AGU PUBLICATIONS

Geophysical Research Letters

RESEARCH LETTER

10.1002/2015GL063586

Key Points:

- LSP and GP are key indicators of climate change
- Interannual correlations exist between LSP and GP in Europe
- LSP is used to predict accurately the time of GP while controlling for species

Supporting Information:

- Texts S1–S3, Figures S1–S7, and Tables S1 and S2

Correspondence to:
V. F. Rodriguez-Galiano,
vrgaliano@gmail.com

Citation:
Rodriguez-Galiano, V. F., J. Dash, and P. M. Atkinson (2015), Intercomparison of satellite sensor land surface phenology and ground phenology in Europe, *Geophys. Res. Lett.*, *42*, 2253–2260, doi:10.1002/2015GL063586.

Received 24 FEB 2015
Accepted 10 MAR 2015
Accepted article online 12 MAR 2015
Published online 1 APR 2015

Intercomparison of satellite sensor land surface phenology and ground phenology in Europe

V. F. Rodriguez-Galiano[1], J. Dash[1], and P. M. Atkinson[1]

[1]Geography and Environment, University of Southampton, Southampton, UK

Abstract Land surface phenology (LSP) and ground phenology (GP) are both important sources of information for monitoring terrestrial ecosystem responses to climate changes. Each measures different vegetation phenological stages and has different sources of uncertainties, which make comparison in absolute terms challenging, and therefore, there has been limited attempts to evaluate the complementary nature of both measures. However, both LSP and GP are climate driven and therefore should exhibit similar interannual variation. LSP obtained from the whole time series of Medium-Resolution Imaging Spectrometer data was compared to thousands of deciduous tree ground phenology records of the Pan European Phenology network (PEP725). Correlations observed between the interannual time series of the satellite sensor estimates of phenology and PEP725 records revealed a close agreement (especially for *Betula Pendula* and *Fagus Sylvatica* species). In particular, 90% of the statistically significant correlations between LSP and GP were positive (mean $R^2 = 0.77$). A large spatiotemporal correlation was observed between the dates of the start of season (end of season) from space and leaf unfolding (autumn coloring) at the ground (pseudo R^2 of 0.70 (0.71)) through the application of nonlinear multivariate models, providing, for the first time, the ability to predict accurately the date of leaf unfolding (autumn coloring) across Europe (root-mean-square error of 5.97 days (6.75 days) over 365 days).

1. Introduction

Vegetation phenology, the study of the timing of recurring biological cycles (such as emergence of first leaf or senescence), is an emerging field of climate change science as phenological events are regarded as indicators of global warming [*Menzel et al.*, 2006; *Parmesan and Yohe*, 2003; *Wolkovich et al.*, 2012]. Spring and autumn phenological events occur at a specific time depending on the location and species and local environmental and climatic conditions of the current and preceding months. Therefore, changes in climate are expected to lead to changes in vegetation phenology [*Peñuelas and Filella*, 2001; *Sobrino et al.*, 2011]. The interannual variation in the timing of phenological events is large and has been explained by variation in cumulative temperature, especially in temperate and boreal ecosystems due to climate change, but also due to circulation patterns, solar cycles, and oscillations such as the North Atlantic Oscillation [*Badeck et al.*, 2004; *Maignan et al.*, 2008].

Vegetation phenological studies are currently carried out from two different perspectives: ground observed phenology (GP) and satellite-based phenology, commonly termed land surface phenology (LSP). More recently, vegetation phenological observations have also been obtained using continuous images from fixed digital cameras viewing across the landscape (e.g., the PhenoCam network [*Klosterman et al.*, 2014]. At the ground, the dates of plant phenophases have been observed traditionally through individual plant observations from ground stations. Numerous ground phenological studies have been conducted in Europe [*Ahas et al.*, 2002; *Defila and Clot*, 2001; *Fitter and Fitter*, 2002; *Kirbyshire and Bigg*, 2010; *Luterbacher et al.*, 2007; *Menzel*, 2000; *Menzel et al.*, 2006; *Roetzer et al.*, 2000; *Rutishauser et al.*, 2008; *Wolkovich et al.*, 2012]. These phenological studies have the advantage of long temporal coverage with many of these going back to the early 1900s. However, significant limitations exist in monitoring phenology at the ground level for individual species, mainly due to (i) the difficulty of unifying data records over plant species and phenological events; (ii) the time-consuming nature of observation, undermining the viability of using such data for vegetation change detection at global or regional scales, as here for the European continent; (iii) the difficulty of relating field data with observations of climatic variables which have a very coarse spatial resolution; and (iv) the phenological events identified being representative of individual species rather than communities [*Studer et al.*, 2007; *White et al.*, 2009]. Alternatively, LSP derived from satellite sensor observation overcomes some of these difficulties,

©2015. American Geophysical Union. All Rights Reserved.

allowing the mapping of phenology potentially at the global scale and providing an integrative view at the landscape level [*Jeganathan et al.*, 2010]. On the other hand, LSP is not exempt from uncertainty, as estimates might include signals from multiple sources, such as noise in the satellite sensor data and errors in processing methods, mixed phenological signals from multiple land covers, and human disturbances such us urbanization, political changes, and shifts in agricultural practices [*White et al.*, 2005]. Numerous studies have been published in recent years concerning the LSP of Europe (Table S1 in the supporting information). However, attempts to compare LSP and GP are scarce [*Badeck et al.*, 2004; *Hamunyela et al.*, 2013; *Maignan et al.*, 2008; *Studer et al.*, 2007; *White et al.*, 2009]. Both observation methods should be complementary, and notwithstanding the great challenges in comparing satellite sensor and ground observation, the benefits are twofold. First, GP records are necessary in some situations for supporting (or interpreting) satellite estimates, and second, LSP data are necessary in some situations to upscale GP [*Badeck et al.*, 2004; *Menzel*, 2002; *White et al.*, 2009].

In addition to the specific issues described above, there exist several uncertainties and problems when using GP records for specific vegetation species to validate satellite sensor estimates of LSP [*Hamunyela et al.*, 2013; *Maignan et al.*, 2008; *Studer et al.*, 2007; *White et al.*, 2009]: (i) insufficient observations or spatial coverage; (ii) the species monitored may or may not represent LSP (points versus pixels); that is, a single-point observation may not be representative of the overall pixel characteristics including different climate regimes in regions with significant relief; (iii) unknown measurement accuracy and errors in data entry; (iv) different phenological phenomena measured; (v) different temporal resolutions between ground observations and LSP (day versus composite period); and (vi) nonlinear relationship between GP and LSP.

The goal here is *not* to provide a validation of LSP, but rather to provide a comparison, which allows the above inconsistencies to appear in the observed differences. Since interannual variation in the timing of phenological events is explained by variation in climate, especially in temperate and boreal systems, there is a general expectation of association between LSP and GP timings across time. On the other hand, even with the limitations in comparison mentioned above, LSP should contribute significantly to explain the spatiotemporal variation in the phenology together with other biological and geographical drivers such as plant species, altitude, latitude, and longitude. Thus, the general expectation is twofold: to find similar timing patterns in both LSP and GP, which implies a positive correlation between similar phenophases, and a major contribution through the ability to predict, nonlinearly, GP from LSP.

2. Data and Methods

2.1. Data Set

Three data sources were used for this research: (i) temporal composites of Medium Resolution Imaging Spectrometer (MERIS) Terrestrial Chlorophyll Index (MTCI), (ii) GlobCover 2009 land cover map, and (iii) ground-measured plant phenology of deciduous tree species obtained from the Pan European Phenological database (PEP725).

We used composites of MERIS Terrestrial Chlorophyll Index (MTCI) data at 1 km spatial resolution from 2002 to 2012. Composite periods were equal to 8 days for the period from 2002 to 2007 and 10 days from 2008 to 2012. This data set was supplied by the European Space Agency and processed by Airbus Defence and Space. MTCI data were composited from the MERIS L2 product using an arithmetic mean and flux conservation algorithm. The arithmetic mean is less sensitive to temporal biases and produces consistent images in both the spatial and temporal domains. Details about the estimation of satellite sensor phenology and the land surface phenology maps for Europe (2003–2011) are given in Figures S1 and S2 in the supporting information.

Land cover information was acquired from the Global Land Cover Classification (GlobCover2009) data set at 300 m spatial resolution (http://due.esrin.esa.int/globcover/). Currently, the GlobCover2009 data set, derived from MERIS data, is the most detailed and recent global land cover map available with a hierarchical thematic legend consisting of 22 classes. Globcover2009 was selected for its greater consistency with MERIS MTCI time series and its high geolocational accuracy ($<$150 m) [*Bicheron et al.*, 2011].

The PEP725 ground phenology database, probably the largest record of ground phenological observations across Europe, was used in numerous studies to investigate vegetation phenological responses to climate

©2015. American Geophysical Union. All Rights Reserved.

change [*Cook et al.*, 2012; *Lapenis et al.*, 2014; *Menzel et al.*, 2006; *Scheifinger et al.*, 2002, 2003; *Wolkovich et al.*, 2012]. The PEP725 database includes thousands of phenological time series, representing multiple sites, species, and phenological phases. Primarily, these phases represent observations of leaf development and senescence. Although the value of PEP725 is unequivocal, it has some limitations for comparison with satellite-derived LSP across Europe, for example, a biased distribution of ground phenological stations toward the north-central European region (especially Germany, Switzerland, and Austria), narrow latitudinal gradient, and low species richness compared to many other natural communities and climate zones [*Cook et al.*, 2012].

2.2. Comparison Between Satellite and Ground Phenology

Comparison between the phenological measures estimated from MERIS MTCI time series (onset of greenness (OG) and end of senescence (EOS)) and the phenology observed at the ground was focused on deciduous tree species because this vegetation type was the most abundant in the observations collected by the PEP725 phenology network and because satellite-derived phenology estimates are more reliable for this land cover type as it has a distinct phenology. The comparison methodology constitutes five major procedures: (i) selection of homogeneous pixels of deciduous trees, (ii) extraction of the OG and EOS of deciduous tree pixels, (iii) extraction and filtering of the phenological information of PEP725 and (iv) regression analysis between the interannual differences in satellite and ground phenology time series, and (v) multivariate nonlinear modeling of GP (see Figure S1 in the supporting information).

To increase the reliability of the phenological information extracted for deciduous tree pixels from the satellite time series, only homogeneous pixels of GlobCover2009 deciduous forest at the spatial resolution of MERIS MTCI pixel (i.e., 1 km) were considered. To this end, pixels of the category “closed broad-leaved deciduous forest” in the GlobCover 2009 data set were analyzed. The percentage of areal coverage of deciduous vegetation type in an area approximately equal to 1 km was calculated using a block statistical function. Only pixels with 100% occurrence were included in the analysis. Two thousand seven hundred nineteen homogeneous deciduous point locations were examined visually using fine spatial resolution (60 cm) aerial imagery provided within the software ArcGIS 10.1. If the deciduous tree locations were too close to the boundary of the forest patches or the density of the deciduous trees was low, the pixels were discarded. Additionally, MTCI profiles for the complete studied period (2002–2012) at these point locations were extracted and examined intensively to eliminate points with a noisy or unreliable signal. Figure S5 in the supporting information shows the MTCI profile of the 375 reliable deciduous pixels selected for estimation of the phenological parameters OG and EOS and their comparison with ground data.

The ground-measured plant phenology information used in this study was composed of 116,469 records from 878 stations or sites covering most of central Europe for the years 2003 to 2011. As the objective was to characterize the overall relationship between LSP and GP, we selected the plant phenological events “leaf unfolding” (first visible leaf stalk (LU)) and “autumnal coloring of leaves” (50% of autumnal coloring (AC)) as the closest measures to OG and EOS, respectively. Ground phenological events were then considered for the most abundant deciduous tree species included in the PEP725 records: *Alnus Glutinosa*, *Betula Pendula*, *Fraxinus Excelsior*, *Quercus Robur*, and *Sorbus Aucuparia* for LU and *Betula Pendula*, *Fagus Sylvatyca*, and *Quercus Robur* for AC. Only GP observations with complete temporal coverage (2003–2011) were included in the analysis.

Every estimate of OG and EOS derived from the satellite sensor data for deciduous tree pixels was paired with the nearest PEP725 observation site within a radius of 25 km with no significant difference in elevation ($<$100 m). We characterized the overall relation between the multiyear land surface phenology and the corresponding ground phenology records by correlating OG and EOS estimations with the LU and AC records of every plant species of those given above and with the average of LU and AC of all the species observed in a station. The Pearson’s product-moment correlation coefficient was used to determine if a positive association existed between OG and EOS and LU and AC, respectively. As our central intent at this step was to characterize the relative relation among LSP estimates, and measured GP, formal rejection or acceptance of a null hypothesis was not critical, and thus, correlations are reported as being greater than or less than the standard 0.05 cutoff [*White et al.*, 2009].

The statistically significant associations between GP and LSP were considered in a more advance regression analysis to establish a quantitative relationship between ground- and space-observed phenology. GP was

©2015. American Geophysical Union. All Rights Reserved.

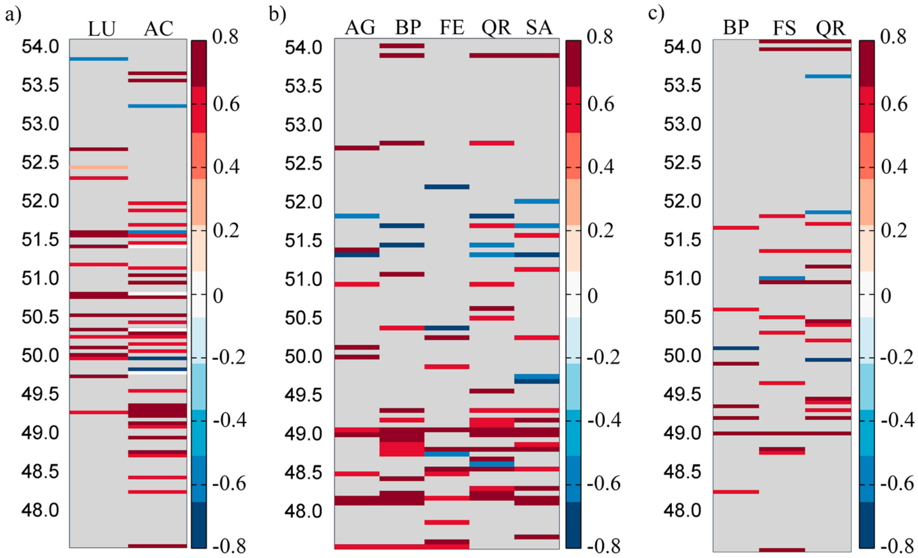

Figure 1. Averaged Pearson's product-moment correlation coefficients between GP and LSP estimates at every 0.5 of latitude. The results of regression of interannual time series from 2003 to 2011 are shown. The blue colors indicate negative correlations; the red colors indicate positive correlations. (a) First column shows the results of regressions between OG LSP and leaf unfolding (LU) of a species mixture; second column shows the results of regressions between EOS LSP and autumnal coloring (AC) of species mixture. (b) Correlation coefficients between OG LSP and LU of different deciduous tree species: AG, *Alnus Glutinosa*; BP, *Betula Pendula*; FE, *Fraxinus Excelsior*; QR, *Quercus Robur*; and SA, *Sorbus Aucuparia*. (c) Correlation coefficients between EOS LSP and AC of different deciduous tree species: BP, *Betula Pendula*; FS, *Fagus Sylvatica*; and QR, *Quercus Robur*.

modeled using a multivariate nonparametric regression method (Random Forest) [*Breiman*, 2001] (see supporting information for detail description). The spring and autumn models were built from the information contained in LSP, the specific species name of the given GP record and other geographical drivers such as altitude, latitude, and longitude. The pseudo R^2 correlation coefficient and the root-mean-square error (RMSE) of the prediction of the Julian date of the phenological events were used to quantify the association between GP and LSP. Additionally, estimation of the importance of every predictor provided by this method was applied to obtain new insights into the relationship between GP and LSP.

3. Results

The 9 year series of estimates of OG and EOS were correlated using the Pearson's product-moment correlation coefficient with deciduous tree species leaf unfolding and autumnal coloring for the same period located mainly in Germany, Austria, and Switzerland. After masking data to include only ground observation points with at least 9 years of data, we were able to assess 3048 correlations between point-based measured phenology on the ground and pixel-based OG and EOS from satellite (considering different species and phenophases). Figure 1 summarizes the average correlation coefficient at every 0.5° of latitude. In general, for deciduous trees and especially for certain species, there were more positive than negative correlations (i.e., most of the locations reveal that when OG or EOS tends to increase or decrease, the same pattern can be observed in LU or AC, respectively). Large positive correlations were found for all species at many different locations. Most of these positive correlations are located in areas of large patches of deciduous forest, especially between 48.5 and 52.0° and around 53° latitude. Correlations between OG and LU of *Betula Pendula* outperformed all other species, with *Fraxinus Excelsior* having the smallest positive or even negative correlation coefficients (Figure 1b). The AC dates of *Betula Pendula* were also positively correlated with EOS (Figure 1c). However, other deciduous tree species not included in the LU record, for example, *Fagus Sylvatica*, exhibited closer agreement than *Betula Pendula* regarding the EOS. The relationship between this last species and OG could not be studied as not enough ground spring phenophase records were available. The closest agreement, between *Fagus Sylvatica* and *Betula Pendula*, can be explained by the distribution of deciduous trees in the area considered for the assessment where, according to *Brus et al.* [2012], both species are dominant at many locations.

©2015. American Geophysical Union. All Rights Reserved.

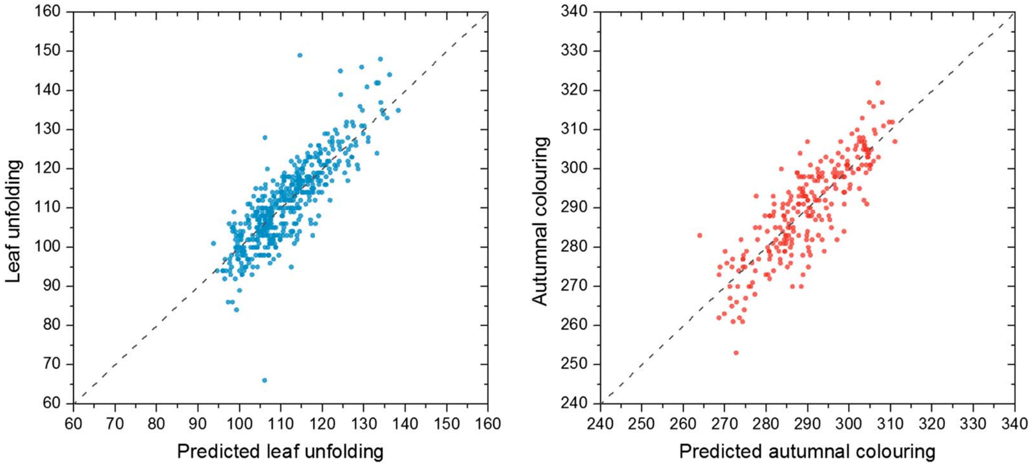

Figure 2. Scatterplots between the original values of GP and those predicted by the Random Forest model using LSP. Values are given in Julian days.

The multivariate predictive models for spring and autumn phenology showed a strong spatiotemporal association between LU/AC and OG/EOS, respectively. Pseudo R^2 correlation coefficient showed a similar performance between the autumn and spring ground phenology models (0.70 and 0.71, respectively). However, the RMSE, computed from an independent cross validation, was slightly lower for the estimation of the spring phenology than that of autumn (5.97 days and 6.75 days over 365 days, respectively). Figure 2 shows the scatterplots between the LU and AC original values and those obtained through the application of the GP phenology models to the independent cross-validation subset. Although both predictions can be considered robust, the autumn phenophases present a higher dispersion than spring.

4. Discussion

We used the most comprehensive ground phenological records over Europe to compare with our LSP estimates. We fitted thousands of regression models between the LSP parameters estimated from homogeneous patches of deciduous forest and ground observations of different species of deciduous trees in Europe to investigate their association. The comparison was based on a regression of the time series in GP on the equivalent time series in LSP, rather than a comparison of absolute dates, as systematic shifts or displacements were expected between satellite and ground phenology (see Figures S6 and S7 in the supporting information), mainly because ground observations and remote sensing vegetation indices monitor qualitatively different phenological events (GP determines the date of an event and LSP a characteristic change in reflectance) [*Badeck et al.*, 2004]. Moreover, a different amount of temporal bias could be expected depending on the method of LSP estimation. The analysis represents, thus, a relative assessment rather than an absolute assessment. The R value measures relative association and ignores bias.

Despite the challenges of performing an intercomparison described in the Introduction, the results indicate close agreement between the satellite-derived phenological estimates and ground observations of certain species, when considering their interannual variation. The consistency between the satellite-derived LSP and the ground observations is greater for some deciduous tree species (such as *Betula Pendula* or *Fagus Sylvatica*). This may be due to a (spatial) dominance of these tree species at certain latitudes (or at the spatial resolution of the satellite sensor data) or the presence of species with a similar response to meteorological forcing [*Brus et al.*, 2012].

Considering that the MTCI data used have a spatial resolution coarse enough to integrate the contribution from many different vegetation species, we also fitted a regression model between the satellite-derived data and the average of the phenology observed on the ground for different species. However, the correlation for a mixture of species was not larger than that for single species, which means that the species combination is not representative of the composition of the vegetation communities of the study area or that integration of species with different phenological patterns can introduce greater uncertainty in the analysis (e.g., the

©2015. American Geophysical Union. All Rights Reserved.

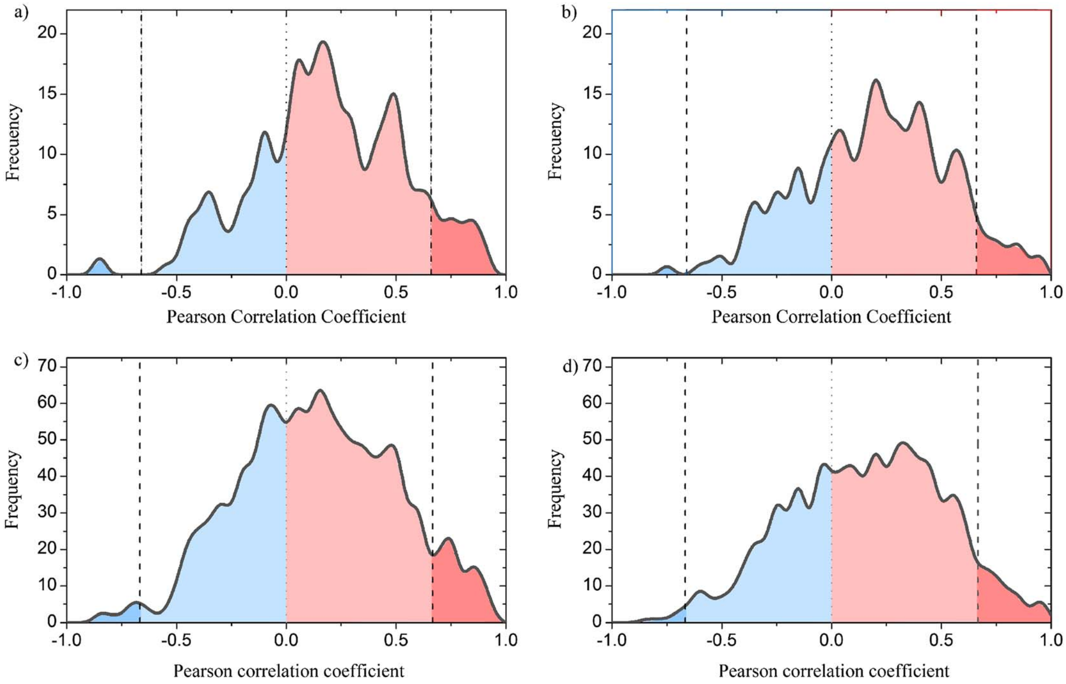

Figure 3. Distributions of significant correlation coefficients at 95% confidence level of the regressions between the interannual time series in land surface phenology (LSP) and ground phenology. (a) Onset on greenness (OG) versus *Betula Pendula* leaf unfolding (LU). (b) End of senescence (EOS) versus *Fagus Sylvatica* autumnal coloring (AC). (c) OG versus species mixture LU. (d) EOS versus species mixture AC. The blue colors indicate negative correlations; the red colors indicate positive correlations.

species composition of deciduous forest is not well known and therefore difficult to take into account). This contrasts with the results of *Studer et al.* [2007], who found reasonably close agreement between a multispecies index and LSP in Switzerland. However, it should be noted that the spatial resolution of the data used in the study by *Studer et al.* [2007] is much coarser, which can affect the results (0.1° versus 1 km). On the other hand, *Badeck et al.* [2004] found small correlations when comparing National Oceanic and Atmospheric Administration/advanced very high resolution radiometer normalized difference vegetation index time series with ground observations of deciduous trees in Germany.

To evaluate the reliability of the averaged correlation coefficients shown in Figure 1, the distribution frequency of the statistically significant regression results prior to the averaging of every 0.5° is shown in Figure 3. The same pattern in interannual variation is expected (increase or decrease) between LSP and GP, which means that a significantly greater number of positive correlations should be obtained. The majority of regression models (75%) led to positive correlations when the most representative species were used (*Betula Pendula* for spring phenophases and *Fagus Sylvatica* for autumn). It is important to note that about 90% of the significant correlations at a 95% confidence level were positive. This finding suggests that for *Betula Pendula* and *Fagus Sylvatica*, OG and EOS are strongly correlated to LU and AC, respectively. These encouraging results support the role of LSP as a consistent estimator of phenology across space and time, making it reliable and valuable at the Europe-wide level for a wide range of applications. However, the signal for species mixtures is more ambiguous (66% for spring and 69% for autumn) and less clear as there were similar proportions of negative and positive correlations (Figures 3b and 3c). Additionally, the distribution between significant correlations of first leaf appearance and senescence was balanced, which contrasts with the results of other studies which reported greater difficulty in observing reliably the autumnal phenophases [*Studer et al.*, 2007]. However, the number of years available to compare the interannual variation in LSP and GP limited the results, given that very large correlation coefficients are needed to obtain significance ($R > 0.66$).

The results of a further regression analysis suggested that there might be a nonlinear relationship between GP and LSP. Figure 4 shows the importance of the different predictors in the modeling of LU and AC. LSP could contribute significantly to the explanation of the spatiotemporal variation of GP, although the

©2015. American Geophysical Union. All Rights Reserved.

association between LU and OG was greater than that between AC and EOS. The performance of the spring and autumn models decreased greatly when LSP was not considered as a predictor (see Table S2 in the supporting information). However, LSP must be complemented with the identification of the plant species to establish robust relationships between both binomial LU-OG and AC-EOS. This finding highlights the importance of the use of the species in the prediction or upscaling of GP.

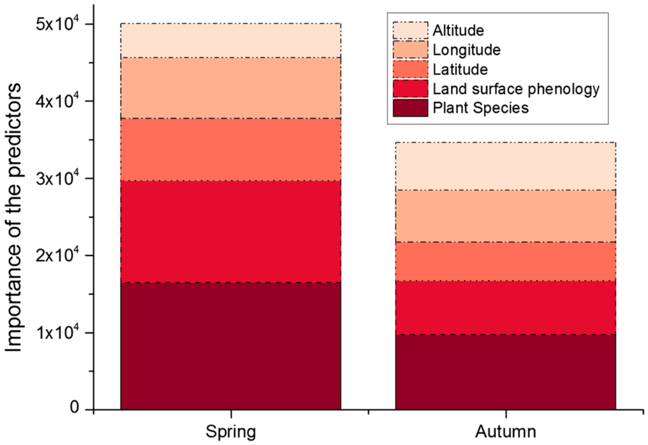

Figure 4. Importance of the different predictors in the modeling of GP. Alt, altitude; Lon, longitude; Lat, latitude; and Sp, scientific name of the species. The importance of predictor is dimensionless (see section "Multivariate nonlinear modeling of GP using Random Forest" in the supporting information).

The correspondence of the temporal and spatiotemporal variability of ground and satellite phenology indicates that both MERIS MTCI and PEP725 ground phenology records provide the opportunity to study vegetation phenology cycles at different spatial scales. The comparison exercise presented here is limited because of the difficulty in obtaining ground reference data distributed across the whole European continent and the length of the MERIS time series. Thus, the continuity of MTCI time series as well as a more evenly distributed network of phenology observations, which accounts for species abundance and distribution, is desirable. Future research will focus on the inclusion of alternative methods to estimate phenology from PhenoCams and flux towers to represent ground phenology, which perhaps provide a representation of the vegetation at a scale that is more comparable with satellite sensor data. However, such data are currently very limited for comparison with the European-wide LSP maps analyzed here.

5. Conclusions

PEP725, despite its limitations related to geographical extent (see section 2.1) and the uncertainties in the definition and estimation of phenological events, represents the most exhaustive ground phenological database across Europe and therefore the best available reference data set for comparison with satellite sensor LSP across Europe. Nevertheless, these two sources of information do not observe exactly the same phenological events and, thus, rather modest correlations between interannual observations are to be expected.

A significant number of positive correlations (90%) were obtained from the regressions between the interannual time series of LSP and GP for certain species of deciduous trees (*Betula Pendula* and *Fagus Sylvatica*). Thus, satellite-derived phenological estimates are comparable to ground observations when interannual variation is considered and when the ground phenological records correspond to tree species that are abundant and representative at the landscape level.

A new methodology to relate LSP and GP is proposed through the application of Random Forest, a nonparametric method which allows for nonlinear relationships between phenology variables and for the inclusion in the modeling process of categorical predictors—plant species in our case. The proposed method can recognize complex patterns between LSP and the phenology of multiple specific plant species, integrating them into a unique overall model, rather than generating multiple models for every species. Additionally, it is data driven, which means that there is no need to incorporate previous knowledge about the species composition in the landscape, but it considers the different plant species of GP. There exists a nonlinear spatiotemporal relationship between GP and LSP, which is particularly strong for spring phenophases. Multivariate nonparametric models based on LSP and other predictors were able to predict LU and AC accurately (pseudo R^2 equal to 0.70 and 0.71, respectively; RMSE equal to 5.97 days and 6.75 days, respectively).

©2015. American Geophysical Union. All Rights Reserved.

Future research is needed to explore (i) if longer MTCI series can increase the agreement between LSP and GP (therefore, continuity of MTCI time series is desirable) and (ii) how the spatial resolution of the satellite sensor data, species composition, the spatial distribution of the phenological records, and the phenological phases observed influences the results.

Acknowledgments

The first author is a Marie Curie Grant holder (reference FP7-PEOPLE-2012-IEF-331667). The authors are grateful for the financial support given by the European Commission under the Seventh Framework Programme and the Spanish MINECO (project BIA2013-43462-P). PEP725 data were provided by the members of the PEP725 project. The data are available at the Pan European Phenology Project website (http://www.pep725.eu). Special thanks are given to Markus Ungersböck for preparing the ground data.

The Editor thanks an anonymous reviewer for assisting in the evaluation of this paper.

References

Ahas, R., R. Aasa, A. Menzel, V. G. Fedotova, and H. Scheifinger (2002), Changes in European spring phenology, *Int. J. Climatol.*, *22*, 1727–1738.

Badeck, F.-W., A. Bondeau, K. Böttcher, D. Doktor, W. Lucht, J. Schaber, and S. Sitch (2004), Responses of spring phenology to climate change, *New Phytol.*, *162*, 295–309.

Bicheron, P., et al. (2011), Geolocation assessment of MERIS GlobCover orthorectified products, *IEEE Trans. Geosci. Remote Sens.*, *49*, 2972–2982.

Breiman, L. (2001), Random forests, *Mach. Learn.*, *45*, 5–32.

Brus, D. J., G. M. Hengeveld, D. J. J. Walvoort, P. W. Goedhart, A. H. Heidema, G. J. Nabuurs, and K. Gunia (2012), Statistical mapping of tree species over Europe, *Eur. J. For. Res.*, *131*, 145–157.

Cook, B. I., et al. (2012), Sensitivity of spring phenology to warming across temporal and spatial climate gradients in two independent databases, *Ecosystems*, *15*, 1283–1294.

Defila, C., and B. Clot (2001), Phytophenological trends in Switzerland, *Int. J. Biometeorol.*, *45*, 203–207.

Fitter, A. H., and R. S. R. Fitter (2002), Rapid changes in flowering time in British plants, *Science*, *296*, 1689–1691.

Hamunyela, E., J. Verbesselt, G. Roerink, and M. Herold (2013), Trends in spring phenology of Western European deciduous forests, *Remote Sens.*, *5*, 6159–6179.

Jeganathan, C., J. Dash, and P. Atkinson (2010), Characterising the spatial pattern of phenology for the tropical vegetation of India using multi-temporal MERIS chlorophyll data, *Landscape Ecol.*, *25*, 1125–1141.

Kirbyshire, A. L., and G. R. Bigg (2010), Is the onset of the English summer advancing?, *Clim. Change*, *100*, 419–431.

Klosterman, S. T., K. Hufkens, J. M. Gray, E. Melaas, O. Sonnentag, I. Lavine, L. Mitchell, R. Norman, M. A. Friedl, and A. D. Richardson (2014), Evaluating remote sensing of deciduous forest phenology at multiple spatial scales using PhenoCam imagery, *Biogeosci. Discuss.*, *11*, 2305–2342.

Lapenis, A., H. Henry, M. Vuille, and J. Mower (2014), Climatic factors controlling plant sensitivity to warming, *Clim. Change*, *122*, 723–734.

Luterbacher, J., M. A. Liniger, A. Menzel, N. Estrella, P. M. Della-Marta, C. Pfister, T. Rutishauser, and E. Xoplaki (2007), Exceptional European warmth of autumn 2006 and winter 2007: Historical context, the underlying dynamics, and its phenological impacts, *Geophys. Res. Lett.*, *34*, L12704, doi:10.1029/2007GL029951.

Maignan, F., F. M. Bréon, C. Bacour, J. Demarty, and A. Poirson (2008), Interannual vegetation phenology estimates from global AVHRR measurements: Comparison with in situ data and applications, *Remote Sens. Environ.*, *112*, 496–505.

Menzel, A. (2000), Trends in phenological phases in Europe between 1951 and 1996, *Int. J. Biometeorol.*, *44*, 76–81.

Menzel, A. (2002), Phenology: Its importance to the Global Change Community, *Clim. Change*, *54*, 379–385.

Menzel, A., et al. (2006), European phenological response to climate change matches the warming pattern, *Global Change Biol.*, *12*, 1969–1976.

Parmesan, C., and G. Yohe (2003), A globally coherent fingerprint of climate change impacts across natural systems, *Nature*, *421*, 37–42.

Peñuelas, J., and I. Filella (2001), Phenology: Responses to a warming world, *Science*, *294*, 793–795.

Roetzer, T., M. Wittenzeller, H. Haeckel, and J. Nekovar (2000), Phenology in central Europe: Differences and trends of spring phenophases in urban and rural areas, *Int. J. Biometeorol.*, *44*, 60–66.

Rutishauser, T., J. Luterbacher, C. Defila, D. Frank, and H. Wanner (2008), Swiss spring plant phenology 2007: Extremes, a multi-century perspective, and changes in temperature sensitivity, *Geophys. Res. Lett.*, *35*, L05703, doi:10.1029/2007GL032545.

Scheifinger, H., A. Menzel, E. Koch, C. Peter, and R. Ahas (2002), Atmospheric mechanisms governing the spatial and temporal variability of phenological phases in central Europe, *Int. J. Climatol.*, *22*, 1739–1755.

Scheifinger, H., A. Menzel, E. Koch, and C. Peter (2003), Trends of spring time frost events and phenological dates in central Europe, *Theor. Appl. Climatol.*, *74*, 41–51.

Sobrino, J. A., Y. Julien, and L. Morales (2011), Changes in vegetation spring dates in the second half of the twentieth century, *Int. J. Remote Sens.*, *32*, 5247–5265.

Studer, S., R. Stöckli, C. Appenzeller, and P. L. Vidale (2007), A comparative study of satellite and ground-based phenology, *Int. J. Biometeorol.*, *51*, 405–414.

White, M. A., F. Hoffman, W. W. Hargrove, and R. R. Nemani (2005), A global framework for monitoring phenological responses to climate change, *Geophys. Res. Lett.*, *32*, L04705, doi:10.1029/2004GL021961.

White, M. A., et al. (2009), Intercomparison, interpretation, and assessment of spring phenology in North America estimated from remote sensing for 1982–2006, *Global Change Biol.*, *15*, 2335–2359.

Wolkovich, E. M., et al. (2012), Warming experiments underpredict plant phenological responses to climate change, *Nature*, *485*, 494–497.

©2015. American Geophysical Union. All Rights Reserved.