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# Change and Persistence in Land Surface Phenologies of the Don and Dnieper River Basins

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# Change and persistence in land surface phenologies of the Don and Dnieper river basins

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**Abstract**
The formal collapse of the Soviet Union at the end of 1991 produced major socio-economic and institutional dislocations across the agricultural sector. The picture of broad scale patterns produced by these transformations continues to be discovered. We examine here the patterns of land surface phenology (LSP) within two key river basins—Don and Dnieper—using AVHRR (Advanced Very High Resolution Radiometer) data from 1982 to 2000 and MODIS (Moderate Resolution Imaging Spectroradiometer) data from 2001 to 2007. We report on the temporal persistence and change of LSPs as summarized by seasonal integration of NDVI (normalized difference vegetation index) time series using accumulated growing degree-days (GDDI NDVI). Three land cover super-classes—forest lands, agricultural lands, and shrub lands—constitute 96% of the land area within the basins. All three in both basins exhibit unidirectional increases in AVHRR GDDI NDVI between the Soviet and post-Soviet epochs. During the MODIS era (2001–2007), different socio-economic trajectories in Ukraine and Russia appear to have led to divergences in the LSPs of the agricultural lands in the two basins. Interannual variation in the shrub lands of the Don river basin has increased since 2000. This is due in part to the better signal-to-noise ratio of the MODIS sensor, but may also be due to a regional drought affecting the Don basin more than the Dnieper basin.

**Keywords:** PAL, GIMMS, AVHRR, MODIS, Ukraine, Russia, land cover change, Soviet, post-Soviet

## 1. Introduction

Land surface phenology (LSP) studies various observable phenomena on the terrestrial surface relevant to cycles in vegetation growth and development (de Beurs and Henebry 2004a). LSP uses image time series of remotely sensed land surface properties to characterize dynamics of vegetation cover, such as the normalized difference vegetation index (NDVI), leaf area index (LAI), fraction of absorbed photosynthetically active radiation (FPAR). Satellite imagery can provide synoptic views spanning large areas difficult to access on the ground (de Beurs and Henebry 2005a).

Persistence of seasonal characteristics of land surface properties is a product of the interaction of surface composition, land use, and climatic factors. Quantifying this persistence using LSPs provides the basis for an integrated assessment of simultaneous climate and land cover/land use change. Weather variability is strongly a function of the regional climate as modulated by local factors. Changes in LSP related to regional climate change are gradual (decades to centuries) and can be modulated by climate modes (White *et al* 2003, Zhang *et al* 2007, de Beurs and Henebry 2008a, Potter *et al* 2008). Anthropogenic impacts on LSPs occur on faster timescales (de Beurs and Henebry 2008b, de Beurs *et al* 2009). Spatially, those changes can be quite dispersed and in most cases, high resolution imagery is required to detect and quantify anthropogenic changes (White *et al* 2005, Kuemmerle *et al* 2008). However, some events can produce pervasive

 

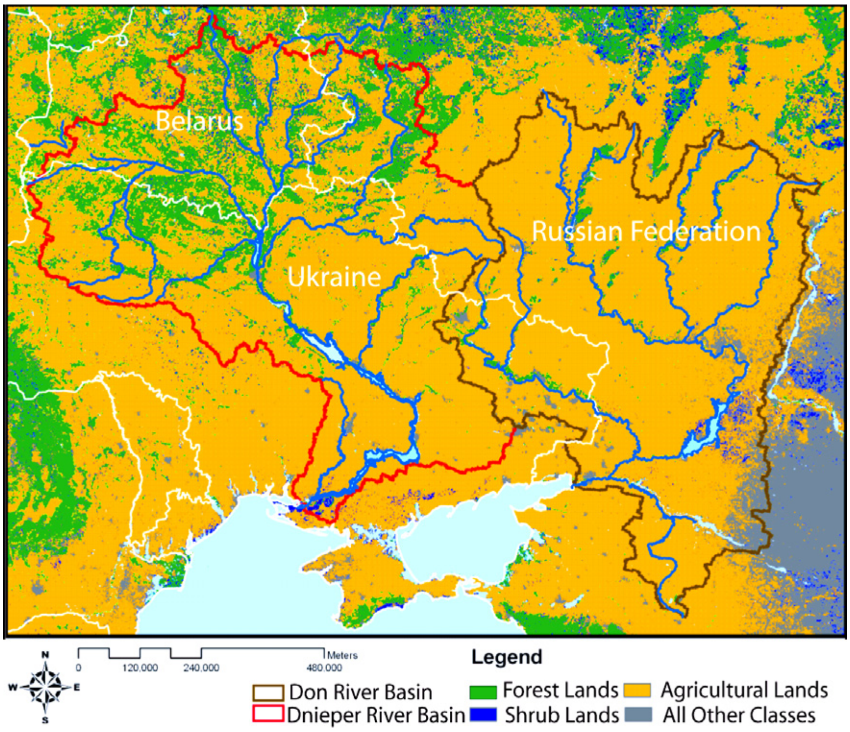


**Figure 1.** Study areas of the Dnieper and Don river basins. Red outlines the Dnieper basin and brown the Don basin. White delineates national boundaries. Five land cover super-classes are displayed: forest lands, agricultural lands, shrub lands, open water, and other.

spectral changes detectable by moderate spatial resolution sensors records (de Beurs and Henebry 2004a, 2005b, 2008b). One such event occurred during the remote sensing era, presenting the opportunity for us to study the contributions of both climatic and anthropogenic change to the persistence of land surface phenologies of various land cover types.

The collapse of the Soviet Union at the end of 1991 produced major socio-economic and institutional dislocations across the agricultural sector. Without planting schedules or crop energy subsidies in the form of fertilizers, pesticides, and fuel, and without price supports and access to guaranteed markets, the agricultural sector contracted sharply during the 1990s throughout the Former Soviet Union and its client states (Lerman *et al* 2004). Myriad institutional changes brought by the collapse of the Soviet Union induced changes in the distribution and extent of land cover types, land use intensity (Hölzel *et al* 2002, de Beurs and Henebry 2004a), enforcement of water pollution regulations (Kimstach *et al* 1998, Zhulidov *et al* 2000), availability and choice of consumer products in urban areas (Money and Colton 2000), the economic productivity in the industrial and agricultural sectors (Lerman *et al* 2003, Ahrend 2004, Ostapchuk 2005), and changes in regional biogeochemical cycles (Smith *et al* 2007, Kurganova *et al* 2008, Vuichard *et al* 2008, Henebry 2009). This transformation also manifested as significant changes in land surface phenologies observed through spaceborne sensors, as has been described for Kazakhstan (de Beurs and Henebry 2004a, 2005a).

Differences in land management practices and institutions affecting land management can result in heterogeneous spatial patterns including abrupt transitions at national borders (Kuemmerle *et al* 2008). We explore here the change, variability, and persistence of land surface phenologies in the industrial and agricultural heartland of the former Soviet Union during the socio-economic transition from socialism. The Don river basin, mostly in Russia, and the Dnieper river basin, mostly in Ukraine, were similar in several respects before the collapse. We hypothesize that observed trends in LSPs following the collapse arise primarily from institutional changes and secondarily from climatic variability and, further, that the land surface dynamics in the basins diverged after the collapse, particularly in the agricultural lands.

## 2. Study area

We focus on the basins of two major eastern European rivers: the Don and the Dnieper. These basins are the most populated and industrialized regions of the former Soviet Union. Both the Dnieper and Don rivers belong to the Black Sea drainage basin and have comparable characteristics. Both rivers start in the central part of European Russia and pick up their tributary waters on their way to the Black Sea through the steppes of southeastern Europe. Their watersheds are adjacent to each other and lie on the territories of Ukraine, the Russian Federation, and Belarus (figure 1).

Originating south of Moscow, the Don river flows for nearly 2000 km south through the Central Russian Upland and discharges into the Gulf of Taganrog at the northern end of the Sea of Azov. The Don river basin covers more than 45 000 000 ha of which roughly 83% is used for agricultural purposes (Revenga *et al* 2003). Average population density within the Don river basin is 47 persons km$^{-1}$ with seven cities having more than 100 000 inhabitants (Revenga *et al* 2003).

**Table 1.** Areal extent of analyzed super-classes.

| Land cover super-class | Don basin ($km^2$) | Don basin (%) | Dnieper basin ($km^2$) | Dnieper basin (%) | Total across basins ($km^2$) | Total across basins (%) |
|---|---|---|---|---|---|---|
| Agricultural lands | 379 579 | 90.01 | 376 873 | 77.09 | 756 452 | 83.07 |
| Forest lands | 9 340 | 2.21 | 87 893 | 17.98 | 97 233 | 10.68 |
| Shrub lands | 4 540 | 1.08 | 15 984 | 3.27 | 20 524 | 2.25 |
| All other | 28 260 | 6.70 | 8 153 | 1.66 | 36 413 | 4.00 |
| Total within basins | 421 719 | 100.00 | 488 903 | 100.00 | 910 622 | 100.00 |

The Dnieper stretches from Russia through Belarus and Ukraine before flowing into the northern Black Sea at Kherson. The Dnieper river basin covers more than 53 000 000 ha, of which roughly 87% is used for agricultural purposes. Average population density within the Dnieper river basin is 64 persons $km^{-1}$ with 16 cities having more than 100 000 inhabitants (Revenga *et al* 2003).

In the middle of last century the Don and Dnieper underwent major changes in their water regimes as the rivers were harnessed for hydroelectric power production. As a result, five very large surface water reservoirs were built within the basins. They cover at total of 862 000 ha or 17% of the impounded surface area in the Former Soviet Union. Consequently, a large portion of cropland relied on water from these reservoirs for irrigation. Collapse of the Soviet Union resulted in the loss of financing for maintenance of irrigation infrastructure, resulting in sharp decreases in water consumption for agriculture (Ostapchuk 2005, Zhovtonog *et al* 2005, Wegren 2008).

## 3. Data sources and methods

We used two NDVI datasets based on NOAA Advanced Very High Resolution Radiometer (AVHRR) data. The two datasets have undergone different atmospheric correction procedures. They share the same principle of retaining only the maximum NDVI value within the compositing period, but their compositing periods are not the same. The PAL (pathfinder AVHRR land) uses 10 day composites in contrast to the 15 day period for GIMMS. Both datasets have a nominal spatial resolution of 8 km. The AVHRR datasets cover 1982–2000. For 2001–2007 we used products from the NASA MODIS sensors, specifically the Nadir BRDF-adjusted reflectance (NBAR) product (MOD43B4). We chose the Climate Modeling Grid resolution of 0.05° and resampled the data to 8 km to match the spatial resolution of the AVHRR data. The most recent version (Collection 5) comes as an 8 day composite. We used this 8 day composite to contrast with the PAL data but resampled to a 16 day composite to contrast with the GIMMS data.

For land cover information, we used the IGBP classification in the MOD12Q1 land Cover Product. To match the spatial resolution in the PAL and GIMMS data, we resampled the land cover to 8 km using a majority filter (figure 1). Original IGBP scheme of 17 land cover classes were aggregated to eight 'super-classes': water, forest lands, shrub lands, grasslands, wetlands, agricultural lands, urban and built-up, and not vegetated. We restricted our analyses to three super-classes—agricultural lands, forest lands, and shrub lands—as they constitute most of the area in each basin (table 1).

As MODIS land cover products are available only starting in 2001, we decided to use this year as the baseline. The IGBP scheme was selected as it is widely used in the climate community and provides more categories than the other schemes available in the product. We are interested in the dynamics of NDVI rather than change in land cover categories *per se*. Thus, by fixing land cover boundaries, we can assess whether changes in LSPs dynamics occurred following the collapse of the Soviet Union and the recovery.

To attenuate interannual variability in LSPs, we calculated accumulated growing degree-days (AGDD) using a base temperature of 0 °C (273.15 K). We chose 0 °C as the base temperature because it has been used successfully to track phenologies in prairie (Goodin and Henebry 1997), steppe (de Beurs and Henebry 2004a), and boreal and arctic environments (de Beurs and Henebry 2005b, 2008a). Using a common base across a variety of land covers/vegetation types is appropriate because AGDDs calculated using different bases are very highly correlated during the height of the growing season. Tracking LSPs by AGDD, instead of by the day of year, offers the advantage of aligning vegetation growth and development by thermal regime, which is a good surrogate of daylength and insolation at the surface.

To provide consistent coverage across the two basins, we used near surface air temperature data from the NCEP Reanalysis 2 (R2) (Kanamitsu *et al* 2002), which provide daily maximum and minimum temperatures on a grid roughly 2° × 2°. R2 aimed to fix known errors in the first NCEP Reanalysis (Kalnay *et al* 1996) and to incorporate updated physical parameterizations. Accumulated growing degree-days (AGDD base 0 °C) were calculated for the compositing periods of each NDVI dataset (10 days for PAL; 15 days for GIMMS; 8 and 16 days for MODIS) and basin separately using the R2 data as follows:

$$\mathrm{AGDD}_t = \mathrm{AGDD}_{t-1} + \mathrm{maximum}(0, \{\mathrm{MaxTemp}_t - \mathrm{MinTemp}_t\}/2 - \mathrm{BT}) \qquad (1)$$

where $t$ is the temporal index, MaxTemp is maximum daily temperature, MinTemp is minimum daily temperature, and BT is a base temperature of 273.15 K (=0 °C). We integrated the NDVI time series by growing degree-day using trapezoidal integration:

$$\mathrm{GDDINDVI}_t = \sum_t \left( \frac{\mathrm{NDVI}_t + \mathrm{NDVI}_{t-1}}{2} \times (\mathrm{AGDD}_t - \mathrm{AGDD}_{t-1}) \right). \qquad (2)$$

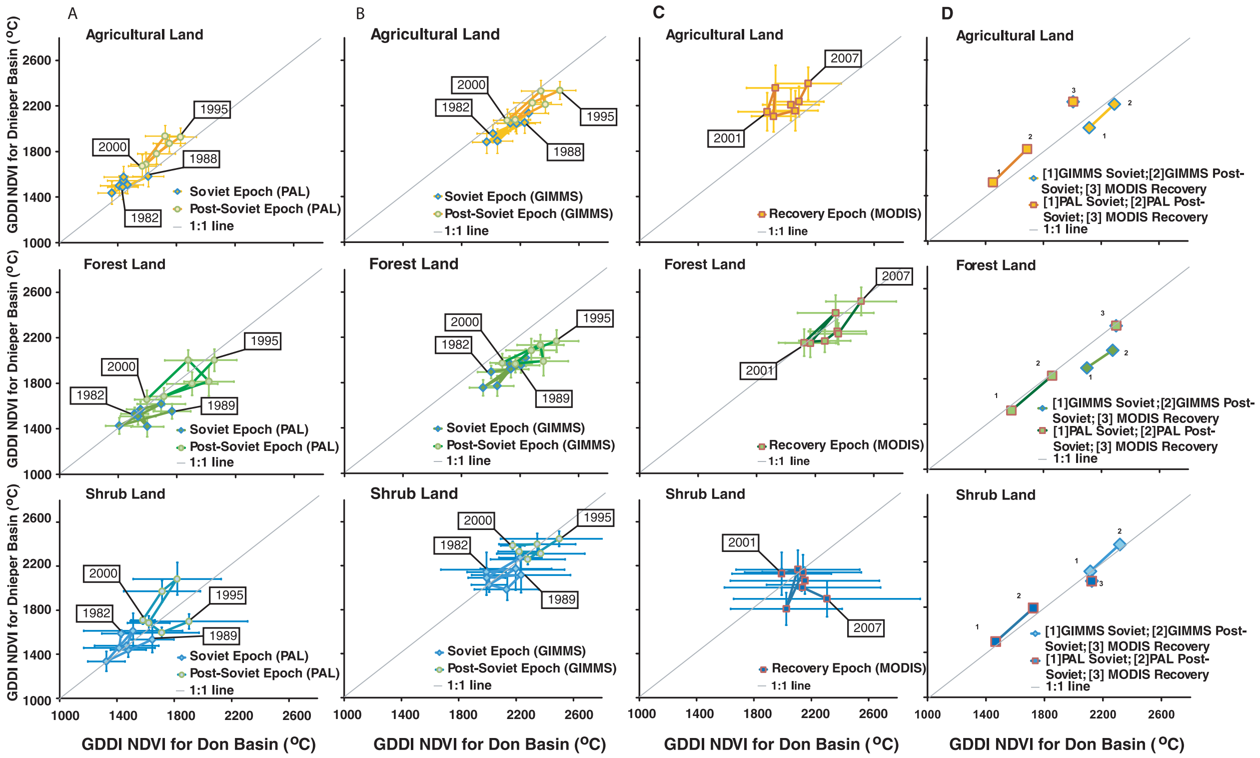


**Figure 2.** Change and variation in growing degree-day integrated NDVI for super-classes, where super-class medians are bounded by interquartile ranges. Column A displays AVHRR PAL 10 d composites. Column B displays AVHRR GIMMS 15 d composites. Column C displays the MODIS 8 d composites. Column D displays the means for each epoch.

To facilitate integration, the AGDD time series were resampled to match the spatial resolution of the NDVI data using linear interpolation. The growing degree-day integrated (GDDI) NDVI trajectories were calculated on a pixel-wise basis for each year for each basin for each of three super-classes (agricultural lands, forest lands, and shrub lands). To characterize the distribution of GDDI NDVI trajectories within areas of interest, we calculated two measures of central tendency (mean and median), and two measures of dispersion (standard deviation and interquartile range).

We divided the study period into three epochs that highlight different socio-economic environments while avoiding known problems with the sensors (Rao and Chen 1999, de Beurs and Henebry 2004b): Soviet (1982–1988), post-Soviet (1995–2000), and Recovery (2001–2007). The first two epochs are covered by the AVHRR datasets and the third is MODIS. Due to sensor and dataset artifacts (de Beurs and Henebry 2004b), the PAL data from NOAA-11 (1989–1994) were excluded from the analysis.

## 4. Results

High interannual variability is apparent in the GDDI NDVI trajectories within each super-class in each basin (figure 2). Although the GDDI NDVI distributions do not explicitly quantify the spatial heterogeneities across each basin, they are implicit in the dispersion around the central tendency, namely, the interquartile ranges that bracket the medians in figures 2(A) and (B). The three super-classes consistently exhibit a higher interannual variability within the Don basin during each three epochs. The interannual variabilities of GDDI NDVI in forest lands are lower than in agricultural lands (with exception of Dnieper forests in the GIMMS data). Both GIMMS and PAL show that the shrub lands increased in heterogeneity in Don basin during the post-Soviet epoch. shrub lands in the Dnieper basin were also variable between years.

In PAL, the GDDI NDVI values of agricultural lands in Dnieper basin were higher than those of Don basin (above the 1:1 line in figure 2(A)); however, GIMMS show opposite results (figure 2(B)). Forest lands in PAL and GIMMS vary in parallel; however, the PAL values straddle the 1:1 line while those of GIMMS fall those below 1:1 line, indicating that the Don basin has higher values (figures 2(A) and (B)). In general, the GIMMS data showed lower interannual variability than the results from PAL (figure 2(A)) or MODIS (figure 2(C)).

Values of GDDI NDVI derived from PAL were considerably lower across super-classes and basins (figure 2(D)). Median values from GIMMS and MODIS were similar. There were no apparent differences between the MODIS 8 day and 16 day composites, leading to the apparent superposition of the two MODIS composites for each super-class in figure 2(D). However, the interquartile ranges of MODIS derived outcomes were considerably higher than those of either PAL or GIMMS. There was a shift toward higher GDDI NDVI during the post-Soviet period in results from both GIMMS and PAL for every super-class (figure 2(D)).

## 5. Concluding discussion

The analysis reveals a temporal shift in GDDI NDVI between epochs that is consistent in direction, if not magnitude, between the two AVHRR datasets. Averaged values of post-Soviet epoch were higher for all super-classes across databases; however, GIMMS exhibits smaller shifts than PAL (figure 2(D)). The shifts were consistent for both river basins and may reflect climatic forcing or socio-economic repercussions or both.

A direct comparison between AVHRR and MODIS values at particular locations is not appropriate due to differences in spectral band widths and band centers and in spatial resolutions; moreover, even direct temporal comparisons within the AVHRR data record are complicated by sensor differences and imperfect cross-calibration (de Beurs and Henebry 2004b). Inclusion of MODIS data, however, is valuable: it illustrates how the improved signal-to-noise ratio of MODIS over AVHRR translates into higher variability in each super-class due to higher sensitivity to spatial heterogeneity.

The persistent and increasing departures above the 1:1 line for the agricultural land super-class in the PAL and MODIS data (figures 2(A) and (C), top) suggest increasing differences between the Don and Dnieper basins due to a diversity land management practices, laws and policies that arose following the establishment of independent states in 1991 (Lerman *et al* 2004, Zhovtonog *et al* 2005, Wegren 2008). Were the deviations due to drought alone, then the interannual trajectory would be expected to return to the neighborhood of the 1:1 line. In contrast to both the PAL and MODIS data, the GIMMS data show little tendency to venture above the 1:1 line (figures 2(B) and (C), top) and, indeed, the Soviet and post-Soviet epoch means fall below that line (figure 2(D) top).

This discrepancy between AVHRR datasets also appears in the forest land super-class. While the forest lands in the PAL and MODIS data show little tendency to deviate persistently from the 1:1 line (figures 2(A) and (C), middle), the GIMMS data fall well below the 1:1 line (figures 2(B) and (D), middle). There is agreement between PAL and GIMMS, however, of an increase in GDDI NDVI between the Soviet and post-Soviet epochs.

The shrub land super-class tells a similar story, except the very high spatial variability within the Don basin and the relatively rarity of this super-class in either basin complicates ready interpretation. In the Dnieper basin the shrub lands are concentrated around the mouth of the river; whereas, the shrub lands are scattered across the interior of the Don basin. The variability in GDDI NDVI values arises in part from this spatial dispersion and from differences in habitat—wetlands in the Dnieper basin versus steppe in the Don basin.

Although we can interpret the temporal pattern of deviations from the 1:1 line, causal attribution remains beyond the scope of the remote sensing data. Observed changes in agricultural lands do coincide, however, with major agricultural reforms in Ukraine (Zhovtonog *et al* 2005, Borodina and Borodina 2007) and with widespread cropland abandonment in the central part of Russia, e.g., Don basin (Ioffe *et al* 2004, 2006, Wegren 2008, Henebry 2009, Shvidenko 2009). Sharp decreases in irrigation and fertilizer use in Ukraine, primarily in the Dnieper basin, are also a contributing factor (Ostapchuk 2005, Shvidenko 2009). Further investigation is needed to understand how LSPs respond to land use and land management changes because multiple responses are possible (de Beurs and Henebry 2004a).

Forests of the region were largely influenced by institutional changes and other anthropogenic factors (Shvidenko and Nilson 2003, Shvidenko 2009). Withdrawal of human activity from zone around Chernobyl led to forest regrowth in the Polissa region of Dnieper basin (Lyalko *et al* 2009). Both GIMMS and PAL results show gradual increases in GDDI NDVI for both basins; however, GIMMS data exhibit less variability and yield greater GDDI NDVI values in Don basin than in the Dnieper. Potential influences on the divergence between basins including loss of wind-rows in Russia (Shvidenko 2009) and increasing frequency of forest fires in Ukraine (Shvidenko and Nilson 2003, Ostapchuk 2005).

A changing climate does contribute to the observed LSP changes. Both model simulations and station observations reveal a warming trend across Ukraine in the last quarter of the 20th century (Klein Tank *et al* 2005). Robock *et al* (2005) found divergence between model reanalysis projections of summer desiccation of soil moisture and observed trends in long term soil moisture records during the last half of the 20th century. Li *et al* (2007) found a comparable discrepancy between the observational records of soil moisture in Ukraine and southern European Russia compared to ensemble simulation of IPCC Fourth Assessment Report (AR4) model driven by 20th century climate forcings. They argued that the observed increases in summer soil moisture could not be accounted by observed changes in temperature and precipitation. Instead, they hypothesized that reductions in insolation could have led to reductions in evapotranspiration (Li *et al* 2007).

Furthermore, Spernanskaya (2009) reports an absence of significant trends in soil moisture data in the upper 20 cm across European Russia based on analysis of 52 long term monitoring stations located in meadows or lands with winter crops. Anisimov *et al* (2007) find a relatively low rate of warming (+0.3 °C/decade based on data from 1970 to 2004) in the three federal districts of Russia that lie within Don and Dnieper basins. Each of these studies has focused on the large scale dynamics of climate neglecting the potential role of land use/land cover change in affecting observed moisture and temperature trends. Furthermore, all of these studies find smooth gradients of climatic variables across the study region. Thus, climate alone cannot explain the observed LSP trends, especially the divergent trends in agricultural lands between the basins.

Although we attempted to minimize interannual variability in LSPs through integrating by growing degree-day, substantial variation remains due, in part, to variation in the amount and timing of precipitation and other aspects of weather. Additional variation may arise from changes in land use that translate into changes in land cover. A key limitation of crisp land cover classes is the treatment of borderline cases, especially in classes with high intrinsic variability, such as shrub lands.

A final point relates to the comparison between datasets. The high signal-to-noise ratio of MODIS enables more distinct values and thus a greater possibility of expressed variation. In contrast, both AVHRR datasets exhibit reduced absolute values of GDDI NDVI, with the GIMMS dataset consistently higher than PAL. Relative changes in GDDI NDVI before and after the collapse of the Soviet Union are greater in PAL than GIMMS. An apparent reduced sensitivity of GIMMS dataset raises questions as to what impacts the myriad processing improvements of GIMMS have had on its utility to detect actual change amidst a noisy background (de Beurs and Henebry 2008a).

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