Land degradation in Central Asia:

Identifying dynamics of pasture resources in heterogeneous landscapes using remote sensing

by

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Abstract

Rangeland degradation is an issue of global concern yet it can be challenging to accurately assess. In Kyrgyzstan, the post-Soviet transition led to wide-ranging environmental changes in pasturelands, though comprehensive and spatially explicit data remains scarce. Remote sensing vegetation indices (VI) are often used to assess pasture condition where higher VI are assumed to indicate greater productivity. However, pasture productivity may be degraded owing to declining vegetation productivity or changes in plant species composition, both of which can differentially affect vegetation indices. Here, we examined these two aspects using satellite-derived vegetation indices. In Chapter 1, we compared temporal trends (2000-2015) and seasonal maximums of Moderate-Resolution Imaging Spectroradiometer (MODIS) VI in field sites with varying cover of plant species unpalatable to livestock. Relative to other pastures, we found pastures with unpalatable plant cover were associated with higher seasonal maximums of VI ($r^2 = 0.23-0.31$) and increases in VI over time ($r^2 = 0.08-0.16$). These findings were problematic for pasture monitoring using remote sensing, as detrimental changes in species composition may be conflated with desirable increases in plant cover. In Chapter 2, we examined pixel-based temporal trends in the Normalized Difference Vegetation Index (NDVI) in Naryn oblast, Kyrgyzstan from 2000-2015. We then examined trends in the residuals after applying a regression relationship linking NDVI as a function of precipitation and temperature metrics in order to differentiate anthropogenic from climate-induced impacts to pasture resources. Trend maps were validated against areas of overgrazing identified from interviews with local pasture managers. Temporal trends in NDVI and the regression residuals were overwhelmingly negative (24.0 and 15.2% of the landscape, respectively) outside of row crop agricultural fields, particularly in the lower elevation spring/fall and winter pastures, and were consistent with local managers’ perceptions of pasture degradation. While our approach was limited by the topographic complexity of the study region, it was most successful in the semi-arid steppe region where pasture degradation is believed to be worst.
Preface

This thesis is based on my work conducted in Dr. Sarah Gergel’s Landscape Ecology lab. I conceptualized the study and sampling design with assistance from Sarah Gergel and I also executed all data collection with the exception of interview data used in Chapter 2. I conducted all analyses and wrote the manuscript with editorial and statistical assistance from Sarah Gergel, Geoff Henebry and Nicholas Coops. Herder interviews were designed by Jordan Levine, Aiganysh Isaeva, Hisham Zerriffi and Shannon Hagerman and interviews were conducted by Jordan Levine. Interviews were conducted in accordance with the Behavioural Research Ethics Board of UBC, as part of the “Commons Governance Under Transition: Enhancing Long-Term Socio-Ecological Monitoring and Research for Development in Central Asia” project, BREB #H15-01053.
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I. Introduction

**Rangelands are extensive but undervalued ecosystems critical to human well-being**

Rangelands are ecosystems that are grazed by either domestic livestock or wild animals. They are the most extensive anthropogenic landscape on Earth, occupying a third of the terrestrial ice-free surface (Ellis and Ramankutty 2008). In addition to providing livelihoods for one billion people and fodder for livestock that sustain over 30% of the world’s population (Reynolds et al. 2007), rangelands provide numerous essential goods and services for people. Many of these are services that regulate and support ecosystem processes. For example, 15% of the global soil organic carbon is sequestered in rangelands (Lal 2004). Other supporting services include soil retention and the maintenance of biodiversity (Yahdjian et al. 2015). Rangelands also form an inseparable element of many cultures, from North American ranchers to nomadic herders in Africa, that place great value in the lifestyle associated with herding livestock (Brown and MacLeod 2011).

The majority (83%) of residential rangelands reside in Asia and Africa, in some of the world’s poorest countries (Ellis and Ramankutty 2008). Rangeland inhabitants are among the most marginalized populations on earth, owing to a combination of socioeconomic and biophysical factors (Reynolds et al. 2007). The low population density and migratory nature of pastoral societies often limits access to health care and markets (Sayre et al. 2013). Furthermore, rangeland inhabitants often reside in areas politically and geographically removed from decision-making (Reynolds et al. 2007). Thus, residents of rangelands often lag in measures of health and well-being, such as infant mortality and per capita gross national product, even after adjusting for ‘rurality’ (Reynolds et al. 2007).

A geographical bias exists against rangelands relative to their global area. First, ecological research favours forests, protected areas, and wealthy countries (Martin et al. 2012). Furthermore, supporting ecosystem services have been historically undervalued relative to the more tangible provisioning services (Martín-López et al. 2012). This has likely contributed to the perception of
rangelands as ‘marginal’ land. Further, the benefits provided by ecosystems such as forests or agricultural lands with planted row crops may have more direct economic value (Brunson 2014; Yahdjian et al. 2015). Property values of rangelands tend to be significantly lower than those of irrigable or tillable land (Brunson 2014). Lastly, Central Asia rangelands have been particularly neglected, as most research has centred on case studies in wealthier Australia and western North America.

**Managing the widespread pressures affecting rangelands has been controversial**

Globally, rangelands and their inhabitants face a multitude of stressors that have no historic precedent (Reid et al. 2014). Because forage availability in arid and semi-arid rangelands is heavily influenced by inter-annual variability in rainfall (Vetter 2005), pastoral livelihoods are particularly vulnerable to climate change. Changes in the frequency of extreme weather events such as droughts can spell disaster for herders, and may lead to long-term changes in plant communities (Shafran-Nathan et al. 2013). The spread of invasive species has fundamentally transformed rangelands, in some cases creating novel ecosystems (Belnap et al. 2012). Increasing population pressure and land conversion have fragmented formerly communal grazing systems (Galvin et al. 2008). This has been exacerbated by management reforms that have sought to privatize land in an attempt to solve the ‘tragedy of the commons’ but instead limited herders’ abilities to migrate in response to local variation in forage availability, creating the ‘tragedy of enclosure’ (Monbiot 1994). Many rangelands exist in societies undergoing political and economic transitions, leading to insecure and uncertain land tenure and loss of traditional ecological knowledge (Bedunah and Angerer 2012).

These processes have resulted in widespread rangeland degradation, defined as a long-term loss of ecosystem function and productivity caused by disturbances from which land cannot recover unaided (Bai et al. 2008). This problem was believed to be so severe that the United Nations formed the United Nations Convention to Combat Desertification in 1994 as a direct recommendation of the famed UN Conference on Environment and Development held in Rio de Janeiro in 1992 (Behnke and Mortimore
However, the extent to which grazing influences rangeland degradation has become a controversial topic (Behnke and Mortimore 2016).

Assessing rangeland degradation is a complicated endeavour; global estimates of rangeland degradation vary widely (Lund 2007), dependent upon the data and methods used (Wessels et al. 2012), and the definitions and timeframes adopted (Robinson et al. 2003; Reid et al. 2014). Rangeland inhabitants have been incorrectly blamed for rangeland degradation, and institutional efforts to address degradation have often had disastrous social and ecological consequences (Sayre et al. 2013). Some studies have questioned the entire relationship between grazing pressure and rangeland condition, positing that stochastic weather events reduce herbivore numbers before they are able to reach population levels that cause any lasting effects on land quality (Wehrden et al. 2013). Nevertheless, there is widespread agreement that intensive grazing can have negative and long-lasting effects on rangelands, including self-reinforcing changes in plant communities, soil structure, and vegetative cover (Asner et al. 2004), although the strength of these relationships vary according to multiple abiotic factors (Derry and Boone 2010).

**Rangeland research in a Central Asian context**

Central Asia possesses the largest contiguous area of rangeland in the world (Mirzabaev et al. 2016a) yet very limited capacity for managing it (Kerven et al. 2011). Vertical transhumance, the seasonal migration of people and livestock between summer and winter pastures, has been practiced for millennia. In early summer, herders move their animals to distant, high elevation pastures where they spend summers living in yurts while the animals graze on the highly productive montane grasslands. Upon the arrival of snow in the autumn, they retreat to pastures of intermediate distance from villages. During winter, the animals graze in small pastures or harvested crop fields adjacent to villages, where forage is supplemented with fodder cultivated during the previous summer. Such a herding strategy allows herders to exploit vast areas of grassland while mitigating the droughts and other natural hazards associated with the highly continental climate of the region.
In the early 20th century, Central Asia fell under the control of the Soviet Union. A period of radical and rapid social economic transformation followed, with forced collectivization and sedentism ending the traditional nomadic pastoralism practiced in the region (Mirzabaev et al. 2016a). Each Central Asia republic was made to specialize in a particular commodity such as wheat, cotton, or wool (Hamidov et al. 2016). This transition to monocultures had often disastrous ecological consequences, most notably the decline of the Aral Sea from unsustainable irrigation projects as well as the massive conversion of steppe to cropland and subsequent loss of topsoil during Khrushchev’s Virgin Lands program (Steimann 2012). Soviet efforts to maximize productivity led to detailed inventorying and monitoring of biological attributes of land and livestock (Kerven et al. 2012), as well as describing associated degradation processes, though detailed mapping of degradation was not prioritized (Robinson 2016).

De-collectivization following the end of the USSR coincided with the decline of Central Asia’s research institutes (Robinson 2016). In the past twenty five years, there have been almost no long-term field studies on rangelands in the region (Kerven et al. 2011). The post-Soviet era also saw livestock numbers rapidly collapse. Despite this drastic reduction in herd size, the issue of pasture degradation has not retreated from the spotlight. Numerous government reports citing unsustainable pasture use have emerged (World Bank 2007), and been subsequently criticized (Kerven et al. 2012; Robinson 2016) for using outdated, inconsistent, and circular data. Most studies identify land degradation as severe but rely on qualitative expert estimates to gauge the extent (Mirzabaev et al. 2016b). There remains a need for empirical and spatially explicit assessments of pasture condition at sub-national levels (Kerven et al. 2011; Wolfgramm et al. 2013).

**Rangeland management and remote sensing share a long history**

Satellite imagery has been a valuable tool for rangeland management (Wessels et al. 2012; Eckert et al. 2015). The frequent sampling period, low cost, and wide coverage makes remote imagery ideal for monitoring large, inaccessible landscapes (Morgan et al. 2010). Sensors mounted on the satellite platform record the light reflected from the Earth at different portions of the electromagnetic spectrum (USGS
Satellite imagery varies according to four characteristics: the spatial resolution (the size of the area captured), spectral resolution (the wavelength width captured by the sensor), radiometric resolution (the sensitivity of the sensor to the incoming light), and temporal resolution (the sampling frequency). The amount of light reflected in each spectral channel or band provides information regarding the land surface within a pixel. This has enabled the creation of remote sensing indices that represent the ratio of reflected light in different bands.

One of the most widely used vegetation indices is the Normalized Vegetation Difference Index (NDVI), which uses the red and infrared wavelengths to assess vegetation status (Tucker 1979). Because live vegetation contains chlorophyll which absorbs red light and healthy leaf structure reflects infrared light, the NDVI value within a pixel provides an indirect measurement of important metrics such as leaf area index and cover (Carlson and Ripley 1997). The earliest reported use of NDVI was to study rangelands in the Great Plains (Rouse et al. 1973). Several decades of research subsequently led to the recognition of the limitations of NDVI and the development of additional vegetation indices to address them (Jiang et al. 2008).

Overview of research approach

This research explores rangeland ecology in Kyrgyzstan, a small Central Asian country with an extensive history of pastoralism. Pastures constitute approximately half the land area, and the economy is heavily dependent upon the production of meat and wool. Kyrgyzstan is an interesting case study of rangeland degradation as the country contends with several of the issues faced in sustainable management of pastures compounded by the challenges of mountainous societies. As with other Central Asia countries, many pastures in Kyrgyzstan are suffering from varying levels of degradation despite lower stocking densities than during Soviet times. Such problems are attributed to multiple causes, including climate change, declining infrastructure, loss of traditional ecological knowledge, and a lack of regulation and enforcement of grazing (Dörre and Borchardt 2012; Crewett 2012; Mirzabaev et al. 2016a). Recent legislation designed to dramatically reform pasture management and ameliorate degradation have largely
been deemed failures (Crewett 2012). Research into the spatial dynamics of Kyrgyz pastures and their change over time has been very limited, and focused mainly on the western range of the Tien Shan Mountains, where the climate is more humid and pastures are scarcer (Sorg et al. 2012). Literature reviews have identified the need for more fieldwork and modeling to build a more holistic, empirical understanding of the multiple interacting causes and feedbacks influencing the social-ecological system of pasture use (Wolfgramm et al. 2013). With this in mind, I aim to investigate trends in vegetation indices on the landscape of Naryn, Kyrgyzstan, and their socioecological linkages.

My second chapter uses field measurements at several sites in Naryn to examine the influence of plant cover and species composition on vegetation indices widely used for rangeland monitoring. Because impacts to vegetation from grazing are not always consistent, understanding local ecology is crucial for operationalizing remote sensing. I then examine trends over time, looking for evidence of weed encroachment. In Chapter 3, I expand the study area from the field sites of Chapter 2 to the entire Naryn oblast. I ask whether trends in vegetation indices support the argument of widespread decreases in the productivity of more accessible pastures. I aim to control for climatic variability in order to assess anthropogenic effects on pasture vegetation. By utilizing local environmental knowledge of pastures, I explore whether purported degradation measured using remote sensing is consistent with areas known by pasture managers to be overgrazed.
II. Does weed encroachment confound conventional approaches to pasture management using vegetation indices?

Introduction

Remote sensing systems have been used for decades with some success to map and measure rangeland degradation (Graetz 1987; Ringrose and Matheson 1987; Pickup et al. 1994). Many remote sensing products are low-cost or free, easily available online, and possess global coverage at frequent sampling intervals, ideal for monitoring remote ecosystems (Morgan et al. 2010). Typically, vegetation indices such as the Normalized Difference Vegetation Index (NDVI) or the Enhanced Vegetation Index (EVI) are used to approximate net primary productivity (NPP) of pastures (Wessels et al. 2012). A declining index is indicative of worsening grazing conditions. However, these methods are not without controversy: the relationship between precipitation and NPP varies widely across systems, degradation can be difficult to detect depending on its intensity and duration, and trend detection methods may show contradictory results when different methods are applied (Wessels et al. 2012).

Perhaps most problematic is that the assumption that an increasing index signifies improving grazing conditions may be unreliable. Grazed sites in Mongolia had a higher EVI than ungrazed sites, despite lower plant cover and above-ground biomass at grazed sites (Karnieli et al. 2013). The grazed pastures had been invaded by unpalatable species with a denser leaf structure and consequently exhibited a higher spectral response in the near infrared portion of the electromagnetic spectrum, thus confounding the assumed relationship between vegetation indices and pasture degradation. Similarly, a comparison of expert evaluations of grazing quality in Australian pastures with remotely sensed estimates of changes in vegetation cover found that while there was generally good agreement between the two datasets, grazing conditions in some pastures had changed without showing detectable trends in the Landsat imagery, attributed to changes in the relative abundance of unpalatable and palatable grasses (Bastin et al. 2012). While in this example weed encroachment went undetected by the trend analysis as opposed to a
conflicting estimate of improved grazing conditions, the latter did arise in a multi-decadal study of rangelands in Greece using a Spectral Mixture Analysis of Landsat imagery. Temporal trends in the vegetation cover of pastures, induced by increases in stocking rates, were dependent upon underlying vegetation communities, with positive relationships between stocking rate and vegetative cover detected for some communities, while others had multidirectional relationships (Röder et al. 2008). A study of semi-arid rangelands in Senegal using in-situ sensors to obtain measurements of surface reflectance found NDVI was influenced greatly by species composition (Mbow et al. 2013). The highest NDVI values occurred in the year when biomass and rainfall were lowest, owing to the dominance of a drought-tolerant legume.

Unpalatable and ruderal plants are not necessarily undesirable. What constitutes pasture degradation is debatable as pastures provide numerous other ecosystem services in addition to fodder for livestock, thus a decline in forage productivity might be countered by an increase in another service. In Kyrgyzstan, the opinions of local herders are often positive towards many unpalatable plants, even some considered problematic by pasture managers. For example, *Dracocephalum integrifolium* Bunge, an unpalatable perennial indicative of heavy grazing, is valued by beekeepers (Venuss et al. 2010). *Caragana pleiophylla* (Rule) Pojark., is a leguminous xerophytic shrub known to rapidly colonize denuded slopes (Fitzherbert 2000). Its spines can be lethal to livestock when consumed, making it undesirable to herders. However, *C. pleiophylla* can provide an important fuel source in arid rangelands, and historically it was left undisturbed when growing on the steepest slopes to control erosion. Many unpalatable herbs, such as *Artemisia dracunculus* L., have important medicinal and cultural uses (MSRI 2012) and may limit soil erosion specifically in drought years when overall grass cover is lower.

Despite many international development projects focusing on sustainable pasture use in Kyrgyzstan, there is little spatially explicit information characterizing the nature and extent of pasture degradation (Robinson 2016). As a result, the use of geographic information systems (GIS) for spatial planning is seriously underutilized (UNECE 2009). Data scarcity issues extend to the country’s climate
stations; few have remained active since 1990 (Dedieu et al. 2014) and most have frequent gaps in their precipitation records (Groisman and Legates 1995). At the same time, the topography of the country, with over 40% of the territory above 3000 metres (Iliasov and Yakimov 2009), has left it highly vulnerable to climate change (Lioubimtseva and Henebry 2009), yet extremely difficult to access directly and monitor. Similar to other montane regions, future climatic trends are expected to be more extreme and variable than global averages (Dedieu et al. 2014). As such, the region’s pastures face growing risks yet the country lacks fundamental information needed to evaluate pasture resources.

The purpose of this research is to examine conventional vegetation indices and how they correspond to field measurements of pasture condition, with the aim of providing improved recommendations for long-term pasture monitoring in Kyrgyzstan using remote sensing. The relationships between NDVI and two ruderal, unpalatable plant species were of particular interest. We ask two questions: 1) how does the abundance of two pasture weeds, *C. pleiophylla* and *A. dracunculus*, influence remotely sensed vegetation indices in Naryn pastures? And 2) How are the abundances of these species linked with temporal trends in vegetation indices? We hypothesize that pastures considered degraded due to the presence of unfavourable plant species may show increased vegetation index values relative to healthy pastures, and consequently pastures invaded by unpalatable species will show gradual increases in vegetation index values over time. Our goal is to understand how this potentially adverse effect might impact inferences about pasture health using remote sensing data, in order to provide improved advice for pasture monitoring in this data scarce region.

**Methods**

**Study region**

Naryn is the poorest oblast in Kyrgyzstan, and also the oblast with the most extensive pastures (Crewett 2012). The short growing period and availability of mountainous pasture have fostered the development of an economy almost exclusively dependent upon semi-nomadic pastoralism, placing great importance on sustainable rangeland management. Mean annual precipitation is 290 mm, the majority
occurring from April-July, and the daily mean temperature ranges from -15.8°C in January to 18.2°C in August (as measured in the valley). Pastures in the area are dominated by *Artemisia tianschanica* and *Festuca* spp., with *Phlomis* and *Geranium* spp. meadows in cooler areas. Warming trends in winter and summer temperatures have had a visible impact on the region’s glaciers, which have declined in area considerably since the 1970s (Sorg et al. 2012). Trends in precipitation have been more variable (Dedieu et al. 2014), and vary locally with topography (Sorg et al. 2012).

Pasture degradation caused by weed encroachment is an enduring issue in the region. For example, data from the state property registry office indicated that in 2006, 27% of the pasture area in the Ak-Muz municipality contained large amounts of unpalatable species (Crewett 2012). One of the more problematic species is *A. dracunculus*, a perennial forb native to the region. It can outcompete palatable grasses to such an extent that that during Soviet times, considerable resources were allocated to eradicating the plant using mechanical treatments and pesticides. *C. pleiophylla* encroachment in pastures is also increasingly a concern (Egamberdiev 2013), particularly in the neighbouring oblast of Issyk-kul (Fitzherbert 2000).

**Landscape-level sampling design**

A landscape level sampling design was implemented enabling the comparison of remote sensing vegetation indices with field-based measurements of pasture condition while mitigating the impact of confounding variables. Based upon field observations and literature, four geophysical variables were hypothesized to be most influential in determining pasture vegetation: elevation, solar insolation, slope, and topographic wetness (Borchardt et al. 2011). All four variables were derived from the USGS SRTM 30 metre digital elevation model (DEM). Solar insolation and slope were calculated using ArcGIS v. 10.1, as was the topographic wetness index (TWI) which was modeled using a flow accumulation raster. The above variables were used to stratify the placement of potential field sites in the Naryn and At-Bashy districts of Naryn, Kyrgyzstan, along with pasture use class (summer, winter, spring/fall) and
administrative control (community managed pastures and leskhozes, territories managed by state-owned forest departments).

Ground-truthing and vegetation sampling was conducted during field visits in late June and July 2015. Areas of approximately one km² with a relatively homogenous assemblage of plant species were sampled for each site in order to ensure that spectral variability would be minimized. In addition, all sites were a minimum of 250 m from any forest stand, major road, or body of water to minimize in the influence of such features. A total of thirty three sites were selected, situated between 2000-3400 metres above sea level within the meadow and semi-arid steppe geobotanical zones (Figure 1). Twenty-eight sites were in communal pastures managed by local pasture management associations, four were grasslands located in leskhozes, and one was within a national park, where grazing by goats and sheep was prohibited, though horses and cows were permitted. Presence of either sheep or horse manure in all field sites confirmed they had been actively grazed within recent months. Summary statistics for the geophysical variables were calculated for all sites using the median values within sites (Table 1). DEM elevation was verified with GPS measurements in the field. The distributions of slope, solar insolation, and elevation were all approximately normal among sites using the Shapiro-Wilkes test for normality. However, TWI was eventually excluded from the regression analyses due to its collinearity with slope.

Table 1: Summary of geophysical variables across all sites (n = 39)

<table>
<thead>
<tr>
<th>Variable</th>
<th>Mean</th>
<th>Median</th>
<th>Standard deviation</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elevation (m.a.s.l)</td>
<td>2611</td>
<td>2573</td>
<td>263</td>
<td>2101-3341</td>
</tr>
<tr>
<td>Slope (deg)</td>
<td>12.4</td>
<td>11.4</td>
<td>6.9</td>
<td>1 - 25.8</td>
</tr>
<tr>
<td>Solar insolation (W/m²)</td>
<td>1.52 x 10⁶</td>
<td>1.53 x 10⁶</td>
<td>1.26 x 10⁵</td>
<td>1.14 x 10⁶ – 1.74 x 10⁶</td>
</tr>
<tr>
<td>Normalized TWI (0 - 1)</td>
<td>0.302</td>
<td>0.291</td>
<td>0.053</td>
<td>0.272 - 0.538</td>
</tr>
</tbody>
</table>
Figure 1: Location of the field sites in Naryn, Kyrgyzstan

**Sampling protocol**

Field sampling began with the placement of a 100 m transect 250 m from the site boundary. Vegetation cover was recorded in 10 1x1 m quadrats randomly spaced within 10m increments. Cover was recorded for all plant species combined, as well as for specific species of interest based on palatability. For simplicity, species were considered palatable if any plant part could be safely consumed by sheep (the dominant form of livestock in the region), though in reality, palatability is better represented as a gradient. Cover was recorded as the median estimate of the three-person field crew. Upon completion of a transect, the next transect was placed 250 m perpendicular and 150 m parallel. This was repeated once more for three transects with ten quadrats each, totalling 30 quadrats per site. On slopes, transects were oriented diagonal to the dominant slope to reduce the effect of local ecotones biasing cover estimates. GPS measurements were taken at the start and end of each transect. Georeferenced photos were taken of each plot to aid in cover estimates and species identification. At the site level, the presence of soil erosion or
excessive trampling by livestock was also recorded. GPS line data for roads and point data for settlements within the vicinity of the sites was also gathered. The mean of the three transects was used to measure site vegetation characteristics (Figure 2).

![Graphs showing vegetation cover and proportion of unpalatable cover](image)

**Figure 2:** Percent vegetation cover and proportion of unpalatable cover at the scale of quadrat, transect, and site.

Six additional sites were included in the remote sensing analysis but not sampled for vegetative cover. These included four sites dominated by *C. pleiophylla*, which is routinely found in the region yet
which was absent from the study sites. The other two sites were located in a state nature reserve and a national park, where grazing by all livestock was prohibited. Because *C. pleiophylla* forms dense thickets occurring on steep rocky slopes, these sites were not amenable to the transect design and consequently were not sampled. Similarly, the sites within the national parks were not sampled due to their limited accessibility but were delineated using aerial photographs.

**Vegetation Indices**

We used the Moderate Resolution Imaging Spectroradiometer (MODIS) MOD13Q1 product to calculate the maximum EVI, NDVI, and the NDVI-derived Wide Dynamic Range Vegetation Index (WDRVI) for all sites during the 2015 growing season. MODIS is an instrument on board NASA’s Terra and Aqua satellites that captures data in 36 spectral bands at multiple spatial resolutions. Together the satellites image the Earth every 1 to 2 days. The MOD13Q1 product consists of 16-day maximum NDVI and EVI composites at 250 m resolution. NDVI is a vegetation index that uses two spectral regions, the red and near infrared, to infer biophysical properties of vegetation such as aboveground biomass and vegetation cover.

\[
NDVI = \frac{(Near\ Infrared - Red)}{(Near\ Infrared + Red)}
\]

The WDRVI is a non-linear modification of NDVI that is designed to increase index sensitivity in areas with moderate to high vegetation density (Gitelson 2004), and is calculated of the form

\[
WDRVI = \frac{(a \times Near\ Infrared - Red)}{(a \times Near\ Infrared + Red)}
\]

where \(a\) is a weighting index. Following Viña and Gitelson (2005), we use a weighting coefficient of 0.2.

The EVI was designed for similar purposes as the NDVI but uses the blue band to control for aerosol influences in the red band (USGS 2016b). The formula for the MODIS EVI is

\[
EVI = 2.5 \times \frac{(Near\ Infrared - Red)}{(Near\ Infrared + 6 \times Red - 7.5 \times Blue + 1)}
\]
We also calculated the timing of peak NDVI to test for potential differences in the phenology of pasture vegetation.

Characterizing the often small and incremental changes in phenology requires long-term, frequent, and consistent observations. Therefore, in order to assess vegetation change over time, the eMODIS 250m NDVI product was collected during 2000-2015 growing season (May to September). eMODIS NDVI is derived from calibrated radiance data measured by the Aqua and Terra satellites using the maximum NDVI over 10 day periods to produce composite images available in five day intervals. For example, the eMODIS NDVI imagery for the month of June 2015 includes the maximum NDVI occurring from June 1st–10th, 6th–15th, 11th–20th, 16th–25th, 21st–30th, and 26th–July 5th. The eMODIS product was created to provide improved temporal sensitivity and real-time monitoring capabilities in comparison with the NASA-EOS MODIS product (Jenkerson et al. 2010). Each image was masked for cloud cover, ice, and snow using the provided quality assurance file. Composites were occasionally missing during the earlier years in the time series (August 1-15th, 2000; June 10th-30th 2001); these were treated using the median value of the 2000-2015 subseries. Likewise, missing values from individual pastures introduced by the cloud/snow mask were dealt with in similar fashion. These were uncommon, occurring primarily during May in high elevation sites due to late snow cover. The median of the all NDVI pixel values within each site was used to produce a single 16-year time series for each site.

Statistical analyses

Several contrasting types of analyses were performed. First, we were interested in comparing 2015 NDVI patterns among pastures and determining the influence of site and plant cover/composition (Q1). Second, we applied time series analysis to assess long-term trends in pasture greening and browning. Thirdly, we examined the results relative to confounding drivers of species composition and terrain (Q2). We used trend detection techniques capable of identifying multiple abrupt (breaks) and gradual changes occurring over long-term time series (Verbesselt et al. 2010a), as well as simple non-parametric methods for calculating slope. Backwards stepwise regression was applied on 2015 NDVI
variables as well as trend parameters (magnitude of breaks and the slope of gradual changes). Models were selected based on maximizing $R^2$ with all variables significant ($p < 0.05$). Finally, to compare VI values in areas dominated by $C. pleiophylla$, sites were grouped into six categories: protected grassland in the meadow steppe, meadow steppe pasture, meadow steppe degraded by $A. dracunculus$, semi-arid pasture, semi-arid pasture degraded by $A. dracunculus$, and semi-arid steppe degraded by $C. pleiophylla$. Pastures were considered degraded if the fractional cover of $A. dracunculus$ exceeded 0.25. Sites were then compared using Tukey’s range tests (Tukey 1949).

**Trend detection with BFAST**

The 2000-2015 10 day NDVI time series were first tested for structural breaks using the Breaks For Additive and Seasonal Trend method (BFAST), developed by Verbesselt et al. (2010a). BFAST uses an additive decomposition model to iteratively fit a piecewise linear trend and seasonal model of the form

$$Y_t = T_t + S_t + e_t \quad (t = 1, \ldots, n)$$

where $Y_t$ is the observed data at time $t$, $T_t$ is the linear trend, $S_t$ is the seasonal component, and $e_t$ is the remainder component (Verbesselt et al. 2010b) (Figure 3). The de-seasonalized time series is tested for structural breaks using an ordinary least squares residuals-based moving sum test. For each site, the Bayesian Information Criterion was used to select models with either one or zero breaks. The magnitude of the break is obtained using the slope and intercept of the two linear components. An advantage of this technique is that it can identify potential order-reversing trends within a time series, as opposed to other frequently employed methods that test solely for monotonic trends.
Figure 3: Example of the BFAST algorithm (Verbesselt 2010a). Shown is the BFAST algorithm applied to eMODIS 250m NDVI time series of two Kyrgyz pastures for 2000-2015. The top panel is the original MODIS NDVI time series. The second panel shows a harmonic seasonal model fit to the time series. The third panel shows the fitted linear trend and the bottom panel shows the residuals. The hatched line indicates the timing of the break with the confidence intervals in red. Two periods of significant declines were detected for the pasture on the left, but only the decline after the break was significant for the pasture on the right.

Seasonal Sen’s slope estimator

Because the BFAST analysis found a similar pattern in most sites, i.e. negative trends interrupted by a break at the beginning of 2009, the seasonal Sen’s slope estimator was used to directly compare the slope of NDVI from 2000-2008 and 2009-2015 at all sites using the Trend package in R (Pohlert 2015). Sen’s slope estimator is a non-parametric method for fitting a line to a set of points using the median slope (Sen 1968). For seasonal data, the slope is calculated for every combination of pairs within a subseries, and the estimator is the median of the medians (Hirsch et al. 1982). In comparison with linear regression, it is more robust against heteroscedasticity and non-normality.
Results

*Artemisia dracunculus* was the most widespread unpalatable species

The cover of unpalatable plants was low relative to palatable plants across most pastures, with few exceptionally weedy pastures (Table 2). Among individual unpalatable plant species, *A. dracunculus* was by far the most prevalent, in the number of sites as well as cover (Table 2). *C. pleiophylla* was mostly absent (outside of the four sites chosen deliberately for their high cover of *C. pleiophylla*), though it was present in three semi-arid sites. No other unpalatable plant comprised more than 20% of the plant cover within a single site (Table 2). Other species commonly considered indicators of pasture degradation were rare, though *D. integrifolium* was present at nine sites.

Table 2: Proportional abundance of unpalatable plant species found at two or more sites.

<table>
<thead>
<tr>
<th>Plant species</th>
<th>Sites present</th>
<th>Max, cover (0 – 100%)</th>
<th>Mean, cover (0 - 100%)</th>
<th>Mean prop. of veg (0 – 1)</th>
<th>Max prop. of cover (0-1)</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Artemisia dracunculus</em> L.</td>
<td>21</td>
<td>29</td>
<td>12</td>
<td>0.19</td>
<td>0.59</td>
</tr>
<tr>
<td><em>Caragana pleiophylla</em> (Regel) Pojarkova.</td>
<td>3</td>
<td>19</td>
<td>7.5</td>
<td>0.15</td>
<td>0.34</td>
</tr>
<tr>
<td><em>Dracocephalum integrifolium</em> Bge.</td>
<td>9</td>
<td>9</td>
<td>3.5</td>
<td>0.05</td>
<td>0.13</td>
</tr>
<tr>
<td><em>Draba nemorosa</em> L.</td>
<td>5</td>
<td>3</td>
<td>1</td>
<td>0.02</td>
<td>0.05</td>
</tr>
<tr>
<td><em>Euphrasia peduncularis</em> Juz.</td>
<td>3</td>
<td>2</td>
<td>1</td>
<td>0.02</td>
<td>0.05</td>
</tr>
<tr>
<td><em>Galium verum</em> L.</td>
<td>10</td>
<td>7.5</td>
<td>1.5</td>
<td>0.02</td>
<td>0.09</td>
</tr>
<tr>
<td><em>Lappula spp.</em></td>
<td>14</td>
<td>3</td>
<td>1</td>
<td>0.02</td>
<td>0.06</td>
</tr>
<tr>
<td><em>Onopordum acanthium</em> L.</td>
<td>4</td>
<td>1</td>
<td>1</td>
<td>0.02</td>
<td>0.02</td>
</tr>
<tr>
<td><em>Ranunculus</em> sp.</td>
<td>5</td>
<td>5</td>
<td>2</td>
<td>0.02</td>
<td>0.06</td>
</tr>
<tr>
<td><em>Rhinanthus songoricus</em> Stern (B. Fedsch.)</td>
<td>3</td>
<td>2</td>
<td>1</td>
<td>0.01</td>
<td>0.03</td>
</tr>
</tbody>
</table>

Q1. Pastures invaded by *A. dracunculus* were found to have higher vegetation index values

Maximum NDVI in 2015 was positively correlated with percent vegetation cover ($r^2 = 0.37, p < 0.001$) and the fractional cover of *A. dracunculus* ($r^2 = 0.31, p < 0.001$), which together with slope, solar insolation, and elevation explained 0.82 of the variation (Table 3, Figure 4). The 2015 maximum WDRVI
showed similar results, with all variables significant but with a slightly lower partial $r^2$ for *A. dracunculus* (0.29, $p < 0.001$) and model $R^2 = 0.79$. In comparison, EVI was influenced less by plant species composition, as partial $r^2$ for total cover and the proportional cover of *A. dracunculus* were respectively stronger ($0.41$, $p < 0.001$) and weaker ($0.23$, $p < 0.01$). Topographic slope was weakly correlated with all three vegetation indices ($r^2 = 0.04-0.07$, $p = 0.001-0.04$). Elevation explained 0.34 of the variation in the timing of peak NDVI in 2015 and 0.65 of the variation for median timing from 2000-2015, with later green-up correlated with higher elevation. There was no relationship between fractional cover of *A. dracunculus* and the timing of peak NDVI. The Tukey’s range test did not find significant differences in mean NDVI of *C. pleiophylla* sites compared to other semi-arid grasslands (Figure 5).

![Figure 4: Relationships between maximum NDVI in 2015, total vegetative cover, and the proportional cover of *A. dracunculus*. For analyses, the proportion of *A. dracunculus* was arcsine square root transformed.](image-url)
Table 3: Summary regression results for models explaining vegetation indices as a function of percent vegetative cover, the proportional cover of *A. dracunculus*, elevation, slope, and solar insolation using backward stepwise regression (p < 0.05). n = 33.

<table>
<thead>
<tr>
<th>Dependent variable</th>
<th>Independent variables (partial r^2 and sign of coefficient)</th>
<th>Model R^2</th>
<th>Adj. R^2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum eMODIS NDVI (2015)</td>
<td>+ Percent cover (0.37); + Prop. <em>A. dr.</em> (0.31); + Slope (0.07); - Elevation (0.04); + Solar insol. (0.03)</td>
<td>0.82</td>
<td>0.79</td>
</tr>
<tr>
<td>Maximum MODIS WDRVI (2015)</td>
<td>+ Percent cover (0.37); + Prop. <em>A. dr.</em> (0.29); + Slope (0.06); - Elevation (0.04); + Solar insol. (0.03)</td>
<td>0.79</td>
<td>0.76</td>
</tr>
<tr>
<td>Maximum MODIS EVI (2015)</td>
<td>+ Percent cover (0.41); + Prop. <em>A. dr.</em> (0.23); + Slope (0.04)</td>
<td>0.68</td>
<td>0.65</td>
</tr>
<tr>
<td>MODIS NDVI amplitude (2015)</td>
<td>+ Total cover (0.44); + Prop. <em>A. dr.</em> (0.27)</td>
<td>0.71</td>
<td>0.69</td>
</tr>
<tr>
<td>Julian day of peak NDVI (2015)</td>
<td>+ Elevation (0.34)</td>
<td>0.34</td>
<td>---</td>
</tr>
<tr>
<td>Median Julian day of peak NDVI (2000-2015)</td>
<td>+ Elevation (0.65); - Slope (0.05)</td>
<td>0.70</td>
<td>0.68</td>
</tr>
</tbody>
</table>
Figure 5: 2015 maximum of three vegetation indices across all sites, characterized by geobotanical zone and vegetation communities. No grazing control sites exist in the semi-desert zone, while *C. pleiophylla* was not found in the meadow steppe zone. Tukey’s range test was used to test for differences between groups. Groups sharing a letter were not significantly different at $p < 0.05$.

**Time series analysis revealed distinct browning periods in NDVI**

Most sites showed similar long-term patterns of NDVI which consisted of two distinct browning periods separated by an abrupt increase (break) in NDVI in 2009 (Figure 6). Of 39 total sites, 31 sites exhibited breaks at the onset of 2009, and 2 sites exhibited breaks in 2010. The three sites that did not show any trend or break at any period were the grasslands in the national parks and state nature reserve. Three summer pastures showed monotonic browning trends, one summer pasture showed no trend.
followed by a break and a negative trend, while all other sites were classified as having two periods of declining NDVI interrupted by a sudden increase (for example, Figure 3). The slope of NDVI was negative for all sites between 2000-2008 and 2009-2015 when measured with both the seasonal Sen’s slope estimator and BFAST.

Figure 6: Types of trends in NDVI, as measured with BFAST, and their relative frequency among 39 grassland sites.

**Q2. Sites dominated by *A. dracunculus* experienced larger declines in NDVI prior to 2008 but smaller declines afterward**

Among the 33 sites with detected breaks in the time series, the magnitude of the breaks were negatively correlated with percent cover ($r^2 = 0.22, p = 0.01$) and elevation ($r^2 = 0.43, p < 0.001$) (Figure 7, Table 4). Trends in NDVI (% change as measured with BFAST) for period 1 were positively correlated with elevation, percent cover, and slope with a total $R^2 = 0.71$ (Table 4). This differed from the 2000-2008 Sen’s slope of NDVI, which was positively correlated with cover (0.31) and elevation (0.22) while negatively correlated with *A. dracunculus* (0.08), meaning sites with greater cover of *A. dracunculus* exhibited higher NDVI browning.
Table 4: Summary results for models explaining trends in NDVI using percent cover, the fractional cover of *A. dracunculus*, elevation, solar insolation, and slope using backwards stepwise regression (p < 0.05). BFAST metrics only include sites with measured plant cover and detected breaks (n = 29).

<table>
<thead>
<tr>
<th>Dependent variable</th>
<th>Independent variables (partial $r^2$ and sign of coefficient)</th>
<th>Model $R^2$</th>
<th>Adj. $R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sen’s slope 2000-2008</td>
<td>+ Percent cover (0.31); + Elevation (0.22); - Prop. <em>A. dr.</em> (0.08)</td>
<td>0.61</td>
<td>0.57</td>
</tr>
<tr>
<td>Sen’s slope 2009-2015</td>
<td>+ Percent cover (0.27); + Elevation (0.16); + Prop. <em>A. dr.</em> (0.16)</td>
<td>0.59</td>
<td>0.55</td>
</tr>
<tr>
<td>Breakpoint magnitude</td>
<td>- Elevation (0.43); - Percent cover (0.22)</td>
<td>0.64</td>
<td>0.62</td>
</tr>
<tr>
<td>BFAST period 1 % change NDVI</td>
<td>+ Elevation(0.34); + Percent cover (0.31); + Solar insolation (0.05)</td>
<td>0.71</td>
<td>0.67</td>
</tr>
<tr>
<td>BFAST period 2 % change NDVI</td>
<td>+ Percent cover (0.38); + Prop. <em>A. dr.</em> (0.25); + Slope (0.06)</td>
<td>0.70</td>
<td>0.66</td>
</tr>
</tbody>
</table>

Figure 7: Magnitude of break in NDVI time series detected by BFAST and elevation of field sites with detected breaks (n = 33).
Figure 8: Relationships between field measurements of total vegetation cover, proportional cover of \textit{A. dracunculus}, and annual slope of NDVI from 2000-2008 and 2009-2015, measured with the seasonal Sen’s slope estimator. For analysis purposes, proportion data was arcsine square root transformed. Proportional cover of \textit{A. dracunculus} was negatively correlated with change in NDVI in the earlier period and positively correlated in the latter period (p < 0.05).

During the second period (approximately 2009-2015), the BFAST estimate of NDVI change was positively correlated with total cover, the proportional cover of \textit{A. dracunculus}, and slope (Table 4). The 2009-2015 Sen’s slope was similar, with total cover, proportional cover of \textit{A. dracunculus}, and slope all...
positively correlated. Therefore, while both methods found that NDVI declined in all sites after 2009, the sites with greater proportional cover of *A. dracunculus* experienced comparatively smaller declines (Figure 8). Among sites dominated by the shrub *C. pleiophylla*, temporal trends in NDVI during both periods were among the most negative.

**Discussion**

Here we examined vegetation cover and palatability in Kyrgyz pastures and their influence on various remote sensing indices. We found pastures with more unpalatable species had consistently higher NDVI values than pastures dominated by palatable grasses, suggesting grazing-induced encroachment by weedy forbs and grasses leads to higher VI values over time. Such increases may have been detected in the field sites, as pastures with greater proportional cover of *A. dracunculus* experienced larger declines in NDVI prior to 2009 (indicative of greater disturbance in these areas), followed by smaller declines in subsequent years (indicative of encroachment by *A. dracunculus*). Finally, higher elevation pastures, characterized by greater plant cover and steeper slopes, also had smaller declines in NDVI during both periods, underscoring the role of transhumance as a successful livelihood strategy in the region. Our results have implications for how to monitor pasture conditions to ensure they are grazed sustainably in the face of rising stocking rates coupled with environmental change. Next, we examine these key findings in greater depth relative to similar research in other parts of the world.

*A. dracunculus* confounded vegetation indices

*A. dracunculus* increased the values of the MODIS remote sensing vegetation indices, a problematic outcome given that *A. dracunculus* was the most abundant unpalatable plant in the field sites. Of the two MODIS vegetation indices used here, NDVI was more highly correlated with both total plant cover and cover of *A. dracunculus*. Transforming NDVI to the WDRVI did not lead to any substantial model improvements. Elevation, slope, and solar insolation had weak but significant relationships with the vegetation indices that could be attributed to the composition of palatable species found at different terrains, as *A. tiaschanica* and *Festuca spp.* are not as green as the geranium meadows. There were no
significant differences in the timing of peak NDVI that could be attributed to the abundance of *A. dracunculus*, though other phenological metrics may prove more illuminating for detecting weed encroachment, such as the thermal time to peak NDVI, the beginning of green-up (de Beurs and Henebry 2013), or the difference between images acquired earlier and later in the growth season (Peterson 2015).

Our results are broadly in agreement with those of Karnieli et al. (2013), who found unpalatable species in grazed sites in the Mongolian steppe induced higher near infrared spectral reflectance. However, unlike that research, we did not find EVI to be more susceptible to this impact than NDVI. This discrepancy might be explained by differences in the plant communities in the respective sites (succulents and other plants with high NIR reflectance were not found in the Naryn sites), or the brightness of the soil backgrounds. In contrast to our result, in montane rangelands in western China, the proportion (by weight) of unpalatable grasses were found to be negatively correlated with vegetation indices in degraded grasslands (Liu et al. 2004). The abundance of an invasive but palatable grass in the south-western U.S. led to lower NDVI and reduced correlations with biomass (Huang et al. 2009). Thus understanding how invasive and unpalatable species influence vegetation indices is not straightforward and depends upon the particular plant species and vegetation composition of the pasture.

However, species composition is only one approach for characterizing communities, and there are approaches for understanding vegetation communities through lenses other than community ecology that may prove more practical. For example, the difference between hyperspectral images captured in different seasons was successfully used to map the spatial distribution of encroaching shrubs in Namibia (Oldeland et al. 2010). A similar approach was used with Landsat imagery to predict grassland invasion by *B. tectorum* in Nevada (Peterson 2015). MODIS is frequently employed to measure phenological differences in rangeland plant communities, as the temporal frequency reduces the influence of annual variations in climate (Zhang et al. 2003). For example, Huang et al. (2009) compared MODIS NDVI and brightness indices in semi-arid grasslands in Arizona, finding plant communities invaded by the invasive perennial grass *E. lehmanniana* had distinctly different phenologies, with increased intra-annual temporal variation.
...and lower spatial variation. Phenological models derived from MODIS have also used to examine post-Soviet changes on agricultural land cover in Kazakhstan (de Beurs and Henebry 2004a). For Kyrgyzstan, phenological approaches may also lead to an improved understanding of plant communities, as international ecological research has largely neglected the area (Borchardt et al. 2011), particularly the montane and alpine grasslands, despite their exceptional diversity of endemic species (Wagner 2009).

**Cover of A. dracunculus influenced temporal trends in NDVI**

The temporal trends in NDVI detected at the sites were corroborated by the drought and livestock histories of the region. NDVI of pasture vegetation was shown to be declining in nearly all pastures from 2000-2008. A severe drought in 2008 followed by a cold and wet 2009 caused snow cover in alpine areas to greatly increase from the lowest to the highest cover seen in the preceding decade (Klein et al. 2012; Dedieu et al. 2014). Likely due to this, NDVI rapidly rebounded in 2009, followed by subsequent declines at most sites. The largest declines (and subsequent recoveries) were in low elevation semi-arid sites characterized by sparser vegetation cover. The negative effects of drought on pasture greenness may have been amplified by an intensification in grazing pressure to compensate for lower fodder production in the fields (Kerven et al. 2011). Finally, if the increase in pasture stocking rates has occurred primarily in spring/autumn and winter pastures, as hypothesized (Crewett 2012), then more negative temporal trends in NDVI would be expected at lower elevations.

The fractional cover of *A. dracunculus* was found to be negatively correlated with trends in NDVI preceding the drought and positively correlated with trends afterward, as NDVI declined less in pastures with higher proportions of unpalatable species. A possible explanation for this finding is that plant species composition in pastures has changed over the course of the study period and that a confluence of factors including the drought and increasing grazing pressures may have facilitated the expansion of *A. dracunculus*, which is both drought-tolerant and ruderal. Because *A. dracunculus* does not yellow mid-summer (unlike many palatable grass species), it exhibits a higher infrared reflectance later in the growing season. Consequently, the detected trends in NDVI are consistent with the hypothesis that climate and
anthropogenic induced disturbances have led to pasture degradation in the form of weed encroachment in Naryn.

**Suggestions for future research**

The 250m resolution of the MODIS imagery used here is relatively coarse for rangeland research and typically reserved for analyses at broader spatial scales (Bai et al. 2008; de Beurs et al. 2015; Eckert et al. 2015). While the density of the MODIS time series was suitable for detecting temporal trends given the rapid green-up and senescence of the grasslands, the coarser spatial resolution may obscure ecological processes occurring at much finer scales. For example, many semi-arid systems display self-organized patterns of vegetation patchiness in response to feedbacks between vegetation growth, soil infiltration, evapotranspiration, and the composition of perennial and annual grasses (Rietkerk and van de Koppel 1997; Rietkerk et al. 2004). Under intense grazing, such systems may show discontinuous and irreversible transitions to less productive states, marked by increasing homogeneity of landscape patterns (van de Koppel et al. 2002). Landsat imagery has long been used to study spatial dependencies in grasslands, including grazing-induced disturbances (Henebry 1993; Pickup 1994). The limited selection of Landsat imagery for Naryn, particularly after the 2003 failure of the Scan Line Corrector on Landsat 7, restricted its use in this study, but the launch of Landsat 8 in 2013 will make image availability less of a constraint for future research (Roy et al. 2014).

Many studies assume decreasing NDVI is indicative of land degradation and worsening grazing conditions, albeit with caveats (Bai et al. 2008; Reeves and Baggett 2014; Eckert et al. 2015). However, quantitatively assessing rangeland degradation is not straightforward, and pasture management methods that rely on vegetation indices to interpret grazing conditions in pastures should endeavour to better address both causes of degradation. Due to grazing-induced changes in species composition, spectral responses to grazing may be inconsistent. At a time when regional and global coverage remotely sensed products are increasingly numerous and accessible, with concomitant analyses emphasizing greater spatial
scales with limited field validation, researchers must be cautious when generalizing broader results to particular locations.

**Implications for Kyrgyz landscapes**

While remote sensing offers several advantages for rangeland in Kyrgyzstan, its application can be improved by identifying areas that may be prone to encroachment from undesirable pasture species in response to grazing. For example, in Naryn *C. pleiophylla* was generally limited to slopes in the semi-arid and desert steppe, while *A. dracunculus* was found on wetter, flatter sites above 2400 metres elevation. Spatial models of invasive plants and invasion risk have proven to be successful approaches for managing rangelands with challenges similar to Naryn (Bradley and Mustard 2006; Adams et al. 2015). A further step could categorize vegetation communities according to their predicted VI trajectory in response to grazing (Röder et al. 2008). However, such research may be more suited to Landsat imagery owing to the often finer spatial scales that influence plant community ecology.

In Kyrgyzstan, degradation caused by changing species composition does not receive the same level of scrutiny as dustiness or bareness in pastures (Liechti 2012), despite *Caragana spp.* encroachment alone being responsible for the loss of 60,000 ha of pasture since 1990 (Egamberdiev 2013). Complicating matters is that grazing is only one of several factors influencing plant communities in the region. Rising temperatures may lead to range expansion in many species, including *A. dracunculus* (Zhumanova 2011). Other factors include the conversion of agricultural fields to pasture, often caused by the decline in irrigation, and the cessation of fertilizer and pesticide applications in pastures (Wolfgramm et al. 2013). In some cases, low stocking rates may lead to the propagation of pastures weeds (Liechti 2012), for example if the noxious species is palatable at a specific growth stage or is particularly vulnerable to defoliation from incidental contact with livestock. Accordingly, there is a pressing need for fenced enclosures and long-term field plots in Naryn that could provide a frame of reference for ecological monitoring.
III. Disentangling anthropogenic and climatic influences on landscape dynamics in Naryn, Kyrgyzstan

Introduction

Rangeland degradation is a contentious topic in Central Asia (Kerven et al. 2012; Liechti 2012) for social and ecological reasons. Reports of continued pasture degradation are numerous (Alibekov and Alibekov 2006; Mirzabaev et al. 2016b). In post-Soviet Kyrgyzstan, grassland productivity is estimated to have declined by 1%-34% in pastures near settlements, while increasing 5%-22% in remote mountain pastures (Shigaeva et al. 2007). Yet, basic research is underfunded, and thus the landscape transformations occurring in the post-Soviet era are poorly documented (Robinson 2016). Land degradation at national and regional scales has not been substantiated, and government reports suggesting widespread pasture mismanagement and degradation have been criticized as merely parroting assumptions and preconceptions without offering new or rigorous data (Kerven et al. 2012; Robinson 2016). Accordingly, there is no consensus on management actions required for sustainable pasture management (Wolfgramm et al. 2013) as there is little scientific consensus on the extent, severity, and location of the problem.

The debate is further complicated by discrepancies between Soviet and Western concepts of pasture degradation (Robinson et al. 2003). While land degradation lacks a universally accepted definition, it is generally described as the loss of biological or economic productivity associated with unsustainable land use (Bedunah and Angerer 2012). In rangelands, this occurs primarily through changes in species composition and declines in phytomass. The Soviet ‘rational use’ system sought to maximize productivity using substantial input of fertilizers, seeding, and weed control (Liechti 2012), classifying pastures as degraded when the fodder provided fell short of expectations. Because such investments of labour and resources are largely unachievable given the current economic reality of the country, historical accounts of pasture degradation may not pertain to discussions of contemporary land degradation. The
term degradation continues to pose challenges, and marginal, unproductive land is frequently conflated with overgrazed pasture. Thus herders’ opinions of pasture conditions may not be synonymous with those of governments and NGOs (Liechti 2012), and, in fact, often run to the contrary.

Several arguments have been put forth to explain pasture degradation in Kyrgyzstan, mainly identifying overgrazing as the proximate cause. First, under Soviet rule, wool export was prioritized in Kyrgyzstan, emphasizing sheep production. Since 1990, a 4-5 fold increase in the number of goats has occurred (FAO 2015). However, official data for livestock production likely underestimate herd numbers (Shigaeva et al. 2016), particularly for goats (Kerven and Toigonbaev 2010), which are favoured by poorer households as they are less expensive and easier to rear (Kerven et al. 2011). Second, many studies have emphasized a reduction in herder mobility as the ultimate cause of pasture degradation (Coughenour et al. 2008; Wolfgramm et al. 2013; Mirzabaev et al. 2016a). The privatization of livestock coupled with a reduction in herd size meant that for some herders costs became too high to justify moving livestock to summer pastures, which requires additional labour and vehicles (Kerven et al. 2012). This has been exacerbated by infrastructural decay, with crumbling roads and bridges limiting pasture access. Third, pasture management has been affected by legislation aimed at reforming pasture use. The first reforms passed in 2002 ultimately aggravated the situation (Kerven et al. 2011). Pasture lease fees did not reflect demand (some herders would prefer to rent near-village pastures than graze remote ones for free), managers were incapable of enforcing grazing rights, and the lease system was overly complicated (Kerven et al. 2011; Crewett 2012). The 2009 Pasture Law lacks provisions for enforcing seasonal migration, and many herders feel their interests are weakly represented by the pasture user associations, diminishing their legitimacy (Shigaeva et al. 2016). Finally, the poor state of agricultural machinery has reduced agricultural yields that supplement livestock diets in winter, prolonging the grazing season in spring and autumn pastures (Robinson 2016).

Climate warming is also a proposed driver of rangeland degradation in Kyrgyzstan (Wolfgramm et al. 2013). Changes in seasonal patterns of temperature and precipitation are projected to be especially
pronounced in the region (Lioubimtseva and Henebry 2009). Meteorological station data show temperatures rising consistently across Central Asia. Increases in air temperature have contributed to a lengthier and earlier melting season (Sorg et al. 2012), decreasing the thickness and duration of the snowpack that provides soil moisture in the early spring. Trends in precipitation have been more variable (Mannig et al. 2013). Evapotranspiration is the limiting factor controlling plant growth in much of the arid steppe (Lioubimtseva and Henebry 2009). Thus while a lengthier growing season may improve grassland productivity, there could also be more widespread moisture limitations late season. The IPCC’s Fifth Assessment Report had indicated that, while the latest generation of models have improved temperature projections, “for precipitation, there is medium confidence that there is no systematic change in model performance” (Kirtman et al. 2013).

Time series of remote sensed imagery are often employed to quantify the extent and severity of rangeland degradation (Wessels et al. 2012; Eckert et al. 2015). The frequent sampling intervals over large areas at low cost make them ideal for monitoring expansive and remote landscapes (Morgan et al. 2010). Vegetation indices provide consistent and empirical measurements of photosynthetic vegetation activity, enabling inferences regarding the biophysical conditions on the landscape (Solano et al. 2010). Various methods have been developed for detecting trends within time series of vegetation index data (Verbesselt et al. 2010a; Fava et al. 2012; Reeves and Baggett 2014). Trends in vegetation indices such as the Normalized Difference Vegetation Index (NDVI) or Enhanced Vegetation Index (EVI) are assumed to indicate areas of vegetation degradation or regeneration.

The ability to attribute statistical significance to a trend is dependent upon the length and density of the time series (de Beurs and Henebry 2005; Forkel et al. 2013). Accompanying long-term, spatially-extensive field data, however, are rare. As such, local expert opinion can provide a valuable approach to map validation, comparison and evaluation (Wessels et al. 2012; Selgrath et al. 2016). Integrating local environmental knowledge (LEK) and remote sensing is a growing practice in natural resource systems, for example fisheries (Selgrath et al. 2016) and forestry (Naidoo and Hill 2006). Such research has
improved our understanding of the potential limitations of LEK, which can be subject to several biases (Daw 2010) including shifting baselines (Pauly 1995) and memory illusion (Papworth and Rist 2009). For rangeland systems, problems can arise if the form and spatial scale of degradation perceived by resource users is different from that which is measured (Herrmann et al. 2014). Nonetheless, LEK may represent the only source of long-term field information in data poor regions, and successful pairing with remote sensing can ensure analyses capture changes important to resource users.

Here we investigate whether locally reported declines in pasture productivity are in agreement with satellite-based estimates of pasture vegetation. We are interested in degradation in terms of long-term reductions in phytomass, as opposed to undesirable changes in the composition of pasture plants. We evaluate temporal trends in NDVI from 2000-2015, as well as trends in the residuals after applying a regression relationship linking NDVI as a function of precipitation and temperature metrics to account for climatic factors. We then compare these trend maps to local environmental knowledge gained from interviews with pasture managers. We use MODIS imagery from 2000-2015, a period during which state, national experts, and NGOs reported declines in pasture productivity. Because some herders no longer adhere to traditional livestock migratory patterns established under Soviet times (Crewett 2012), we examine the distribution of such trends relative to historical pasture use to determine whether negative trends are more abundant in the intensively used spring/autumn pastures. Thus we ask 1) Are trends in NDVI present on the landscape of Naryn? 2) Are such trends present after controlling for climatic influences? and 3) How well does local ecological knowledge of pasture trends match the remotely sensed estimates?

**Methods**

**Study area**

In contrast to Chapter 1, this chapter extends the scale of analysis to the entire Naryn oblast, a province in southeastern Kyrgyzstan (Figure 9). Only 10% of the land area in the oblast is arable (Mudahar 1998), confined to a few river valleys. Much of the landscape, however, is used as pasture. Small pockets of
Spruce forest exist at higher elevations, while below 2000 metres the land is typically desert. The rest of the landscape is composed of montane and semi-arid grassland. Two large endorheic alpine lakes are located in the oblast, Chatyr-kul and Son-kul. Both are Ramsar sites of globally significant biodiversity, as well as important pasture areas. The inner ranges of the Tien Shan Mountains form the south and eastern borders, surpassing 6000 metres elevation in the east. Herding typically occurs up to elevations of 4000 metres. Annual variation in the duration of snow cover in Naryn is quite high relative to other parts of the country (Dedieu et al. 2014).

Figure 9: Location of the study region, the oblast of Naryn, as well as the Naryn city weather station
Geospatial and climatic data

MODIS MOD13Q1 250m NDVI imagery was obtained for the growing season in Naryn (May-September) from 2000-2015, as in Chapter 1. The MODIS product consists of 16-day maximum NDVI composites. Clouds, snow, and ice were masked using the provided quality assurance files. Masked pixel values were replaced with the median value for the appropriate date. Any pixel missing data for more than 5% of the total time series was removed entirely (mainly alpine areas due to persistent snow cover). We used the Seasonal Mann Kendall test on the NDVI dataset to test for monotonic trends occurring from 2000 and 2015. As part of the RESTREND analysis (discussed later), we used the integral of growth season NDVI to produce raster images representing the cumulative vegetation productivity for each growth season from 2000-2015. Such an approach has been shown to be an improvement over simple annual NDVI maximums for estimating forage potential (Mbow et al. 2013), and better aligns with the monthly frequency of the precipitation data.

Few weather stations in Kyrgyzstan remain operational from Soviet times. The Naryn city weather station is the only station in the oblast with reliable data. Daily precipitation, minimum and maximum temperature records were obtained for the station from the National Center for Environmental Information (NOAA 2015). Because the precipitation record was particularly poor, gaps in the record were filled with data obtained from Kyrgyz Hydromet, the state meteorological agency, as well as Weather Underground (The Weather Channel LLC 2015). Rainfall was natural log-transformed due to the assumed non-linear relationship between precipitation and vegetation productivity.

As warming temperatures contribute to vegetation development in spring before constraining it in summer (Kulikov et al. 2016), accumulated growing degree days (base 0°C) were calculated for April and May of each year, using the formula:
\[ GDD = \frac{(T_{\text{max}} + T_{\text{min}})}{2} \]

if \( GDD > 0 \), \( AGDD_t = AGDD_{t-1} + GDD_t \)

else \( AGDD_t = AGDD_{t-1} \)

where \( GDD_t \) is the increment of growing degree days at day \( t \) and \( AGDD_t \) is the accumulated growing degree days within a single year.

**Statistical analysis of temporal trends**

We assessed temporal changes in pasture productivity before and after controlling for climatic influences. First, ignoring any potential impact of climate, we analyzed the growth season NDVI data for monotonic trends using the Seasonal Kendall test. The Seasonal Kendall test is a rank-based non-parametric test (Hirsch et al. 1982) and a useful alternative to linear least squares regression requiring fewer assumptions (de Beurs and Henebry 2004b). The first step in the test is calculating the Mann Kendall statistic for each subseries (e.g. June 1\(^{\text{st}}\) 2000, June 1\(^{\text{st}}\) 2001…June 1\(^{\text{st}}\), 2015) by summing the number of times an observation is followed by an observation of greater or lesser value. For lesser values, one is subtracted from the test statistic, ties are neutral, and greater values result in one being added. The Seasonal Kendall statistic is calculated as the sum of the Mann Kendall statistics. It is asymptotically normal with a zero mean and variance defined as the sum of variances for every subseries and covariances for every combination of subseries. Trends were evaluated by comparing the standardized test statistic \( Z \) with the standard normal variate after first correcting for autocorrelation between subseries following Libiseller and Grimvall (2002). Trends with \( p < 0.05 \) were considered significant.

To control for the influence of climate on NDVI, we used the Residual Trend Analysis (RESTREND) approach (Wessels, van den Bergh, and Scholes 2012). RESTREND is based on the assumption that declines in rain use efficiency (the productivity of vegetation per unit rainfall) are indicative of anthropogenic land degradation. It distinguishes between anthropogenic and climate-related variations in NDVI by testing for trends in the residuals of the NDVI/rainfall regression (observed minus
the predicted NDVI). For each pixel, ordinary least squares (OLS) regression was employed to regress the aggregated NDVI against May-July rainfall and accumulated spring growing degree-days. Residuals, r-squared, p-values, and error estimates were the primary outputs. Each set of residuals was tested for non-normality, heteroscedasticity, and serial independence using the Shapiro-Wilk, Breusch-Pagan, and Breusch-Godfrey tests, respectively (Shapiro and Wilk 1965; Breusch 1978; Breusch and Pagan 1979). The final step was testing for the presence of monotonic trends in the NDVI residuals using the Mann-Kendall trend test (the Seasonal Kendall test was unnecessary as there was no seasonal component to the aggregated data). Residuals were only tested for monotonic trends if the pixel R^2 exceeded 0.35. All analyses were performed using the statistical program R (R Core Team 2015) using the raster and trend packages (Hijmans 2015; Pohlert 2015). A 3x3 majority filter was applied to the final five classes (negative trends, positive trends, no trend, no data, and not suitable for RESTREND).

**Assessing the spatial distribution of trends**

To validate the NDVI and RESTREND trend maps, a participatory mapping exercise was conducted to identify locations of potential land degradation. These were obtained via interviews of experienced pasture managers conducted by Dr. Jordan Levine during June-August 2015. Interviews were conducted by providing members of the local pasture committees with laminated high resolution satellite imagery, familiarizing them with the spatial area represented, and asking the interviewees (in Kyrgyz) to indicate with dry-erase markers areas where the height of palatable grass had been noticeably reduced over time due to grazing pressure. Markings were then photographed and georeferenced. We refined the specific phrasing of our interview questions through several iterations (e.g. “areas where grass height had declined due to grazing”) to ensure that the changes in pasture condition identified by LEK were consistent with the form of degradation best suited to the remote sensing analyses. We also mitigated any misunderstandings arising from the use of the term ‘degradation’. Matching the objectives of the participatory mapping exercise with the trend analysis precluded the issue encountered by Herrmann et al. (2014), where resource users identified primarily grasslands degraded by changes in species composition.
We then digitized Soviet-era maps of pasture land use in Naryn oblast, distinguishing four agricultural classes: winter pasture, spring/fall pasture, summer pasture, and row crop agriculture. Due to a concern about potential spatial inaccuracies in the land use maps, we conservatively digitized polygons well within the outer boundaries of the four classes. The polygons were similar in size to the herder-identified degraded areas (~50km²) except for the smaller-sized row crop agricultural fields. Within each polygon, we determined the proportion of both positive and negative trending pixels of NDVI and NDVI-residuals. For the RESTREND data, only pixels that met OLS assumptions with a satisfactory R² were included in the results. Polygons with fewer than 10 NDVI-residual pixels were excluded.

**Results**

**Q1. Trends in vegetation indices were widespread and predominantly negative**

Overall 24.0% of the landscape exhibited negative trends in NDVI, compared to 1.7% that showed positive trends (Figure 10). Positive trends were generally limited to agricultural fields at lower elevations in the Naryn river valley. In comparison, negative trends were distributed more evenly across the landscape, including the high elevation pastures surrounding the lake Chatyr-kol, as well as tracts of land in the Ak-Sai region. This geographic pattern was reflected in the distribution of trends among the four pasture classes. The mean proportion of land with positive trends detected was 0.25 for agricultural lands, 0.02 for spring and autumn pastures, and <0.01 for summer and winter pastures, whereas negative trends were virtually absent in agriculture areas (mean = 0.07), but highly prominent in winter (mean = 0.46) and spring/fall pastures (mean = 0.44) (Figure 11). The mean proportion of summer pastures with negative trends was 0.187.

**Much of the landscape was only moderately correlated with predictors**

The largest source of pixel exclusion overall was caused by the R² threshold of 0.35 applied to remove pixels for which the model was a poor fit. While the majority of pixels met OLS assumptions, outside of the Naryn valley they were weakly correlated with predictors. Among the three OLS
assumptions, heteroscedasticity was the most frequent cause for pixel exclusion, with 8.2% violating the assumption of homoscedasticity (Table 5). Many of these pixels were situated on extremely arid areas with little inter-annual variability in NDVI. There was a large overlap between pixels that failed individual tests.

Precipitation and AGDD were approximately equal in terms of the geographic area over which they were correlated with NDVI (Figure 12). Spearman’s $r$ for the correlation between AGDD and precipitation was -0.46 ($p = 0.07$), suggesting warm springs coincided with dry growing seasons. The correlation with precipitation was positive everywhere except for isolated pixels in alpine areas. The correlation with AGDD was negative at lower elevations but reversed to positive with increasing elevation. Agricultural fields were an exception, as they were positively correlated with AGDD despite their lower elevation.

Figure 10: Results of Seasonal Mann Kendall tests on MODIS NDVI 2000-2015. Insets show positive trends confined mainly to agricultural fields, with negative trends detected in the surrounding rangeland.
Figure 11: Proportional area of polygons with detected trends in NDVI (2000-2015) across pasture classes. The solid line denotes the median, the box the first and third quartile, the whiskers the range multiplied by the interquartile range, and dots denote outliers. The seven red crosses indicate trends in the polygons identified by pasture managers where grass height had declined due to heavy grazing.

Table 5: Filtering procedures applied to data using RESTREND approach

<table>
<thead>
<tr>
<th>Filtering procedure</th>
<th>NDVI pixels masked (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt; 5% missing data</td>
<td>28.1%</td>
</tr>
<tr>
<td>Shapiro-Wilkes test for non-normality</td>
<td>3.8%*</td>
</tr>
<tr>
<td>Breusch-Godfrey test for autocorrelation</td>
<td>5.6%*</td>
</tr>
<tr>
<td>Breusch-Pagan test for heteroscedasticity</td>
<td>8.2%*</td>
</tr>
<tr>
<td>$R^2 &lt; 0.35$</td>
<td>80.0%**</td>
</tr>
</tbody>
</table>

*includes only pixels with less than 5% data missing

**includes only pixels that met OLS assumptions and were significantly correlated to precipitation and AGDD with $p < 0.1$
Figure 12: Coefficients for May-July precipitation (top) and April-May AGDD (below) regressed against ΣNDVI. Results shown only if p < 0.1, parameters were significantly different from zero, and OLS assumptions were met. The inset in the lower panel highlights the positive correlation between AGDD and NDVI at higher elevations (near ice/snow) and in agricultural fields, with negative correlations common at lower elevations. In comparison, correlations with precipitation were uniformly positive.

The strength of the relationship between growth summed NDVI and climate declined from initial $R^2$ values of 0.7 with increasing distance and elevation from the station, indicative of the strong spatial heterogeneities created by the mountainous terrain (Figure 13). The climatic variables were poorest in explaining NDVI among the desert steppe areas found in the west of the study site, the forested areas found on northern aspects, and the Aksai region in the rain shadow of the At-Bashy range, in which elevation exceeds 3000 metres.
Q2. Negative trends in NDVI residuals were prevalent in low elevation pastures

Negative trends in NDVI residuals were most widespread in the spring/fall and winter pastures, where the median proportional area of negative trends was 0.11 (mean = 0.23) for spring/fall pastures and 0.11 (mean = 0.184) for winter pastures. The negative trends were clustered in three regions, near the village of Jergetal, south of Naryn city, and a large section in the west of the oblast (Figure 14). By comparison, the large majority of NDVI residuals with positive trends were detected on row crop fields, as only a few summer and spring/fall pastures showed positive trends in NDVI residuals. Among pixels that satisfied all requirements for the RESTREND analysis, 15.2% exhibited negative trends, whereas only 0.9% showed positive trends (Figure 15). Negative trends were generally absent in agricultural areas and summer pastures. However, there were proportionally far fewer RESTREND pixels in summer pastures than the other pasture classes, reflecting the poor performance of the RESTREND model in the montane areas where conditions are more moist (Figure 16).
Figure 14: 2000-2015 trends in NDVI residuals, the result of regressing growth season integrals of NDVI with AGDD and precipitation. ‘No trend’ includes all pixels that met OLS assumptions and were significantly correlated with AGDD or precipitation with $R^2$ greater than 0.35. The inset shows a hotspot of negative trends, with positive trends detected in agricultural fields.
Figure 15: Proportional area of pastures with detected trends in NDVI residuals. The thick line denotes the median, the box the first and third quartile, the whiskers the range multiplied by the interquartile range, and dots denote outliers. The seven red crosses represent trends in the polygons identified by pasture managers where grass height had declined due to heavy grazing.

Figure 16: The proportional area of each polygon that met OLS assumptions and $R^2$ above 0.35. The lower proportion in summer pastures is indicative of the poorer model fit in high elevation areas.
Q3. Remotely sensed trends and participatory maps were generally in agreement

The pastures identified by managers as overgrazed generally conformed to the expected patterns of decreasing NDVI and NDVI residuals. Pasture managers unexpectedly identified only a single winter pasture as overgrazed compared to three spring/fall and summer pastures. Positive trends in NDVI were absent from all seven pastures identified as degraded (Figure 11, Figure 17). Among the three spring/fall pastures, negative trends in NDVI were proportionally 0.39, 0.49, and 0.90 of the pastures, similar or above the median for spring/fall pastures of 0.42. A large majority of the winter pasture (0.85) contained negative trends in NDVI, well above the winter median of 0.39 (Figure 11). The three summer pastures were less consistent: no significant trends were present in two of them, but 0.70 of the third summer pasture showed negative trends, considerably more than any other summer pasture.

The trends in RESTREND were similar to the trends in NDVI among pastures identified as overgrazed by local experts. Again, no positive trends in RESTREND were present in any of the seven pastures (Figure 15). Negative trends in RESTREND were only slightly more abundant in the winter pasture than the median winter pasture. Likewise, the three spring/fall pastures had proportionally more pixels with negative trends than the median, but were within the third quartile. The two summer pastures that were without trends in NDVI did not exhibit trends in RESTREND either. However, negative trends were detected in 0.16 of the RESTREND pixels in the third summer pasture, among the uppermost of summer pastures.
Figure 17: Examples of RESTREND results for pastures in the winter (top), spring/fall (middle) and summer classes (bottom) that were identified by pasture managers as overgrazed. A 3x3 median filter was applied to the results of the RESTREND analyses to reduce spurious pixels.
Discussion

Pastoral societies in Kyrgyzstan face an uncertain future

Given the general agreement between pasture managers’ perceptions of overgrazing, field observations, auxiliary literature, and the negative trends in NDVI and NDVI residuals, our results add to the growing evidence that pasture degradation has not materialized evenly across the landscape. This could have serious ecological consequences. Spatially heterogeneous pressure has been demonstrated to increase the risk of deleterious changes in semi-arid ecosystems (Schneider and Kéfi 2016). Equilibrium dynamics remain hotly contested in rangelands (Vetter 2005; Derry and Boone 2010), and controversy around land degradation and desertification seems unlikely to subside (Robinson 2016). Regardless, the projected but uncertain increases in aridity (Lioubimtseva and Henebry 2009), continued decline of glaciers (Dedieu et al. 2014), and the expansion of industries competing for land use (Bogdetsky et al. 2002) will expose pastoralists to novel interactions between multiple stressors. Restoring the capacity for basic science and monitoring, in combination with expert knowledge and input from those who are most likely to be affected, i.e. pasture users themselves, is a vital component of managing this uncertain future.

We found negative trends in NDVI – indicating potential land degradation – were far more prevalent relative to positive trends, which were largely confined to agricultural fields in river valleys. This is consistent with browning trends detected using other remote sensing datasets (De Jong et al. 2013). After controlling for climatic variability, positive trends were detected in less than 1% of the NDVI residuals but negative trends were still detected in 15%. Land degradation appears to be manifesting in more arid areas, as negative trends in NDVI were more common at lower elevations. This is likely in response to increased grazing pressure near villages, which also occur disproportionately at low elevations, and to droughts, which were routine during the period of study. Trends in vegetation indices are heavily influenced by climatic factors (Robinson 2016). Repeated droughts in the 2000s coincided with the larger region becoming a global hotspot of vegetation browning in the 2000s (Hu et al. 2014; Zhang et al. 2016). Many of the herders recalled 2014 as one of the driest springs in recent
memory, with some reporting livestock mortality upwards of 50% of herds, while the station data confirm May 2014 was the driest from 2000-2015.

Although the RESTREND analysis appears to corroborate arguments of pasture degradation in winter and spring/fall pastures, some caution is required with their interpretation. While patterns of declining NDVI were present in near village pastures, even after controlling for climatic factors, they are not necessarily indicative of long-term declines in pasture productivity, but rather intensifying grazing pressure. As stocking densities remain far below those during Soviet times, even assuming widespread underreporting (Shigaeva et al. 2016), it would be premature to conclude such declines in productivity are irreversible, even on short time frames. Furthermore, the relationship between climate metrics and NDVI underpinning the RESTREND method is influenced by the timing, rate, and intensity of degradation (Wessels et al. 2012). For example, large increases in grazing pressure occurring midway through the period of analysis can obscure the relationships between rainfall and NDVI. While we did not examine in detail the temporal patterns in NDVI on a pixel wide basis, the field sites from Chapter 1 included areas where trends were most negative. The variegated patterns in NDVI found therein suggests pastures have not crossed any threshold beyond which they cannot recover (von Wehrden et al. 2010). Finally, trend analyses refer to significant changes in a statistical rather than ecological sense, and are applicable only to the observational period. They are heavily influenced by the beginning and end of the time series. For example, droughts occurring towards the end of the time series can bias RESTREND towards negative trends (Wessels et al. 2012). This is concerning given the penultimate year of the period of study, 2014, was exceedingly dry, although both 2013 and 2015 were among the rainiest of the 16 years.

Implications for Kyrgyz landscape management

The negative trends in RESTREND that were detected might be expected given the gradual increase in livestock numbers in the region after the historic lows that followed independence from the Soviet Union. However, the large area of browning detected near Jergetal is most likely caused by a combination of factors including intensive grazing and mineral exploration (Steimann 2012). A foreign-
owned gold mine has caused considerable controversy in the area, as activities related to the mine have caused a reduction in the quality and area of pasture. Even prior to the establishment of the mine in 2006, operations from other mining companies had left behind large ditches, waste pits and tailings ponds on some of the spring/fall pastures (Steimann 2012), exacerbating their intensive use. The lands south of Naryn city are also intensively grazed, as they are easily accessible from the road joining Naryn and At-Bashy, which might explain the extensive negative trends in the NDVI residuals that were detected there. Field visits in 2015 found the slopes in that region were highly terraced, typical for heavily grazed pastures (Liu and Watanabe 2013; Jin et al. 2016), with shallow soil erosion scars.

The positive trends detected in both NDVI and RESTREND in agricultural areas points to the reclamation of farmland abandoned in the post-independence years. This was unexpected, as labour migration, a lack of machinery, and dilapidated irrigation systems has led to widespread abandonment of croplands in Central Asia (de Beurs and Henebry 2005). Cropland in Naryn is almost exclusively devoted to fodder for livestock and forms a valuable source of supplementary feed in winter. Restoring farm productivity is thus a key priority for pasture management as livestock levels continue to recover. Thus these findings are encouraging, and may indicate the success of several community based institutions designed to address the collapse in irrigation systems, such as local Water User Associations (Wolfgramm et al. 2013). Many of these have been implemented exclusively by NGOs and donors, and their formation has been restricted to lower elevation areas, though a comprehensive listing of their location and status does not yet exist (Hill 2013).

**Local environmental knowledge is a valuable resource in data-scarce regions**

Rangeland monitoring has been drastically reduced in post-Soviet Central Asia (Robinson 2016) and collection of in situ data is rare (Hamidov et al. 2016), necessitating alternative approaches to quantify spatial patterns of resource exploitation. The participatory mapping approach used here provided a successful alternative in lieu of ecological field data covering the period of study. Local environmental knowledge was helpful for corroborating remote sensing data and yielded some unexpected results.
Pasture managers identified overgrazed areas in relatively remote locations. However, without a larger sample size it is difficult to infer whether the patterns we observe are representative of broader trends in the region.

Unlike pasture managers, many herders did not hold strong opinions regarding changes in pasture productivity (Jordan Levine, personal comm., April 29th, 2016). However, many herders had transitioned to herding as a livelihood source within the past decade, which may be too short a time period to establish a baseline view of pasture productivity. Though not addressed in detail here, the opinions of herders and managers are the subject of other in-depth work by social scientists associated with the project. That said, the discrepancies in opinion between the two groups emphasizes the need for long-term approaches for monitoring such systems that are independently verifiable. Thus, linking LEK with remote sensing analyses may be a research imperative for many regions of the world, especially those with limited capacity for field–based monitoring.
IV. Conclusion

Central Asian rangelands, which represent one of the most extensive landscape types in the world (Mirzabaev et al. 2016a), provide a vital component of the culture and economy in Kyrgyzstan. As climate change impacts materialize, sustainable management of pasture resources will only become more challenging. Unfortunately Central Asian rangeland systems are among the least studied landscapes globally (Mirzabaev et al. 2016a). The dearth of research belies the sheer extent of the transformations occurring from globalization, development, and institutional and market reforms. Remote sensing can play a particularly important role in monitoring and managing this region, as it offers a cheap and efficient method of observing change over large, remote, and inaccessible areas. This opportunity is not confined to rangelands: the past quarter century in Central Asia has seen the considerable retreat of glaciers (Sorg et al. 2012), massive alterations of water bodies (Lioubimtseva 2014), forest loss (Klein et al. 2012), and cropland abandonment (Lioubimtseva and Henebry 2009). Expanding the application of remote sensing in this region will ensure that such spatially heterogeneous changes do not pass unnoticed.

My second chapter used field data to examine the influence of plant cover and species composition on vegetation indices, revealing that a particular species of pasture weed could lead to fallacious estimates of pasture grazing conditions. Subsequent trend analysis found evidence of weed encroachment in several pastures. In Chapter 3, I expanded the study area from the field sites of Chapter 2 to the entire Naryn oblast. I asked whether trends in vegetation indices support the argument of widespread decreases in productivity, especially in the more accessible pastures nearest villages. I aimed to account for the influence of inter-annual variability in climatic factors that favour vegetation growth to discern whether anthropogenic pressures were contributing to pasture browning. By engaging the knowledge of local experts, I was able to show where detected trends were consistent with areas known by pasture managers to be overgrazed. Taken together, these chapters demonstrate the benefits and pitfalls associated with multi-decadal remote sensing datasets for providing spatially explicit estimates of pasture degradation and its underlying causes. While large-scale efforts of mapping landscape change are
becoming ubiquitous, the results of this thesis show that without ground verification, such methods are at best unable to account for a form of degradation that may be becoming widespread upon the landscape. At worst, they run the risk of conflating increases in forage availability with weed encroachment.

Confirming trends detected by satellite imagery, through either ground verification or the application of auxiliary datasets, is a global challenge for rangelands and particularly for Kyrgyzstan, where the topography greatly impedes movement and post-Soviet ecological programs are still nascent. The success of the participatory approach here is thus encouraging, and could be repeated in other rangelands where physical or social barriers impede movement over large areas. For example, rangeland degradation is often correlates with human conflict, e.g. Sudan (Bedunah and Angerer 2012). Capitalizing on the spatial knowledge of locals might therefore be a safer and more efficient approach than attempting to navigate such an environment.

The RESTREND approach used in Chapter 3 was highly successful in the lower elevation pastures where there was a stronger correlation between climate data and NDVI. The decreases in NDVI were substantiated by several sources, including managers’ perceptions of pasture change, fieldwork, and other literature. Such an approach is necessary for differentiating between anthropogenic and climate driven changes to pasture productivity in Kyrgyzstan, as the frequency and intensity of droughts, severely cold winters, and other extreme weather events have a pronounced effect on vegetation indices. However, a national-level study controlling for climatic variables would be more challenging. The paucity of weather stations in the country may necessitate the adoption of remotely sensed climate measurements as opposed to in situ station data. It remains to be seen if the Global Precipitation Measurement satellite launched in 2014, perhaps coupled with Soil Moisture Active Passive mission data (Entekhabi et al. 2010), will improve our understanding of Kyrgyz highland pastures. Unfortunately, in Kyrgyzstan data scarcity continues to be a serious impediment to advancing scientific knowledge of socioecological systems. The sparse network of weather stations limits future work using the RESTREND approach; gridded data products –such as the GPCC reanalysis data (Schneider et al. 2015)– have been inconsistent.
in matching station data for parts of Central Asia (Wright et al. 2009). Therefore, restoring inactive weather stations (and enabling access to their data) is an important step to improving the potential of remote sensing to contribute to pasture management.

Transhumance was shown to be a successful adaptation to the dramatic seasonal differences existing in Central Asian rangelands. The field visits undertaken for Chapter 2 found summer pastures to be in good condition, a finding supported by the trend analysis in Chapter 3. Not only are these pastures a source of supplementary fodder, they provide refuge from the droughts that afflicted pastures at lower elevations. However, herders are understandably reluctant to migrate to remote summer pastures unless others follow, as spending several months isolated in the mountains can pose grave challenges in the event of an emergency arising. Thus, ensuring summer pastures remain as accessible as possible, by restoring aging infrastructure, is critical for the continuation of transhumance pastoralism in Kyrgyzstan.

**Future directions**

A planned research direction is to pair MODIS data with imagery with very fine spatial resolutions, for example from unmanned aerial vehicles. The goal is to distinguish undesirable and desirable changes in pasture biomass while retaining the broad spatial coverage offered by remote sensing. Unmanned aerial vehicles, or UAVs, represent a promising new method of obtaining cost-effective spatial and temporal data at scales relevant to the study of ecological phenomena such as regime shifts (Anderson and Gaston 2013). They are particularly useful for rangelands, which have been less studied using conventional remote sensing technologies due to the high spatial resolution required for shrub/grass identification (Laliberte 2009). Thus pairing the temporal frequency of MODIS with the spatial resolution of UAVs may provide insight into the ecological conditions that favour weed encroachment and phytomass decline as responses to grazing.

In addition to increasing the spatial scale of analysis, using remote sensing perspectives other than vegetation indices might clarify the nature and causes of the detected trends (de Beurs et al. 2015). For example, the MODIS evapotranspiration product might be used to examine whether the increases in
NDVI detected in agricultural fields coincide with expected increases in evapotranspiration. Discrepancies between these two data sets can provide evidence of changing crop types as opposed to changing crop yields (de Beurs et al. 2015). The tasseled cap brightness index (Crist and Cicone 1984) can be derived from MODIS imagery (Lobser and Cohen 2007) and used as a proxy for albedo. It was found to be the superior index for examining localized soil and vegetation degradation in Kazakh deserts (Karnieli et al. 2008). It could therefore be an interesting alternative to the NDVI for examining degradation in Naryn, as the majority of the negative trends in NDVI were detected in sparsely vegetated areas.

Another proposed research direction is to identify factors that dictate year-to-year grassland productivity in the region beyond precipitation and growing degree-days. The correlation between rainfall and NDVI found here was generally lower than in other studies (Wessels et al. 2012; Zhang et al. 2013), which can only partly be attributed to the limited station data. The rugged topography of the region produces complex weather patterns, where grassland productivity may be determined by several factors (Kariyeva and van Leeuwen 2011). For example, one potential mechanism left unaddressed in this study was the role of snowmelt in influencing pasture productivity in the following year. Winter precipitation is an important source of water for irrigation and has been linked with NDVI-based productivity metrics (Kariyeva and van Leeuwen 2011). One promising development in Naryn is a University of Central Asia project that will expand the network of weather stations, ideally situating some stations in higher elevation pastures where herders will volunteer to maintain them. This will advance monitoring of climate change impacts in the long-term, but could also yield immediate benefits by improving pasture productivity models for montane regions. Central Asian rangelands are complex systems beset by a multitude of challenges yet nonetheless continue to provide livelihoods to millions of the world’s most vulnerable people. They are deserving of far more attention from the global scientific community than they have so far received.
References


Entekhabi D, Njoku EG, O’Neill P, Kellogg KH, Crow WT, Edelstein WN, Entin JK, Goodman SD, Jackson TJ, Johnson J, Kimball J, Piepmeier JR, Koster RD, Martin N, McDonald KC,


Appendix I

While *A. dracunculus* was only one of many unpalatable plants encountered in the field, it was by far the most abundant. Correlation between the proportion of cover consisting of unpalatable species and cover specifically of *A. dracunculus* was 0.87. Included here are the same regression models but with the predictor variable ‘prop. *A. dracunculus*’ replaced with the fractional cover of all unpalatable species (Prop. unpalatable). The resulting model $R^2$ was lower for nearly all cases. This is hypothesized due to many of the other unpalatable species having very low biomass relative to cover (e.g. *Ranunculus* spp.), or low LAI (e.g. *C. pleiophylla*) resulting in negligible effects on vegetation index values. EVI was not correlated with unpalatable cover; however, the model $R^2$ was lower than for other VIs.
Table 6: Summary regression results at the site level (n = 33) for models explaining vegetation indices as a function of percent vegetative cover, the proportional cover of unpalatable species, elevation, slope, and solar insolation using backward stepwise regression

<table>
<thead>
<tr>
<th>Dependent variable</th>
<th>Independent variables (with partial $r^2$ and sign of coefficient)</th>
<th>Model $R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum MODIS NDVI (2015)</td>
<td>+ Percent cover (0.39); + Prop. unpalatable (0.20) + Slope (0.06); - Elevation (0.05); + Solar insolation (0.04)</td>
<td>0.74</td>
</tr>
<tr>
<td>Maximum MODIS WDRVI (2015)</td>
<td>+ Percent cover (0.39); + Prop. unpalatable (0.18); + Slope (0.06); - Elevation (0.05); + Solar insolation (0.04)</td>
<td>0.72</td>
</tr>
<tr>
<td>Maximum MODIS EVI (2015)</td>
<td>+ Percent cover (0.50); - Elevation (0.06); + Solar insolation (0.04); + Slope (0.03)</td>
<td>0.63</td>
</tr>
<tr>
<td>Julian date of peak MODIS NDVI (2015)</td>
<td>+ Elevation (0.34)</td>
<td>0.34</td>
</tr>
<tr>
<td>Median Julian date of peak NDVI (2000-2015)</td>
<td>+ Elevation (0.65); - Slope (0.05)</td>
<td>0.70</td>
</tr>
</tbody>
</table>

Table 7: Summary results for models explaining trends in NDVI using percent cover, the fractional cover of unpalatable species, elevation, solar insolation, and slope using backwards stepwise regression (p < 0.05). Percentage change in NDVI over time was determined using BFAST.

<table>
<thead>
<tr>
<th>Dependent variable</th>
<th>Independent variables (partial $r^2$ and sign of coefficient)</th>
<th>Model $R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sen’s slope 2000-2008</td>
<td>+ Total cover (0.27); + Elevation (0.21); - Slope (0.09)</td>
<td>0.57</td>
</tr>
<tr>
<td>Sen’s slope 2009-2015</td>
<td>+ Total cover (0.26); + Elevation (0.17); + Prop. unpalatable (0.15)</td>
<td>0.54</td>
</tr>
<tr>
<td>Breakpoint magnitude</td>
<td>- Elevation (0.43); - Percent cover (0.22)</td>
<td>0.64</td>
</tr>
<tr>
<td>BFAST period 1 % change NDVI</td>
<td>+ Elevation(0.34); + Percent cover (0.31); + Solar insolation (0.05)</td>
<td>0.71</td>
</tr>
<tr>
<td>% change NDVI 2009-2015</td>
<td>+ Percent cover (0.36); + Prop. unpalatable (0.20); - Slope (0.08)</td>
<td>0.64</td>
</tr>
</tbody>
</table>