland	*Pinus monophylla* *Juniperus osteosperma*
Montane shrubland	Montane sagebrush steppe	*Artemesia arbuscula* *Artemesia tridentata* ssp. *vaseyana*

areas, the re-GAP dataset is the most comprehensive available. Because several species were lumped together in our generalized land cover classes, we combined some of the GAP dominant species to better correspond to our land cover classes. A list of GAP land cover associated with each regional land cover class is presented in Table 1. A total of 3120 validation points were used.

Identification of land cover trends and interannual variability

In order to characterize land cover trends within the Great Basin, we first stratified by land cover class because different classes may have different responses to fluctuations in temperature, precipitation, or anthropogenic activity. To test the degree of phenological response, we used four variables measured every year: timing of SOS, timing of NDVI maximum value, NDVI maximum value, and average summer (June 1–September 30) NDVI value. We chose not to use average annual NDVI due to its strong dependence on duration of winter snow pack in this region. For each of the four parameters, we determined the mean value for each year in the 12-year time series for the eight land cover classes. These time series gave us an estimate of typical interannual variability for each land cover class.

In addition to testing the differences in interannual variability between land cover classes, we assessed relative trends in greenness. For the 12 years of annual maximum NDVI and average summer NDVI, we used a linear regression to determine the mean slopes for each land cover class. There was little difference between slopes of regression lines fit to the timing variables (SOS and timing of NDVI maximum), so these results are not presented. All of these measures allowed us to characterize typical annual and interannual response of the different land cover types and determine whether regional greenness trends might exist within particular land cover classes.

Results

Validation

Based on a comparison with the southwest re-GAP (USGS, 2004) plots, the overall accuracy of the classification was 57% (Table 2). However, misclassification between commonly mixed valley species accounted for a large percentage of the error. Sagebrush classified as salt desert shrubland and vice versa accounted for 9% of the error. Cheatgrass classified as either valley shrub class and vice versa accounted for 10% of the error. Other transition zones, including mixed sagebrush and pinyon-juniper, and mixed nonvegetated and salt desert shrub accounted for an additional 10% of the error. Meadow systems were the poorest fit and were commonly overclassified.

Comparison with other land cover classifications

We compared our phenology-based land cover classification with the most recent MODIS-based product using International Geosphere–Biosphere Program (IGBP) land cover classes (Belward *et al*., 1999; Friedl *et al*., 2002) and to a map of potential land cover based on expert opinion (D. Charlet, unpublished work) (Fig. 4). Color schemes in these three products are similar. The products have slightly different boundaries because the Great Basin was defined differently in each case. The expert opinion-based product (Fig. 4c) assumes that land cover is not affected by human land use (D. Charlet, unpublished work). Thus, invasive cheatgrass and cultivated areas were not included.

Table 2 Accuracy assessment of AVHRR classification using southwest re-GAP plots

	Map prediction								
Field validation	Agriculture	Non-vegetated	Montane	Pinyon-juniper	Meadow	Salt desert shrubland	Cheatgrass grassland	Sagebrush	User's accuracy
Agriculture	**57**	0	8	10	23	22	21	27	**0.34**
Nonvegetated	2	**62**	3	3	12	52	8	28	**0.36**
Montane	0	0	**113**	75	0	2	3	13	**0.55**
Pinyon-juniper	1	1	16	**313**	4	15	7	80	**0.72**
Meadow	3	1	7	5	**20**	3	0	7	**0.43**
Salt desert shrubland	1	38	0	7	21	**368**	66	101	**0.61**
Cheatgrass grassland	3	0	6	6	20	32	**298**	122	**0.61**
Sagebrush	13	1	16	123	47	167	86	**551**	**0.55**
Producer's accuracy	**0.71**	**0.60**	**0.67**	**0.58**	**0.14**	**0.56**	**0.61**	**0.59**	

Numbers in bold are land cover classes correctly identified by the map.

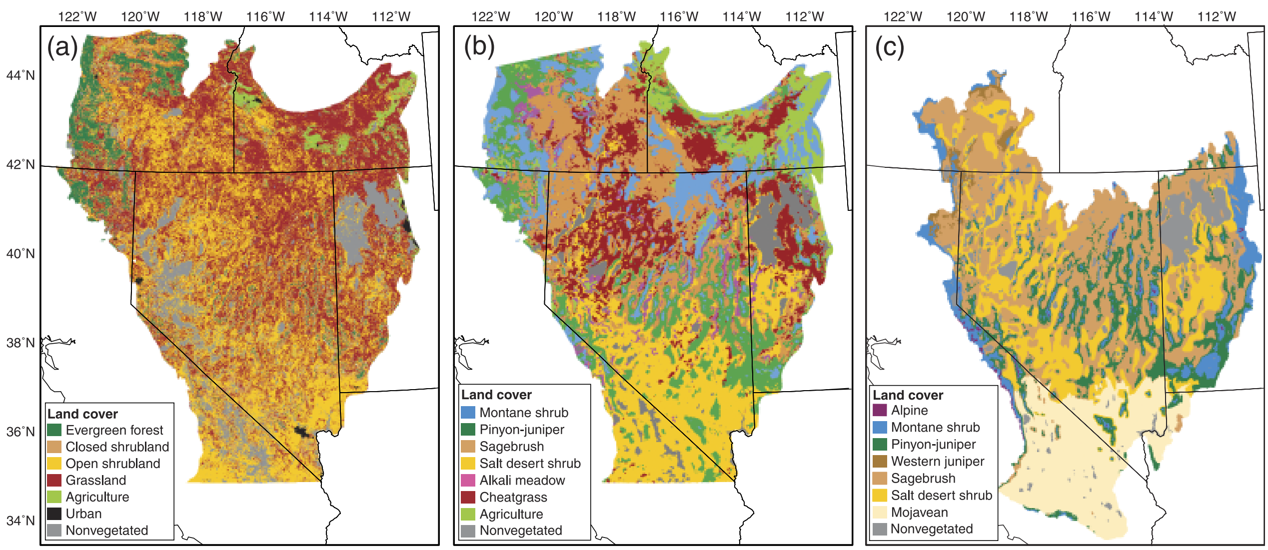

Fig. 4 Land cover classification results from (a) MODIS-derived land cover classification using International Geosphere–Biosphere Program end member land cover classes, (b) the phenology method presented here, and (c) expert opinion of native land cover (D. Charlet, unpublished work). The map based on expert opinion used a different definition of the boundaries of the Great Basin.

Alkali meadows also were not included in this map. Our phenology-based map corresponds well to the spatial extents of sagebrush, pinyon-juniper woodland, montane grassland, and salt desert shrubland. However, the remote sensing technique did not distinguish between salt desert shrubland and mojavean shrubland as the two have similar phenologies and were assumed to have similar structure (i.e. small, sparse shrubs, and minimal native grasses).

Compared with the product created to classify United States land cover using 1 km MODIS data, the phenology-based result is much more realistic for land cover in the Great Basin. Most United States land cover types do not occur in the Great Basin (e.g. deciduous forest, mixed forest, closed woodland), and inability to address regional heterogeneity in land cover results in a poor product. Similarly, most land cover types common in the Great Basin (e.g. sagebrush, salt desert shrubland, cheatgrass grassland) would not be transferable to a land cover classification across the United States. Using regionally derived land cover endmembers (i.e. land cover classes defined by phenological characteristics) is necessary to create a realistic regional land cover product.

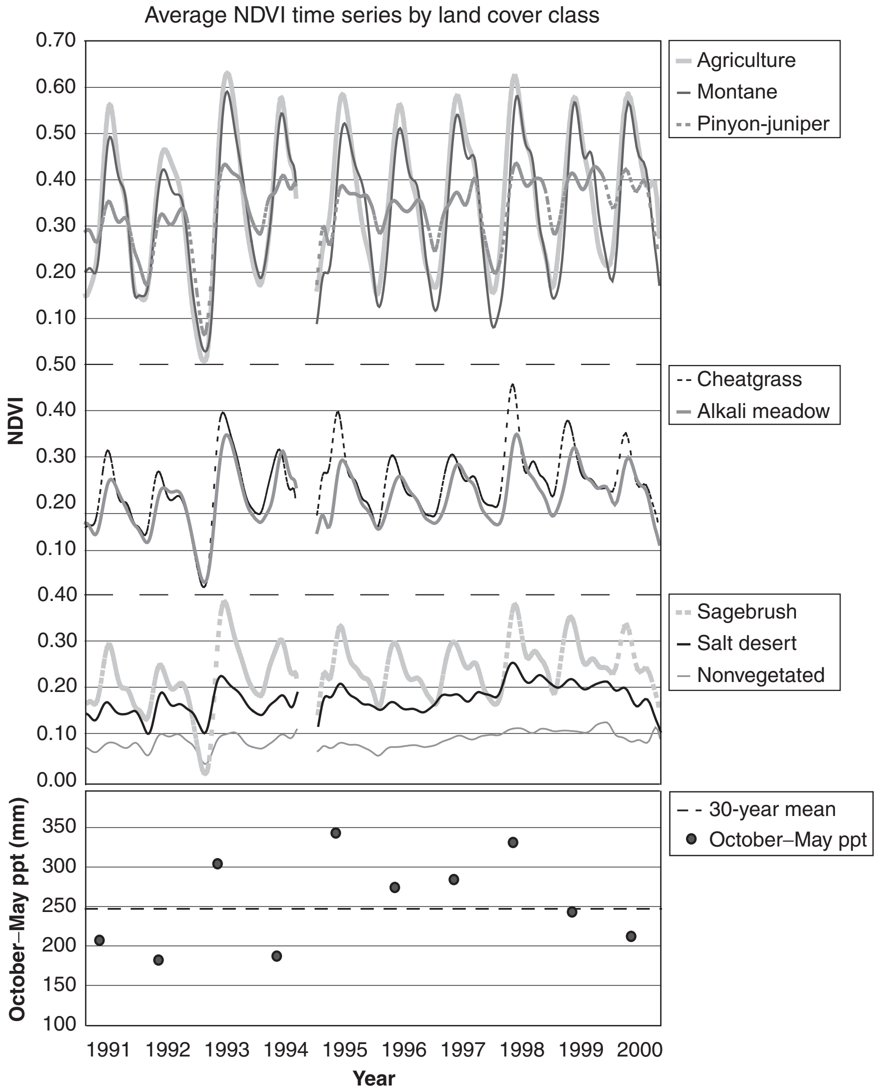

Fig. 5 Interannual time series for Great Basin land cover classes (regional average time series). Time series are offset for ease of observation. Average regional growing season (October–May) precipitation is shown for comparison.

Regional trends in Great Basin land cover classes

The eight Great Basin land cover classes identified using the methodology presented here showed a high degree of interannual variability from 1990 to 2001 (Fig. 5). Mean growing season precipitation values derived regionally from PRISM data (Daly *et al*., 2002) are shown for comparison. NDVI values of montane shrubland and pinyon-juniper woodland were particularly low in 1991 and 1992, following a regional drought lasting from 1989 to 1992. Sagebrush shrubland and cheatgrass grassland were responsive to above-average precipitation, which was high in 1993, 1995, and 1998.

Grass, shrub, and woodland cover types had a SOS by mid-April in an average year, whereas montane shrubland and alkali meadows consistently green up 3–4 weeks later (Table 3). However, all of the land cover classes had large ranges of potential SOS of up to 65 days, or 9 weeks. Interannually, native land cover classes showed consistency in terms of early and late SOS (e.g. SOS for most land cover types was late in 1991, 1993, and 1998 and early in 1992, 1994, and 2000) (Fig. 6). Agricultural plots, which are almost exclusively irrigated, did not follow the same SOS trend as native vegetation.

Similar to the SOS results, the date of maximum NDVI encompassed a large range of dates of at least 40 days, or 6 weeks in most cases (Table 4). Salt desert shrubland and pinyon-juniper woodland showed the highest range in timing of maximum NDVI of up to 90 days (13 weeks).

Slopes fit to annual maximum NDVI values were positive for each land cover class (Fig. 7). Mean slopes for montane shrubland ($m = 0.0109$; $\rho = 0.05$) and pinyon-juniper woodland ($m = 0.0099$; $\rho = 0.02$) had higher positive slopes than valley land cover classes. Cheatgrass also showed a higher positive slope ($m = 0.0104$; $\rho = 0.23$), which is likely a result of amplified response to above average rainfall in 1998.

Similar to the slopes fit to maximum NDVI values, slopes fit to summer average (June 1–September 30) NDVI values for each land cover class were all positive (Table 5). Montane shrubland had highest slope relative to other land cover types ($m = 0.0083$ NDVI yr^{-1}; $\rho = 0.09$). Pinyon-juniper woodland also showed a positive trend in summer average ($m = 0.0058$ NDVI yr^{-1}; $\rho = 0.15$). Valley ecosystems (salt desert shrubland, sagebrush shrubland, alkali meadows, and cheatgrass) showed slight positive trends ($m = 0.0036$–0.0051 NDVI yr^{-1}; $\rho = 0.21$–0.32).

Discussion

Comparison of land cover classes

Land cover classes appropriate at the global scale are not appropriate for regional land cover modeling (Fig. 4). The IGBP land cover endmembers (e.g. evergreen forest, open shrubland, grassland) effectively classify only nonvegetated land and high-density agriculture, which is clearly insufficient in the Great Basin. By selecting regional land cover endmembers (e.g. pinyon-juniper, sagebrush, cheatgrass) and a phenology-based decision tree approach, our results were more consistent with land cover mapped by expert opinion. Although overall accuracy of the map was 57% based on comparison with southwest re-GAP plots (USGS, 2004), the majority of the error can be attributed to small-scale spatial heterogeneity within land cover classes. Valley land cover classes of salt desert shrub, sagebrush, cheatgrass, and nonvegetated playa are commonly mixed within 1 km pixels. Spatially heterogeneous landscapes present a challenge for field-based validation.

Mixed pixels and incorrect classification introduces error into the analysis of interannual variability and long-term trends. However, the regional classification is an improvement over national and global land cover products. A comparison of the two classifications underscores the danger of assuming that global land cover products are representative of regional land cover

Table 3 Twelve-year mean and range of start of season (Julian Day) for different land cover types

Land cover	Mean (1991–2000)	Range of mean (1991–2000)
Alkali meadow	120	93–139
Montane shrubland	118	93–139
Agriculture	111	97–124
Salt desert shrubland	97	80–120
Pinyon-juniper woodland	95	59–124
Cheatgrass grassland	92	64–111
Sagebrush shrubland	88	56–113

Table 4 Twelve-year mean and range of date of maximum NDVI (Julian Day) for different land cover types

Land cover	Mean (1991–2000)	Range of mean (1991–2000)
Pinyon-juniper woodland	199	151–238
Montane shrubland	193	173–210
Alkali meadow	183	157–195
Agriculture	179	163–205
Sagebrush shrubland	155	133–173
Salt desert shrubland	153	112–202
Cheatgrass grassland	149	126–164

NDVI, Normalized Difference Vegetation Index.

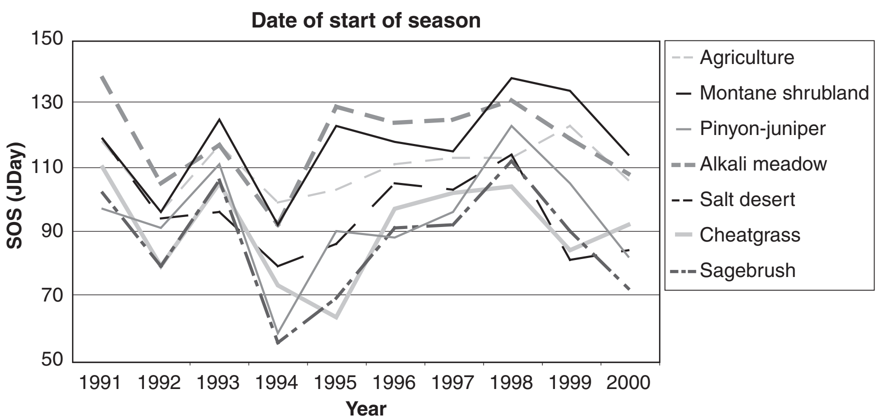

Fig. 6 Average start of season during the 1990s for Great Basin land cover classes.

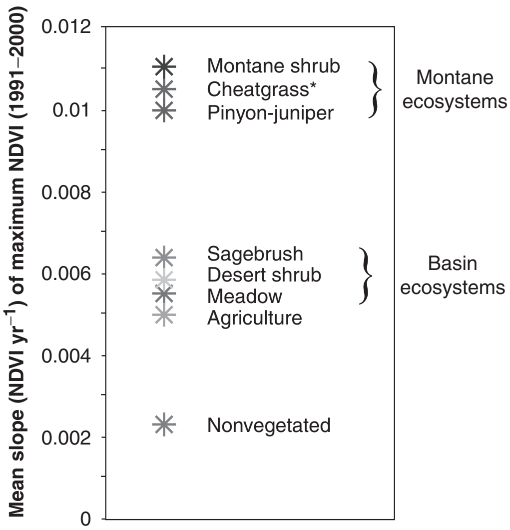

Fig. 7 Average slope (NDVI yr^{-1}) of maximum NDVI values from 1991 to 2000 for Great Basin land cover classes. Montane ecosystems have higher slopes over the decade than valley ecosystems. Cheatgrass has a high average slope value due to its amplified response to rainfall in 1998.

Table 5 Slope (NDVI yr^{-1}) of interannual summer (June 1–September 30) average NDVI values for different land cover types

Land cover	Mean slope (1991–2000)	ρ value
Montane shrubland	0.0083	0.09
Pinyon-juniper woodland	0.0058	0.15
Agriculture	0.0055	0.26
Alkali meadow	0.0051	0.22
Cheatgrass grassland	0.0049	0.32
Salt desert shrubland	0.0048	0.21
Sagebrush shrubland	0.0036	0.28
Nonvegetated	0.0016	0.36

NDVI, Normalized Difference Vegetation Index.

(Fig. 4). Conventional trend analysis and change detection using global land cover products may fail to correctly identify ecosystem change, or may mistake interannual variability for change (Bradley & Mustard, 2005). For example, a trend analysis using MODIS global land cover classes could identify montane shrubland and cheatgrass as anomalous due to their high 10-year slope (Fig. 7). In fact, these trends are characteristic of particular land cover classes' response to interannual variability in precipitation. Without a regional land cover classification, differences in phenological response among land cover classes confound identification of land cover change.

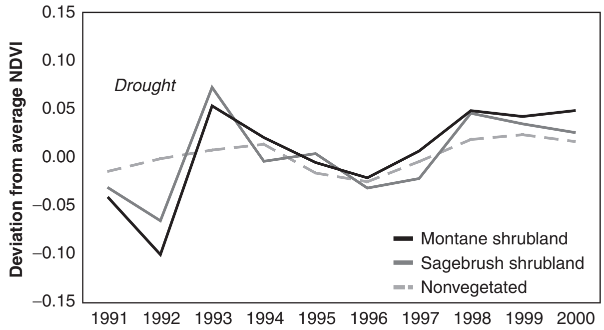

Fig. 8 Comparison of maximum NDVI trends for montane shrubland, sagebrush shrubland, and nonvegetated land cover from 1991 to 2000. The mean has been subtracted from every time series.

Regional trends in Great Basin land cover

Great Basin land cover classes have a high degree of interannual variability. All land cover types had substantial shifts in the timing of phenology (Tables 3 and 4). A large degree of interannual variability is expected in semi-arid regions where ecosystems must take advantage of favorable temperature and moisture conditions regardless of day of year. Interannual variability is also affected by the methodology for detecting SOS using the half-maximum technique (White *et al.*, 1997). Although this method of identifying SOS is one of the most stable, a longer growing season and later timing of NDVI maximum will make the timing of the SOS measurement later. There is no indication of a trend in SOS in any Great Basin land cover class (Fig. 6). The degree of interannual variability in this region would make it difficult to identify any trends in the timing of phenology without a substantially longer time series.

However, there is some indication of differential slope in both maximum NDVI (Fig. 7) and average summer NDVI (Table 5). Cheatgrass showed a large positive slope in maximum NDVI. Montane shrubland and pinyon-juniper woodland had large positive slopes in both maximum NDVI and average summer NDVI. These trends do not result from change within the land cover classes or from a decadal increase in greenness (evidenced by the insignificant ρ-values in most cases). Instead, the cheatgrass trend can be attributed to an amplified growth response in 1998 related to above average precipitation (a strong El Niño event) (Fig. 5). The trends in the montane ecosystems are likely caused by a poor growth response to the prolonged drought during 1989–1992. The average montane shrubland pixel had below average NDVI values from 1991 to 1992 and responded poorly to drought relative to the average sagebrush shrubland pixel (Fig. 8).

Although the different slopes are at first glance suggestive of long-term trends in regional Great Basin land cover, it seems more likely that these apparent trends were driven by interannual variability in the climatic triggers of phenology, including an early 1990s drought and above average precipitation in 1998. None of the land cover classes had a decadal greenness trends that could be attributed to long-term change. However, differences in the decadal trends between land cover types were suggestive of susceptibility to future climate change.

Potential community responses with future climate change

The US Global Change Research Program describes three potential future scenarios for the Great Basin ecoregion: increased temperature with decreased precipitation, increased temperature with no change in precipitation, and increased temperature with increased precipitation (IPCC, 1996; Wagner, 2003). The third scenario may have a lesser impact on Great Basin land cover because increased evaporation and decreased snow pack would be offset by increased rainfall, although the timing and magnitude of increased precipitation may not be beneficial to vegetation. The first two scenarios could modify land cover throughout the region. Increased temperature alone would lengthen the summer season, resulting in more precipitation as rain rather than snow and faster melting and runoff of snow. This would create more water loss through runoff and less recharge of groundwater through melting of snow cover, resulting in decreased overall moisture availability for plants. In all of these scenarios, warmer ocean temperatures will likely magnify the El Niño/La Niña cycle, making prolonged droughts and extreme rainfall events more likely.

In light of these future climate scenarios, the observed trends during the 1990s suggest that cheatgrass growth will increase with more extreme El Niño, while montane ecosystems are more susceptible to prolonged drought. Relative to native land cover, cheatgrass has an amplified growth response during wet years. Because cheatgrass growth is strongly coupled to wet El Niño years, more extreme precipitation events will increase the productivity of cheatgrass (Bradley & Mustard, 2005). Higher productivity creates an increased fuel load that leads to severe fires (Whisenant, 1990; D'Antonio & Vitousek, 1992) and promotes further invasion.

Montane shrubland and pinyon-juniper woodland had low NDVI values during the 1991–1992 growing seasons (Fig. 5). Compared with basin sagebrush shrubland, montane shrubland productivity is below average in the early 1990s during a drought and above average in the late 1990s under wetter climate conditions (Fig. 8). Relative to other Great Basin land cover classes, this poor response at the beginning of the time series causes the large slope values fit to maximum and average summer NDVI.

If montane shrubland and pinyon-juniper woodland continue to perform poorly under drought conditions, these ecosystems will be susceptible to change under future climate conditions. Less overall moisture availability and more extreme droughts may lead to lower productivity and mortality. In fact, extensive tree mortality in the southwest US has been observed as a result of an extreme drought in 2002–2003 (Breshears *et al*., 2005). Observed trends in montane ecosystems during the 1990s suggest that extreme droughts could lead to similar mortality in the Great Basin.

Conclusion

In this paper we characterized land cover trends in the Great Basin and identified anomalous response at the regional scale for the period 1991–2000. We showed that refined knowledge of land cover classes is an important first step to assessing long-term trends so that regional responses of land cover classes can be analyzed independently. During the 1990s, Great Basin land cover classis did show differential trends in NDVI; however, these trends were a result of interannual variability in response to climate and were not indicative of change. The degree of interannual variability, particularly during severe dry and wet years is suggestive of ecosystem susceptibility to future climate change. Montane systems may have decreased growth and increased mortality during severe drought, while invasive cheatgrass may expand during extreme El Niño events. The methodology presented here is appropriate for regional scale studies to assess current land cover, document regional trends in land cover, and identify land cover response to interannual climate variability.

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