Landscape Ecol (2009) 24:465–472
DOI 10.1007/s10980-009-9328-x

REPORT

Landscape phenology: an integrative approach to seasonal vegetation dynamics

Liang Liang · Mark D. Schwartz

Received: 28 October 2008 / Accepted: 24 January 2009 / Published online: 10 February 2009

Abstract This brief report addresses the theory and methodology of landscape phenology (LP), along with synopsis of a case study conducted in the northern Wisconsin temperate mixed forest. LP engages questions related to ecosystem phenology, landscape genetics, and vegetation change science across multiple scales, which have rarely been addressed by existing studies. Intensive in situ observations, remote sensing data, and spatiotemporal analysis are employed for understanding patterns and processes within the complexity of seasonal landscape dynamics. A hierarchical upscaling approach is also introduced. Results from the case study suggest that plot-scale phenology lacks spatial autocorrelation and varies individualistically, with genetic heterogeneity overriding small microenvironmental gradients. However, at the landscape level, forest phenology responds coherently to weather fluctuations. The resultant LP index confirms the relative reliability of moderate resolution imaging spectroradiometer (MODIS)-based land surface phenology (LSP). Due to technological advancement in spatial data acquisition and analysis, LP has the ability to connect conventional plant phenology studies back to their intricate ecological context, and provides a new approach to validating coarse-scale monitoring and modeling of LSP and other seasonal ecosystem processes.

L. Liang (✉) · M. D. Schwartz
Department of Geography, University of Wisconsin-Milwaukee, P.O. Box 413, Milwaukee, WI 53211, USA
e-mail: lliang@uwm.edu

M. D. Schwartz
e-mail: mds@uwm.edu

Keywords Landscape phenology · Temperate mixed forest · Spatiotemporal analysis · Scaling · Land surface phenology

Introduction

Over the past 50 years, records and models of plant phenology (which track environment-driven plant life cycle events) reveal the profound impact of climate change on the biosphere (Cleland et al. 2007; Schwartz et al. 2006). In addition, remotely sensed land surface phenology (LSP) developed over the past 25 years has enabled inexpensive monitoring of vegetation dynamics across continents and shown similar biome-dependant responses to a warming climate (Friedl et al. 2006; de Beurs and Henebry 2005; Zhang et al. 2007). However, most currently available ground phenological data and on-going observations are restricted to phenophases recorded for individual plants at discrete locations isolated from or neglecting their biophysical environments (Schwartz 2003; Morisette et al. 2009). Therefore, it is difficult for these measurements to represent phenology of plant functional types, which bridge plant physiology and community and ecosystem processes in relation to global change (Diaz and Cabido 1997), or phenology of ecosystem functional types (conceptually related to plant functional types) which focus on the exchange of energy and matter in ecosystems (Paruelo et al. 2001). Since LSP is based on moderate resolution satellite sensors designed for global applications (operating at dramatically coarser scales than in situ phenology), bridging the spatial gap between ground and satellite measures has been a primary challenge to improving phenological modeling and monitoring ability (Zhang et al. 2003; Fisher and Mustard 2007).

Phenology examines organism-environment relationships using critical life cycle phenomena as the primary window. The need to reconnect plant phenology studies with ecological complexity (from yards/trees to the forest) was a crucial impetus for developing the theory and methodology of landscape phenology (LP). LP is an approach to seasonal vegetation dynamics that integrates phenological patterns (mainly spatial) and processes (mainly temporal) within heterogeneous biophysical environments across multiple scales. As a perspective of study, LP probes into complex ecosystem functioning related to interactions of primary producers with seasonal and interannual environmental variability across landscapes. Practically, LP also addresses the crucial need to compare in situ observed phenology with remotely sensed phenology, as well as other satellite or tower-based ecosystem seasonality measurements (from the forest to biomes) by providing upscaled plant phenology measures at the landscape level (LP index). Units used for the LP index should ideally inherit in situ phenophase measures if vegetation type is simple. However, for mixed forests, physiological differences between conifers and deciduous trees have to be accounted for in upscaling. Therefore, the LP index can yield alternate adjusted unit systems depending on applications (for instance, in order to cross-validate with LSP, units in accordance to satellite pixel reflectance-based vegetation indices are most useful). We hence report a case study that demonstrates LP in a temperate mixed forest environment. An upscaling method of deriving an applicable LP index for calibrating LSP is also introduced. Lastly, LP theoretical issues are discussed in the context of the case study.

Methods

Data collection

The study area is located in the Chequamegon National Forest (northern Wisconsin), about 1 km away from an AmeriFlux tall tower (Park Falls/WLEF, 45.946°N, 90.272°W, Fig. 1). In summer 2005, 216 trees/shrubs from representative forest species were sampled in a 625 m × 275 m area with a cyclic sampling scheme (Burrows et al. 2002). Trees were identified to species along with diameter at breast height (DBH) measurements. Plant communities and microenvironments were also empirically identified during the initial and follow-up field campaigns. Spring tree/shrub phenologies were scored with carefully defined field protocols (for both deciduous and coniferous species) every other day during the springs of 2006 and 2007. The observation protocol is designed to include five major phenophases derived from those used for weekly phenology surveys at the Morgan–Monroe forest (Indiana) AmeriFlux site (J.C. Randolph, personal correspondence) and is cross referenced to the German Biologische Bundesanstalt, Bundessortenamt and Chemical industry (BBCH) scheme (Meier 2001): 0 = nothing happens (BBCH code 100); 1 = bud visible (100% BBCH code 120); 2 = bud swollen, but not open (100% BBCH code 140); 3 = bud open, leaf visible (100% BBCH code 160); 4 = leaf out, not fully unfolded (100% BBCH code

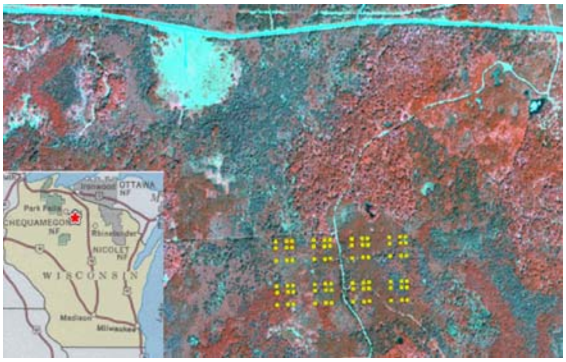

Fig. 1 Study area with 10 m radius *plots* shown in *yellow*, overlaid on a 2002 IKONOS summer image (*false color* composite). The Park Falls/WLEF AmeriFlux tower location appears in the *upper left* (*circular cyan* feature). *Inset map* shows the location of the Chequamegon National Forest in Wisconsin

180); and 5 = full leaf unfolded (95% BBCH code 199). Concurrent grass phenologies were also recorded for 21 1 m × 1 m plots at bi-daily frequency with a Kodak DX4530 visible-light digital camera during the spring of 2007. Air temperature and humidity were measured with Onset HOBO sensors continuously (10 min interval) throughout the spring seasons (14 plots for 2006, 27 plots for 2007). Other ancillary data used include Light Detection and Ranging (LiDAR) measured Digital Elevation Model (DEM) and tree heights, soil types, and high resolution multispectral images (IKONOS, 2002 and QuickBird, 2006 and 2007).

Spatiotemporal analysis

Intensive field phenological measurements provide substantial data to support analyzing phenological variations and phenology–environment interrelationships over time and space. Besides tree phenological scores for each day, dates of two critical phenological phases (beginning of leaves out, completion of leaves unfolding) and regression slopes of phenological score time series were used for analyses. The percentages of greenness were calculated for grass phenology digital photos by translating red–green–blue (RGB) color bands into hue-saturation-luminance (HSL) color space in order to separate brightness/luminance (affected by illumination conditions) from the hue, thus providing better estimation of leaf pigment alterations (Graham et al. 2009). Digital photo conversion from RGB to HSL was done with Erdas Imagine 9.2 software.

Intraspecific spatial dependence of phenology was diagnosed with Moran's I and semivariogram methods. Individual plant phenologies were compared with gradients of temperature (Kriging estimation), moisture (Kriging estimation), microtopography (LiDAR DEM), soil types, as well as biological parameters (DBH and tree heights estimated from LiDAR) using Geographic Information System (GIS) supported visual assessment and correlation analysis. Accumulated growing degree hours (AGDHs) and air water potential (derived from relative humidity and temperature, Lambers et al. 1998) were the primary microclimatic indices used. GIS and statistical analyses were performed with ArcGIS 9.2, Erdas Imagine 9.2, IDRISI Andes, and SPSS 16.0 software.

Landscape upscaling

The Hierarchical Patch Dynamics (HPD) paradigm, as elaborated by Wu (1999), demonstrates a way to simplify the complexity of nature, along with an applicable scaling ladder approach. Akin to HPD strategy, the conceptual model for building a LP index followed the nested hierarchical organization of an ecosystem. According to this model, phenological measurements taken for individual organisms need to progress through three upward scale transitions in order to be translated into an index at the landscape level: namely from Organism Individual Phenology to Population Phenology, from Population Phenology to Community Phenology and from Community Phenology to LP. The derived LP index equates phenology of an ecosystem patch, or patch of a plant functional type, and is comparable in size to medium resolution satellite LSP (pixel-based, 250 m–1 km). Here the scales are categorized with respect to ecosystem hierarchy. Therefore, phenology at each level is composed of both spatial and ecological features that are distinct from other levels.

We suggest that averaging individual phenologies of the same species found in a relatively small area with sufficient sample size (>20) provides adequate representation of the population phenology (for particulars please see the next section). Major species sampled do fulfill this empirical criteria, thus we averaged the individual phenologies of the dominant species to approximate the population phenologies. Phenologies for each community were mainly derived from population phenologies and community compositions which are determined by the presence and abundance of species. A multi-temporal linear spectral unmixing method was employed on two QuickBird images (one leaf-off and one leaf-on) using IDRISI Andes and Erdas Imagine 9.2 software to estimate the respective fractions of deciduous, coniferous and non-vegetated endmembers within each pixel (Eastman 2006; Roberts et al. 1998; Wu and Murray 2003). Endmember signatures were extracted from manually digitized training sites and reviewed with principal component analysis and a minimum noise fraction transform. Representative species that make up each community were identified from detailed field surveys. For each community, dominant

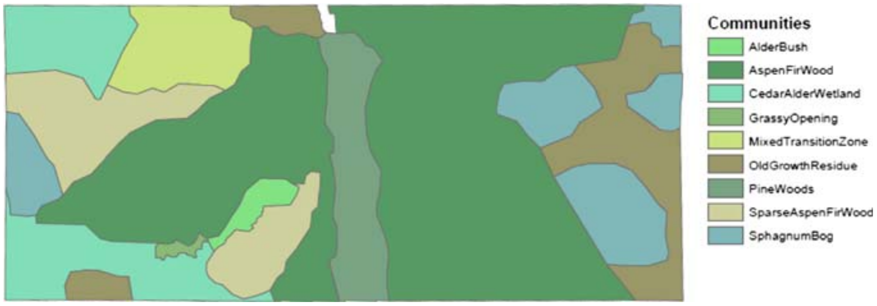

Fig. 2 Plant communities delineated according to field survey and supervised classification of a 2002 IKONOS summer image

population phenologies were selected to represent phenologies of deciduous tree/grass and coniferous trees. Given that phenologies of deciduous trees, coniferous trees, and grass have different degrees of impact on landscape greenness, specific weights (estimated from statistical modes of phenological change histograms for homogeneous covers) were assigned to calibrate the phenological differences among the three different vegetation types.

The LP Index is based on aggregation of community phenologies found within the study area. The distribution and boundaries of communities were acquired through both field survey and supervised classification of an IKONOS image (Fig. 2). Combining calibrated community phenologies and community distribution, the LP index was calculated by doing an area-weighted average of all community phenologies across the study area.

Composites of moderate resolution imaging spectroradiometer (MODIS, 16-day at 250 m resolution) normalized difference vegetation index (NDVI) and enhanced vegetation index (EVI) data (collection 5) from March to July for both 2006 and 2007 acquired from the Oak Ridge National Laboratory distributed active archive center (ORNL DAAC, http://www.daac.ornl.gov/MODIS/modis.html) were carefully extracted according to the ground study area. Start of season (SOS) dates of MODIS-based LSP were calculated using the logistic model based maximum curvature change method used for deriving National Aeronautics and Space Administration (NASA) MODIS land cover dynamic products (Zhang et al. 2001). The same algorithm was applied to the LP index time series for SOS determination. Dates of beginning of leaf out for major plant populations were also included for cross-scale comparison.

Results

Spatial patterns of landscape phenology

Phenologies of individual plants of the same species are far from uniform across space. For example, *Populus tremoloides* (trembling aspen) showed 20 (2006) and 12 (2007) day ranges of beginning leaf out dates. The same range level even exists between individuals found within the same plot. Consequently, consistent spatial autocorrelations were not detected among phenologies within each species. This spatial discontinuity invalidates an assumption of geostatistical interpolation which was accepted at the beginning of this project, so an alternative approach to population phenology estimation was required. Through sample size analysis (using *P. tremoloides* as an example, as the largest population we sampled) we decided that a sample average for each species could be used to approximate population phenology if the sample size is sufficiently large (empirically >20, when standard errors of the mean fall below the resolution of the employed phenology protocol).

Furthermore, spatial variations of plant phenology are not clearly accounted for by gradients of known microenvironmental factors (elevation, slope, aspects, soil type, air temperature, and air humidity). However, microenvironmental relationships are coherent within themselves (microclimates are predicted by microtopography and tree canopy structures).

Drawing from the dominant population phenologies, community distribution, community composition, as well as reflectance calibration factors, the LP index was calculated for each day of observation over the entire study area.

Temporal processes of landscape phenology

Although spatial heterogeneity is prevalent, interspecific differences are consistent among different species across years, each population showing unique temporal progression characteristics. Especially after leaf out, the progression speed of population phenologies respond corporately to antecedent AGDHs (especially in the prior 2 days). Further, grass phenology progression in 2007 was sensitive to air water potential confirming the impact of an observed spring drought on forest ground in the mesic environment. LP in 2006 advanced more rapidly in the beginning of spring than 2007, and afterwards was slowed by a snow/ice storm in early May (Fig. 3).

The LP index was calibrated with NDVI levels from two QuickBird images and takes a range similar to VI values (0–1) to indicate the degree of phenological progression and cross-reference to satellite measured land surface greenness change. The LP index values are systematically lower than the MODIS NDVI (Fig. 3). However, strong linear relationships between LP index and MODIS NDVI are evident with an R-squared of 0.98 for 2006 and 0.93 for 2007. In addition, LSP tracks the LP index SOS accurately for both years, and shows general agreement with population phenologies (Table 1).

Discussion

Scale issues

Scale is known to affect landscape pattern analysis over dimensions of time, space and organizational levels (Qi and Wu 1996; Wu and Li 2006). In this case study, phenologies of individual plants behave quite individualistically as they do not correlate with phenologies of nearby individuals of the same species, and even of similar size (DBH), nor do they correlate with microclimatic gradients. This likely reflects the genetic differences determining the start of leaf out. However, we are not excluding the possibility that other unmeasured microenvironmental factors (like soil temperature, etc.) may play a role in affecting phenological variations over space, as well as that more drastic environmental gradients could lead to stronger impact on spatial patterns of phenology as suggested by studies in other locations (Fisher et al. 2006). Population phenologies which

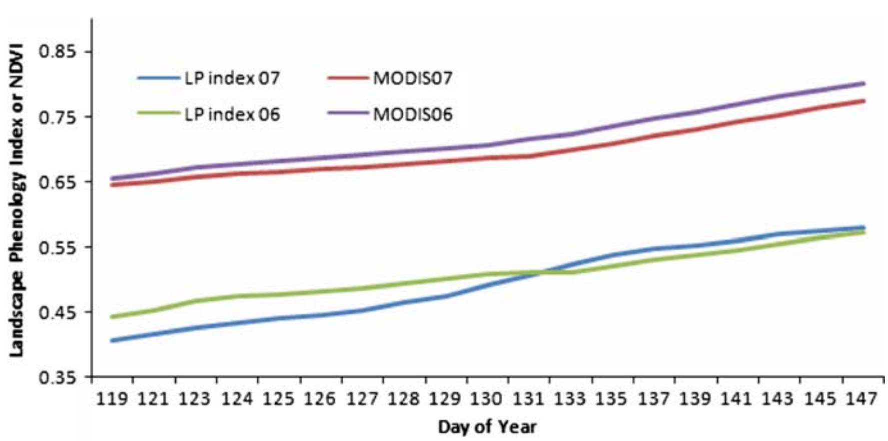

Fig. 3 Temporal progressions of landscape phenology index (*bottom two lines*) and MODIS NDVI based land surface phenology (*top two lines*, truncated from logistic model fitted curves) in 2006 and 2007

Table 1 Landscape phenology index and MODIS VI based land surface phenology start of season (SOS) dates (day-of-year values) and beginning leaf out dates for selected populations (sample size > 20) for 2006 and 2007

Year	Landscape phenology	MODIS NDVI	MODIS EVI	*Acer rubrum*	*Alnus rugosa*	*Abies balsamea*	*Populus tremoloides*
2006	124	124	124	123	123	131	119
2007	124	124	124	125	123	134	128

represent individuals found within the entire landscape do respond corporately to weather change. Based on analysis of our two-year data, it is evident that LP coherently repeats itself according to its acclimated nature at this given ecosystem patch, and with weather fluctuations as the primary source of interannual variations. This shows that at the individual plant or plot-scale, genetically determined phenological differences are more important. At the landscape scale, corporate characteristics of plant phenology (or vegetation phenology) appear to be more dominant. These scale-dependent phenological behaviors are worthy of further study.

Framework of landscape phenology

Here we offer the framework for defining and implementing LP (Fig. 4). Different from conventional phenological observation, which tracks mainly temporal process of plant individuals, LP integrates spatial patterns into the temporal processes for multiple populations and communities found within a landscape. The fundamental task for LP is to probe phenological variations and environmental impacts within complex ecosystems as they exist in three domains, namely the genetic, temporal and spatial. The genetic domain addresses the intrinsic source of intraspecific and interspecific variations of LP as determined by genotypes and phenotypes of plants. The spatial domain offers a means to address heterogeneity of LP and environmental gradients. The temporal domain in this study is illustrated with the corporate phenological progression pattern driven by weather conditions across the entire landscape.

Given the practical need to validate large scale phenological monitoring and better understand relationships between phenology and ecological functionalities (especially the seasonality of carbon cycling) LP provides a holistic metric that could address both questions. As shown by the results from the case study, the derived LP index provides considerable information for ground truthing LSP. The LP index, which integrates both forest plant phenologies and landscape heterogeneity, should be useful for gauging related remotely sensed ecosystem function measures, as well as tower-based energy and matter exchanges between the landscape and atmosphere. Further studies are needed to evaluate the practical applications of LP for ecosystem flux monitoring and modeling efforts.

Sensitivity and recommendations

Moderate resolution imaging spectroradiometer LSP captured the general trend for both years and the earliness of 2006 phenology, however, failed to detect subtle interannual variations especially the dampening effect of 2006 spring snow/ice storm (Fig. 3). This was likely due to the 16-day temporal resolution of MODIS VI products, within which the impact of above-mentioned extreme weather event was lost.

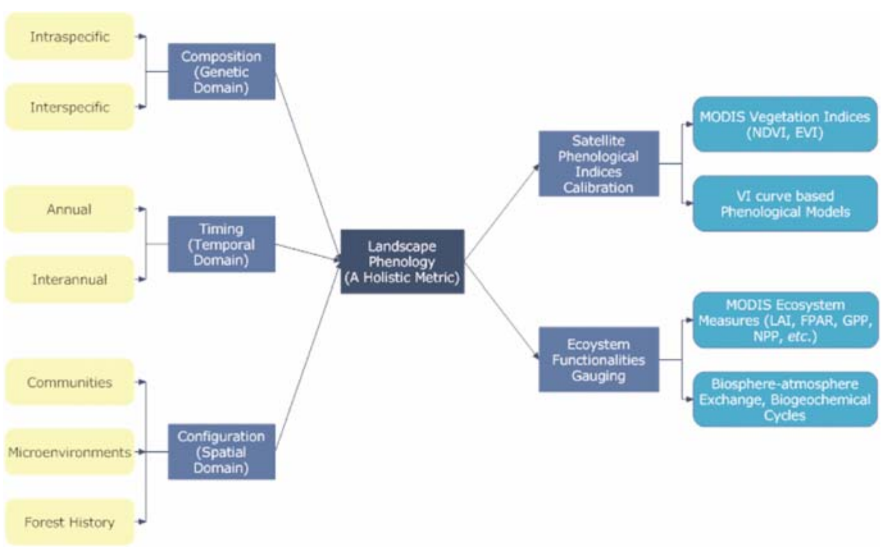

Fig. 4 Framework of landscape phenology; *left portion* shows the supporting components and approaches to establish landscape phenology as a perspective of study; *right portion* displays the practical application of landscape phenology index (as a holistic metric) to address large scale issues related to global change monitoring

The agreement between the LP index and spring onset of LSP is evident for both 2006 and 2007. However, further sensitivity analysis of the landscape phenological model employed in this study is needed. Work to be done in this regard includes testing the sensitivity of the LP index in larger areas near the current study area (by incorporating expanded ground observation transects) and extrapolating the LP index across the entire footprint area of the WLEF flux tower (in order to refine and increase the applicability of LP index within typical temperate mixed forest environments). Lastly, component LP indices (for deciduous and conifers, respectively) that retain in situ phenological meanings will be tested in follow-up studies.

The success of the initial efforts in this study suggest that implementing similar field-based studies in other typical biomes will prove useful for understanding biome-crossing LP variations and advancing global phenological/ecological monitoring validation tasks. Therefore, in addition to the "vertical" effort of upscaling, there is also a need for "horizontal" efforts to bridge inter-biome gaps with techniques such as LP.

Conclusion

Landscape phenology is a method for measuring seasonal vegetation dynamics that integrates spatial patterns and temporal processes within heterogeneous biophysical environments across multiple scales. LP expands the scope and depth of traditional phenological studies by placing plant phenology within its ecological complexity, utilizing state-of-the-art GIS tools for analysis and simulation. We define LP mainly in the context of landscape ecology and focus on the intricate relations and interactions within seasonal landscapes. Although there are still many unanswered questions related to these relationships and interactions (given the limited test offered by our case study), this project has defined LP and shown its usefulness in a practical application. Therefore, we hope this endeavor will provide another useful research tool for phenology studies as they continue to demonstrate their emergence as an integrative environmental science (Schwartz 2003).

The in situ observation-based LP index is meant to be a ground "companion" of satellite-derived LSP measures, both of which integrate signals from biophysical processes and environmental heterogeneity. Therefore, LP can facilitate global change science by providing an approach for calibrating satellite-based detection of climate change impact on ecosystem phenology through substantial groundwork and "wall-to-wall" upscaling. The upscaling approach employed in this study is successful in cross-validating with LSP. However, this approach required high density frequency field measurements as well as high resolution remote sensing imagery. Hence, follow-up work is needed to evaluate the issue of labor/data efficiency and to facilitate similar projects addressing global scale questions in different biomes and diverse environments.

Acknowledgments This project has been supported by the National Science Foundation under grants BCS-0649380 and BCS-0703360. Jonathan Hanes and Rong Yu participated in data collection and/or provided valuable support with data analyses. LiDAR data were provided by Bruce Cook and Ryan Anderson of the University of Minnesota. QuickBird images were provided by NASA. Robert Cook and Suresh-Kumar Santhana-Vannan of Oak Ridge National Laboratory provided valuable help regarding using MODIS products. Changshan Wu, Eric Graham, Jake Weltzin and Jeffrey Morisette provided constructive advice on data analyses and literature review. We thank the anonymous reviewers for their constructive comments. Finally we thank Dr. Jianguo Wu for the invitation to address Landscape Phenology in this brief report for Landscape Ecology.

References

Burrows SN, Gower ST, Clayton MK, Mackay DS, Ahl DE, Norman JM, Diak G (2002) Application of geostatistics to characterize leaf area index (LAI) from flux tower to landscape scales using a cyclic sampling design. Ecosystems (NY, Print) 5:667–679

Cleland EE, Chuine I, Menzel A, Mooney HA, Schwartz MD (2007) Shifting plant phenology in response to global change. Trends Ecol Evol 22:357–365. doi:10.1016/j.tree.2007.04.003

de Beurs KM, Henebry GM (2005) Land surface phenology and temperature variation in the international geosphere biosphere program high-latitude transects. Glob Change Biol 11:779–790. doi:10.1111/j.1365-2486.2005.00949.x

Diaz S, Cabido M (1997) Plant functional types and ecosystem function in relation to global change. J Veg Sci 8:463–474. doi:10.2307/3237198

Eastman R (2006) Idrisi Andes guide to GIS and image processing. Clark University, Worcester, 328 pp

Fisher JI, Mustard JF (2007) Cross-scalar satellite phenology from ground, landsat, and MODIS data. Remote Sens Environ 109:261–273. doi:10.1016/j.rse.2007.01.004

Fisher JI, Mustard JF, Vadeboncoeur MA (2006) Green leaf phenology at landsat resolution: scaling from the field to the satellite. Remote Sens Environ 100:265–279. doi: 10.1016/j.rse.2005.10.022

Friedl M, Henebry G, Reed B, Huete A, White M, Morisette J, Nemani R, Zhang X, Myneni R (2006) Land surface phenology. A community white paper requested by NASA, April 10. ftp://ftp.iluci.org/Land_ESDR/Phenology_Friedl_whitepaper.pdf. Viewed 20 Jan. 2009

Graham EA, Yuen EM, Robertson GF, Kaiser WJ, Hamilton MP, Rundel PW (2009) Budburst and leaf area expansion measured with a ground-based mobile camera system and simple color thresholding. Environ Exp Bot (in press). doi:10.1016/j.envexpbot.2008.09.013

Lambers H, Chapin F, Pons T (1998) Plant physiological ecology. Springer, New York

Meier U (2001) Growth stages of mono-and dicotyledonous plants, BBCH monograph. German federal biological research centre for agriculture and forestry, Berlin

Morisette JT, Richardson AD, Knapp AK, Fisher JI, Graham EA, Abatzoglou J, Wilson BE, Breshears DD, Henebry GM, Hanes JM, Liang L (2009) Tracking the rhythm of the seasons in the face of global change: phenological research in the 21st century. Front Ecol Environ 7 (in press). doi:10.1890/070217

Paruelo JM, Jobbagy EG, Sala OE (2001) Current distribution of ecosystem functional types in temperate south America. Ecosystems (NY, Print) 4:683–698. doi:10.1007/s10021-001-0037-9

Qi Y, Wu J (1996) Effects of changing spatial resolution on the results of landscape pattern analysis using spatial autocorrelation indices. Landscape Ecol 11:39–49. doi:10.1007/BF02087112

Roberts D, Gardner M, Church R, Ustin S, Scheer G, Green R (1998) Mapping chaparral in the Santa Monica Mountains using multiple endmember spectral mixture models. Remote Sens Environ 65:267–279. doi:10.1016/S0034-4257(98)00037-6

Schwartz MD (ed) (2003) Phenology: an integrative environmental science. Kluwer Academic Publishers (now Springer), Dordrecht

Schwartz MD, Ahas R, Aasa A (2006) Onset of spring starting earlier across the northern hemisphere. Glob Change Biol 12:343–351. doi:10.1111/j.1365-2486.2005.01097.x

Wu J (1999) Hierarchy and scaling: extrapolating information along a scaling ladder. Can J Rem Sens 25:367–380

Wu J, Li H (2006) Concepts of scale and scaling. In: Wu J, Jones KB, Li H, Loucks OL (eds) Scaling and uncertainty analysis in ecology: methods and applications. Springer, Dordrecht, pp 3–15

Wu C, Murray AT (2003) Estimating impervious surface distribution by spectral mixture analysis. Remote Sens Environ 84:493–505. doi:10.1016/S0034-4257(02)00136-0

Zhang X, Hodges JCF, Schaaf CB, Friedl MA, Strahler AH, Gao F (2001) Global vegetation phenology from AVHRR and MODIS data. Geoscience and Remote Sensing Symposium, 2001. IGARSS'01. IEEE 2001 International 5: 2262–2264

Zhang X, Friedl MA, Schaaf CB, Strahler AH, Hodges JCF, Gao F, Reed BC, Huete A (2003) Monitoring vegetation phenology using MODIS. Remote Sens Environ 84:471–475. doi:10.1016/S0034-4257(02)00135-9

Zhang X, Tarpley D, Sullivan JT (2007) Diverse responses of vegetation phenology to a warming climate. Geophys Res Lett 34:L19405. doi:10.1029/2007GL031447