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

V Kovalskyy and G M Henebry

Geographic Information Science Center of Excellence (GIScCE), South Dakota State University, 1021 Medary Avenue, Wecota Hall 506B, Brookings, SD 57007-3510, USA

E-mail: geoffrey.henebry@sdstate.edu

Received 2 March 2009
Accepted for publication 5 October 2009
Published 21 October 2009
Online at stacks.iop.org/ERL/4/045018

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...
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 phenomenologies 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 (Kistach 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 phenomenologies 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 phenomenologies 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$^{-2}$ with seven cities having more than 100 000 inhabitants (Revenga et al 2003).
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$^{-2}$ with 16 cities having more than 100 000 inhabitants (Revinga 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 (2009) 045018 V Kovalskyy and G M Henebry).

### 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 data (pathfinder AVHRR land) uses 10 days 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 with 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 (2) (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:

\[
AGDD_t = AGDD_{t-1} + \max(\{\text{MaxTemp}_t, -\text{MinTemp}_t\})/2 - \text{BT}
\]

where \(i\) 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:

\[
GDD_{\text{INDVI}} = \sum_t \frac{\text{NDVI}_t + \text{NDVI}_{t-1}}{2} \times (AGDD_t - AGDD_{t-1})
\]

### 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                 |
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 Polissia 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, Spersnanskaya (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 allows for distinct processing improvements of GIMMS to detect actual change amidst a noisy background (de Beurs and Henebry 2008a).

Acknowledgments

This research was supported in part by the NEESPI and NASA LCLUC project entitled Land cover land use change effects on surface water quality: integrated MODIS and SeaWiFS assessment of the Dnieper and Don river basins and their reservoirs to A Gitelson, University of Nebraska-Lincoln. NCEP Reanalysis 2 data provided by the NOAA/OAR/ESRL PSD, Boulder, CO, USA, from their website (http://www.cdc.noaa.gov/). We acknowledge feedback from the anonymous editor and two referees that helped to clarify the text and strengthen the argument.

References

Ahrend R 2004 Russian industrial restructuring: trends in productivity, competitiveness and comparative advantage OECD Working Paper 408 doi:10.2139/ssrn.619183

Anisimov O A, Lobanov V A and Reneva S A 2007 Analysis of climatic variation, and institutional change: analyzing and institutional change in the analysis of long image time series Int. J. Climatol. 26 1–16

Borodina E and Borodina A 2007 Transformation of agricultural sector of Ukrainian economics: some social and economic results Proc. 10th Seminar of European Association of Agricultural Economists (Budapest) (available at http://ageconsearch.umn.edu/bitstream/77871/1/sp07bo02.pdf)

de Beurs K M and Henebry G M 2004a Land surface phenology, climatic variation, and institutional change: analyzing agricultural and cover change in Kazakhstan Remote Sens. Environ. 89 497–509

de Beurs K M and Henebry G M 2004b Trend analysis of the pathfinder AVHRR land (PAL) NDVI data for the deserts of Central Asia IEEE Geosci. Remote Sens. Lett. 1 282–6

de Beurs K M and Henebry G M 2005a A statistical framework for the analysis of long image time series Int. J. Remote Sens. 26 1551–73

de Beurs K M and Henebry G M 2005b Land surface phenology and temperature variation in the IGBP high-latitude transects Glob. Change Biol. 11 779–90

de Beurs K M and Henebry G M 2008a Northern annual mod distribution of the land surface phenologies of Northern Eurasia J. Clim. 21 4257–79

de Beurs K M and Henebry G M 2008b War, drought and phenology: changes in the land surface phenology of Afghanistan since 1982 J. Land Use Sci. 3 95–111

de Beurs K M, Wright C K and Henebry G M 2009 Dual scale trend analysis for evaluating climatic and anthropogenic effects on the vegetated land surface in Russia and Kazakhstan Environ. Res. Lett. 4 045012

Goodin D G and Henebry G M 1997 Monitoring ecological disturbance in tallgrass prairie using seasonal NDVI trajectories and a discriminant function mixture model Remote Sens. Environ. 61 270–8

Henebry G M 2009 Carbon in idle croplands Nature 457 1089–90

Hölzel N, Haub C, Ingelfinger M P, Otte A and Pilipenko V N 2002 The return of the steppe large-scale restoration of degraded land in southern Russia during the post-Soviet era J. Nat. Conserv. 10 75–85

Ioffe G, Nefedova T and Zaslavsky I 2004 From spatial continuity to fragmentation: the case of Russian farming Ann. Assoc. Am. Geogr. 94 913–43

Ioffe G, Nefedova T and Zaslavsky I 2006 The End of Peasantry? The Disintegration of Rural Russia (Pittsburg, PA: University of Pittsburgh Press)

Kalnay E et al 1996 The NCEP/NCAR 40 year reanalysis project Bull. Am. Meteorol. Soc. 77 437–71

Kanamitsu M, Ebisuzaki W, Woollen J, Yang S-K, Hnilo J J, Fiorino M and Potter G L 2002 NCEP-DOE AMIP-2 reanalysis (R-2) Bull. Am. Meteorol. Soc. 83 1631–43

Kimstach V, Meybick M and Baroudy E (ed) 1998 Statistical Yearbook ‘Environment of Ukraine’ (Kyiv: State Statistics Committee of Ukraine)

Kumar P Y Groisman and S Ivanov (Berlin: Springer) pp 157–164

Lerman Z, Zaslovsky S 2001 High and low vegetation cover change contribution into greenhouse effect by remotely sensed data: case study for Ukraine Regional Aspects of Climate—Terrestrial—Hydrologic Interactions in Non-Boreal Eastern Europe ed P Y Grosmans and S Ivanov (Berlin: Springer) pp 157–164

Money B R and Colton D 2000 The response of the ‘new consumer’ to promotion in the transition economies of the former Soviet Bloc J. World Bus. 35 189–205

Ostapchuk Y M 2005 Statistical Yearbook ‘Environment of Ukraine’ for the Year 2004 (Kyiv: State Statistics Committee of Ukraine) p 260

Potter C, Boriah S, Steinbach M, Kumar V and Klooster S 2008 Terrestrial vegetation dynamics and global climate controls Clim. Dyn. 31 67–78

Rao C and Chen J 1999 Revised post-launch calibration of the visible and near-infrared channels of the Advanced Very High Resolution Radiometer (AVHRR) on the NOAA-14 spacecraft Int. J. Remote Sens. 20 3485–91

Revena C, Nackoney J, Hoshino E, Kura Y and Maidens J 2003 Water Resources eAtlas World Resources Institute (available at http://multimedia.wri.org/watersheds_2003/ceu7.html)
Robock A, Mu M, Vinnikov K, Trofimova I V and Adamenko T I 2005 Forty-five years of observed soil moisture in the Ukraine: no summer desiccation (yet) Geophys. Res. Lett. 32 L03401
Shvidenko A 2009 Non-boreal forests of eastern Europe in a changing world: the role in the earth system Regional Aspects of Climate–Terrestrial–Hydrologic Interactions in Non-Boreal Eastern Europe ed P Y Groisman and S Ivanov (Berlin: Springer) pp 123–33
Shvidenko A and Nilson S 2003 A synthesis of the impact of Russian forests on the global carbon budget for 1961–1998 Tellus B 55 391–415
Smith P et al 2007 Changes in mineral soil organic carbon stocks in the croplands of European Russia and the Ukraine, 1990–2070; comparison of three models and implications for climate mitigation Reg. Environ. Change 7 105–19
Speranskaya N 2009 Soil moisture changes in non–boreal European Russia Regional Aspects of Climate–Terrestrial–Hydrologic Interactions in Non-Boreal Eastern Europe ed P Y Groisman and S Ivanov (Berlin: Springer) pp 165–74
Vuichard N, Ciais P, Belelli L, Smith P and Valentini R 2008 Carbon sequestration due to the abandonment of agriculture in the former USSR since 1990 Glob. Biogeochem. Cycles 22 GB4018
Wegren S K 2008 Land reform in Russia: what went wrong? Post-Sov. Aff. 24 121–48
White M A, Brunsell N and Schwartz M D 2003 Vegetation phenology in global change studies Phenology: An Integrative Environmental Science ed M D Schwartz (Dordrecht: Kluwer) p 592
White M A, Hoffman F, Hargrove W W and Nemani R R 2005 A global framework for monitoring phenological responses to climate change Geophys. Res. Lett. 32 L04705
Zhang K, Kimball J S, McDonald K C, Cassano J J and Running S W 2007 Impacts of large-scale oscillations on pan-Arctic terrestrial net primary production Geophys. Res. Lett. 34 L21403
Zhovtonog O, Dirksen W and Roest K 2005 Comparative assessment of irrigation reforms in Eastern European countries under transition ICID 21st European Regional Conf. 2005 (available at http://www.zalf.de/icid/ICID_ERC2005/HTML/ERC2005PDF/Topic_3/Zhovtonog.pdf)
Zhulidov A Z, Khlobystov V V, Robarts R D and Pavlov D P 2000 Critical analysis of water quality monitoring in the Russian Federation and former Soviet Union Can. J. Fish. Aquat. Sci. 57 1932–9