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LAND SURFACE PHENOLOGIES IN CENTRAL ASIAN MOUNTAIN PASTURES: MODELING CHALLENGES AND OPPORTUNITIES

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ФЕНОЛОГИЯ ЗЕМЕЛЬНЫХ УЧАСТКОВ В ГОРНЫХ ПАСТБИЩАХ ЦЕНТРАЛЬНОЙ АЗИИ: МОДЕЛИРОВАНИЕ ПРОБЛЕМ И ВОЗМОЖНОСТЕЙ

Аннотация: *Для того чтобы изучить уязвимость высокогорного населения в Кыргызской Республике и Узбекистане с изменением климатических, социально-демографических и социально-экономических условий, мы устанавливаем различные устройства по сбору данных дистанционного зондирования для составления характеристики состояния пастбищ вблизи сел на большой высоте (> 2000 м над уровнем моря) и в отдаленных пастбищах на больших высотах. Мы исследуем возможность направления климатических изменений, которые стимулируют изменения состояния пастбищ, через дистанционное зондирование поверхности земли по сезонности (метрика снежного покрова) и поверхности земли фенологии (Индексы растительности) и тщательного анализа данных осадков станции, дополненные дистанционным зондированием осадков и влажности почвы. Здесь мы опишем применение выпуклой квадратичной модели (CxQ) от поверхности земли фенологии в пастбищах Ат-Башинского района, Нарынской области Кыргызской Республики. Мы использовали 16 летнюю (2000-2015) нормализованную разницу вегетационного индекса «Landsat» (НРВИ) вместе с образами «MODIS» и снимки температуры поверхности земли, переработанные в накопитель ежедневно растущего градуса. Пик высоты НРВИ, ключевой фенологической метрики, полученной аналитически подобранными коэффициентами параметров модели CxQ, выставлена чувствительность к несанкционированной и межгодовой изменчивости, с потерей вертикальной структуры в охладителе, более влажный год 2009. Пик теплового времени, другой фенометрики происходит от модели CxQ, выставленной к весьма существенным отрицательным линейным соотношениям с высоты. Эти отношения и связанные с ними модели CxQ по высоте, могут обеспечить образцами, на основании которых возможно обнаружение изменений в состоянии пастбищ.*

Ключевые слова: *дистанционное зондирование; «Landsat»НРВИ; «MODIS»; выпуклая квадратичная модель; фенометрика; Кыргызская Республика.*

Abstract: *To explore the vulnerability of high-elevation communities in the Kyrgyz Republic and Uzbekistan to changing climatic, sociodemographic, and socioeconomic conditions, we are assembling diverse remote sensing datasets to characterize the condition of pastures near villages at high elevation (>2000 masl) and in remote pastures at higher elevations. We are exploring how climatic changes that drive changes in pasture condition can be addressed through remote sensing of land surface seasonality* *(snow cover metrics) and land surface phenology (vegetation indices) and careful analysis of precipitation station data complemented by remote sensing of precipitation and soil moisture. Here we describe the application of the convex quadratic (CxQ) model of land surface phenology to pasturelands in At-Bashi rayon, Naryn oblast, Kyrgyz Republic. We used 16 years (2000-2015) of Landsat normalized difference vegetation index (NDVI) imagery with MODIS land surface temperature imagery processed into accumulated growing degree-days. The peak height of the NDVI, a key phenological metric derived analytically from the fitted parameter coefficients of the CxQ model, exhibited sensitivity to elevation and interannual variability, with a loss of elevational pattern in the cooler, wetter year of 2009. The thermal time to peak, another phenometric derived from the CxQ model, exhibited strong, highly significant negative linear relationships to elevation. These relationships and the associated CxQ models by elevation may provide patterns against which to detect changes in pasture status.*

Keywords*: remote sensing; Landsat; MODIS; convex quadratic model; phenometrics; Kyrgyz Republic*

Introduction

Land surface phenology (LSP) refers to the seasonal pattern of variation in vegetated land surfaces observed using remote sensing [1-2]. The coupling between the land and the lower boundary layer of the atmosphere is greatly affected by LSP: seasonal changes in the surface radiation and energy balances, albedo, roughness length, and evapotranspiration are all driven by vegetation growth and development. Of particular interest to those who study land surface phenology is the characterization of the timing of seasonal transitions (or phenophases) and its interannual variation. Here we show the results of initial analyses for the highland pastures of At-Bashi rayon in Naryn oblast of the Kyrgyz Republic for the period 2000-2015.

Materials and Methods

Data: Landsat We ordered surface reflectance (http://espa.cr.usgs.gov/) for 1,265 Landsat 5 TM, Landsat 7 ETM+, and Landsat 8 OLI scenes from four path/row tiles: 149/31, 149/32, 150/31, and 150/32 for 2000 to 2015 [3]. Next, we filtered poor quality (cloudy, snow covered) observations using the standard “cfmask” and calculated the normalized difference vegetation index (NDVI)

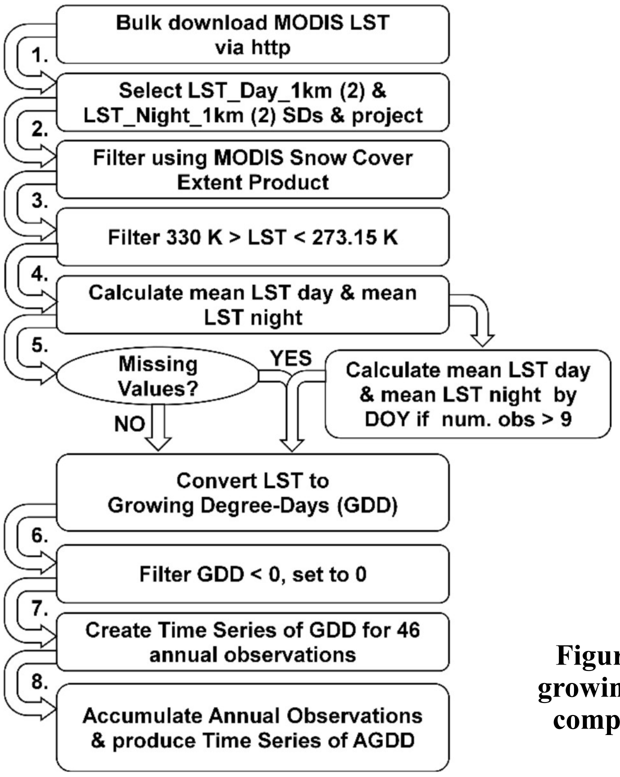

Figure 1. Processing outline for MODIS LST to growing degree-day algorithm that converts 8-day composites of MODIS LST into annual series of AGDD.

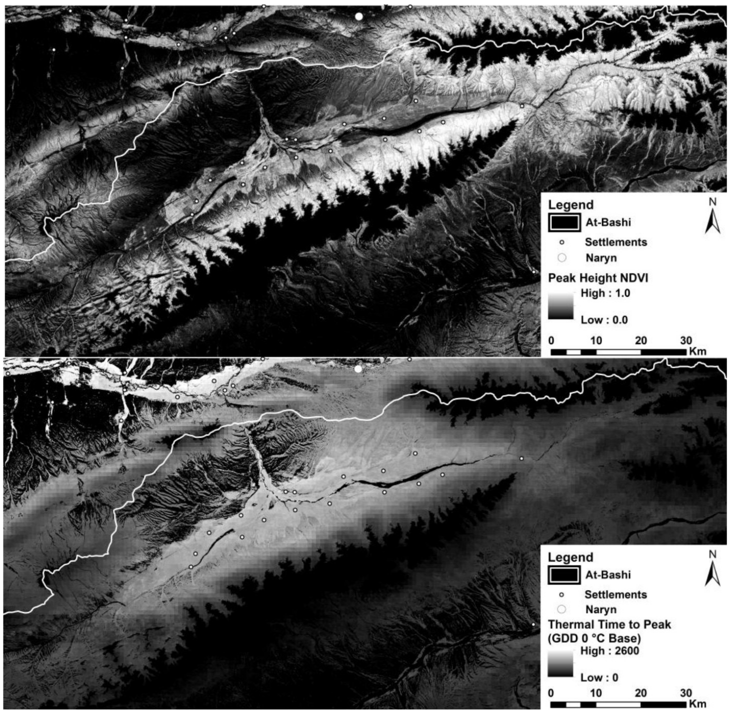

Figure 2. (top) Peak Height of NDVI, PHNDVI, mean of 2000-2015; (bottom) Thermal Time to Peak NDVI (TTP), mean of 2000-2015.

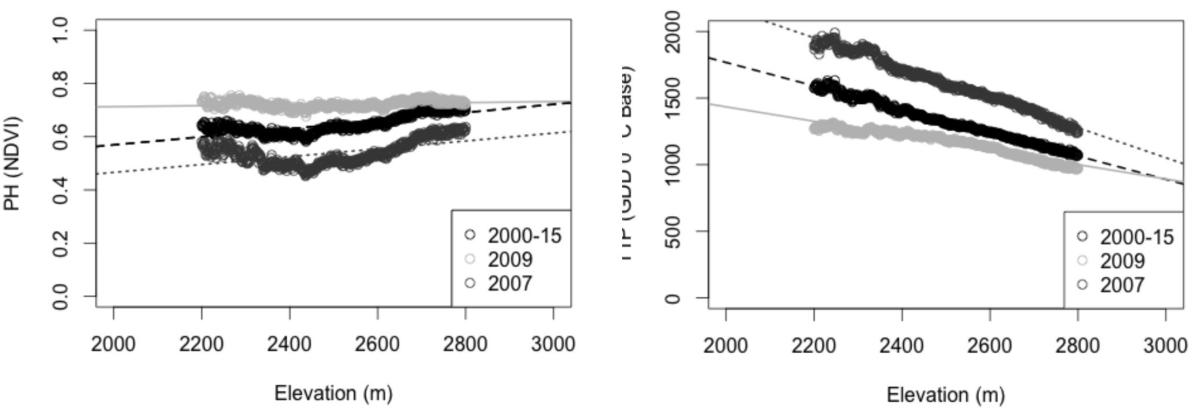

Figure 3. Elevational patterns of PHNDVI (top) and TTP (bottom) in pastures of At-Bashi rayon for 16-year mean (black), the cooler year of 2009 (light gray), and the warmer year of 2007 (medium gray).

for each scene using an Interactive Data Language (IDL) procedure. We screened NDVI < 0.2 to exclude non-vegetated observations. Ultimately we compiled 16-year time series (2000-2015) of the georeferenced and filtered NDVI Landsat 5-7-8 scenes covering the At-Bashi rayon in Naryn oblast. The At-Bashi highland pasture region was selected in part due to the fact that it lies in a Landsat overlap region of the four tiles, thus yielding more scenes for analysis.

Data: MODIS We downloaded the MODIS-Aqua (MYD11A2) and MODIS-Terra (MOD11A2) level-3 global Land Surface Temperature (LST) and Emissivity 8-day composites at 1000 m resolution, which are provided in sinusoidal grid format as the mean clear-sky LST during an 8-day time frame [4]. We used both "LST_Day_1km" and "LST_Night_1km", each with units in Kelvin [4]. The nominal overpass time for MODIS-Terra "LST_Day_1km" is 1030 local solar time and MODIS-Aqua is 1330 local solar time; the overpass time for MODIS-Terra "LST_Night_1km" is 2230 local solar time and MODIS-Aqua is 0130 local solar time [4]. We obtained all M{Y|O}D11A2 observations from 2000-2015 (46 annually; 2690 total) for MODIS tiles h23v04 and h23v05 [4]. We also downloaded the MODIS-Aqua (MYD10A2) and MODIS-Terra (MOD10A2) level-3 global "Maximum Snow Extent" 8-day composite products at 500 meter resolution [5].

Data: Land Use and Terrain We downloaded (http://gdex.cr.usgs.gov/gdex/) the 2000 NASA Shuttle Radar Topography Mission Global (V003) 1 arc-sec digital elevation model (DEM) for the study region [6]. We also used a 2009 land use map produced by the Central Asian Countries Initiative for Land Management (CACILM) program [7]. We resampled both the DEM and land use data to 30 m using the nearest neighbor function in the Environment for Visualizing Images (ENVI) software to match the resolution of the Landsat data.

Methods: LST to AGDD Process We converted the MODIS LST data into growing degree-days (GDD), a biometeorological index of time, sometimes referred to as thermal time. GDD weights each day by the daily temperature above a specified threshold:

$$\text{GDD} = max\left\{\left[\frac{(T_{max} + T_{\min})}{2}\right] - T_{base}, 0\right\} \qquad (1)$$

where Tmax is the daily maximum, Tmin is the daily minimum, and Tbase is the base temperature or threshold, which here is set at 0 °C for all calculations of thermal time. We developed an algorithm to filter and convert MODIS LST into GDD (Fig. 1). We used the MODIS maximum snow extent product to exclude snow-covered MODIS LST observations. We resampled the 500 m resolution MODIS maximum snow extent data to 1000 m using the nearest neighbor method in the Environment for Visualizing Images (ENVI) software to align each pixel with the corresponding MODIS LST 1000 m pixel. MODIS LST observations were additionally filtered to exclude observations below freezing (<273.15 K) or unreasonably high (>330 K). Next we converted the two daytime and two nighttime LST observations from Kelvin to degrees Celsius. The algorithm also calculated the mean daytime and nighttime LST for each 8-day compositing period (DOY) using the 16 observations (2000-2015) available for each DOY. The mean LST by DOY was only calculated when 10 or more years have available data. The 16-year mean daytime and nighttime LST values were later used to fill data gaps where annual observations for a particular DOY have missing values. The script calculated GDD as the maximum of either 0 or the mean of the mean daytime (T1030 and T1330) and mean nighttime (T2230 and T0130) LST values:

$$\text{GDD} = max\left\{\left[\frac{(\text{mean}(\text{LST}_{1030}+ \text{LST}_{1330})+ \text{mean}(\text{LST}_{2230}+\text{LST}_{0130}))}{2}\right] - T_{base}, 0\right\} \qquad (2)$$

The next step created annual time series of GDD multiplied by 8 to account for the 8-day compositing period of the MODIS products and accumulates each observation (GDD in °C) by year. The final product was a 16-year time series of accumulated growing degree-days (AGDD).

Methods: CxQ LSP Model We used a convex quadratic (CxQ) model that has been used successfully in the past to analyze LSP dynamics in temperate regions [1-2, 8-9,10]. The CxQ LSP model links a vegetation index, here the NDVI, with thermal time, here AGDD:

$$\text{NDVI} = \alpha + \beta\text{AGDD} - \gamma\text{AGDD}^2 \qquad (3)$$

Table 1.

TTP gradients for At-Bashi pastures 2200-2800 masl. All regression models were significant at $p<0.0001$.

year	**intercept**	**slope**	**r^2**		**year**	**intercept**	**slope**	**r^2**
2000	2891	-0.62	0.94		2008	4037	-1.06	0.92
2001	3644	-0.95	0.99		2009	2519	-0.54	0.94
2002	3171	-0.81	0.82		2010	3267	-0.83	0.98
2003	4030	-1.04	0.98		2011	2972	-0.62	0.94
2004	3456	-0.87	0.97		2012	3651	-0.95	0.94
2005	3805	-1.02	0.98		2013	3924	-1.08	0.92
2006	3528	-0.84	0.98		2014	3834	-0.96	0.91
2007	4426	-1.12	0.99		2015	3199	-0.72	0.98
					mean	**3522**	**-0.88**	**0.99**

Where α, β, and γ are are are the fitted parameter coefficients for a particular time series. For our study, NDVI contains all NDVI values (unitless; -1 to 1) annually and AGDD (°C) contains all AGDD values for the corresponding year. The CxQ LSP model requires estimation by linear regression of only three parameter coefficients that have ecological interpretations [2]. For each annual pixel time series exhibiting an adequate coefficient of determination ($r^2 \geq 0.4$), two phenometrics were calculated from the fitted parameter coefficients:

$$\text{Peak Height in NDVI } (PH_{NDVI}) = \alpha - \beta^2/4\gamma \quad (4)$$

$$\text{Thermal Time to Peak NDVI (TTP)} = -\beta/2\gamma \quad (5)$$

where PH_{NDVI} is the peak of the fitted curve and TTP is the amount of AGDD required to reach the PH_{NDVI}.

Methods: Regression Analysis Our study area (Fig. 2) contained 14,723,920 pixels at 30 m resolution. Due to the high volume of observations, we limited our analysis to a subset of pixels. Here we used the 2009 CACILM Land Use Map to restrict our analysis to "pasturelands", the DEM to focus on pixels between 2200-2800 masl in elevation, and we only selected pixels exhibiting ($r^2 \geq 0.4$) for all 16 of the years during our study time period. These three criteria left 316,878 pixels (~28,500 ha) for analysis. To evaluate the influence of elevation on pasture phenometrics, we regressed PH_{NDVI} and TTP separately as a function of elevation using 1m increments.

Results

Figure 2 shows the PH_{NDVI} (top) and the TTP (bottom) for the entire study area. Note the location of the villages in the river valley, the progression of NDVI up the northwestern aspect slope of the At-Bashi Ridge, and the smooth gradient of TTP along the same slope. These gradients are more evident when viewing the phenometrics as a function of elevation. Figure 3 displays PH_{NDVI} (top) and TTP (bottom) for three time slices: 16-year mean; 2009 (cooler); and 2007 (warmer).

Note that there is little elevational difference in the high level of PH_{NDVI} evident in the cooler, wetter year of 2009. In contrast, the 2000-2015 average series shows a lower overall expected PH_{NDVI}, a decrease around 2400 masl, and an increasing trend >2500 masl. In the warmer, drier year of 2007, not only is the overall level lower than average, but there is also a marked decrease in PH_{NDVI} over a larger elevational range. The topographic gradient of TTP is striking: decreasing TTP with increasing elevation, with strong linearity above 2400 masl. The slope of the 16-year average is -0.88 indicating that for every 100 m increase in elevation there is a decrease of 88 degree-days in the thermal time to peak NDVI. Moreover, the slope of the TTP elevational gradient varies substantially by year. Table 1 shows a 20% coefficient of variation in slopes with the warm year of 2007 having the steepest negative slope (-1.12), the 16-year average having a less steep negative slope (-0.88) and the cool year of 2009 has the shallowest negative slope (-0.54). Note that the highest (lowest) PH_{NDVI} level co-occurs with the least (most) positive PH_{NDVI} and the least (most) negative TTP slope.

Discussion and Conclusion

Variation in the elevational gradients of the phenometrics indicates substantial sensitivity of the LSP to interannual climatic variability. Moreover, the changes in the shape of the PHNDVI gradient in 2007 into a "depressed" zone with a minimum around 2500 masl suggests the influence of heavier grazing in pastures nearer to villages. This interpretation requires confirmation through field studies and additional remote sensing analyses; however, the initial results are promising. Future steps include temporal trend analysis, modeling of snow cover seasonality, additional analyses with stratification by improved land use and land cover classes, slope and aspect in addition to elevation.

This brief case study shows the potential to link land surface phenologies derived from remotely sensed image time series with elevation in an effort to evaluation the conditions of highland pastures.

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