Phenological monitoring of grassland and larch in the Alps from Terra and Aqua MODIS images

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Abstract
This study compares MODIS NDVI 16-day (250 m) time series, acquired by Terra and Aqua platforms, for monitoring the phenological cycle of larch and grasslands in an alpine environment. The accuracy of MODIS 250 m Terra and Aqua phenological metrics was evaluated for larch forests through comparison with field data. At regional level it was carried out a correlation analysis between the mean dates of start and end of season detected from MODIS Terra and Aqua in different years. Regional maps of start and end of season were derived from MODIS data and the interannual phenological variability of both ecosystems was evaluated. Annual anomalies of the beginning of the growing season, obtained from satellite data, were related with air temperature anomalies, computed from meteorological stations, to evaluate the effects of recent climate variability on the vegetation phenological cycle.
Comparison with field phenological observations showed that the start and the end of phenological cycle can be accurately determined from MODIS Terra and Aqua data and that an increase/decrease of 1°C in spring temperature lead to about 10 days in advance/delay of the start of the growing season.
Keywords: Phenology, larch, grassland; Terra and Aqua MODIS; Alpine region; recent climatic variability.

Introduction
Phenology can be defined as the study of recurrent biological events and of the causes of their temporal change due to biotic and abiotic forces [Lieth, 1974]. As regards plants, phenological studies allow to understand the timing of the main seasonal events, such as bud burst, leaf unfolding, fruit maturing, leaf coloration and leaf fall. Vegetation phenology reflects the combined effects of biosphere-atmosphere interactions at seasonal and longer time scales and it provides a useful tool to better understand the effects of climate change and biogeochemical cycle alterations [e.g., Running and Nemani, 1991; Schwartz, 1992; Sellers et al., 1992; Goetz and Prince, 1996]. Changes in the beginning and the length

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of the growing season have been detected over large areas and are some of the more obvious indicator of climate change effects on biosphere [e.g. Menzel et al., 2006]. These variations have both direct impacts on vegetation growth, affecting both photosynthesis and respiration fluxes, and indirect effects on several aspects of ecosystems functioning (e.g. changes in herbivore-plant interactions, litter quality, fire proneness, and stocks of non-structural carbohydrate reserves in plants).

Many studies have been conducted in the last years to analyze the spatial and temporal variability of vegetation phenology, by combining time series of field phenological observations, remote sensing data and climate-driven models in order to analyze the role of the different factors governing plant phenology [e.g. Schwartz et al., 2002; Picard et al., 2005; Fisher et al., 2006; Delbart et al., 2008; Busetto et al., 2010].

Satellite data can be used to provide maps of green-up dates that may be an important source of spatial distributed information for the analysis of the complex interactions between plant phenology and environmental conditions. These maps are usually generated from the analysis of time series of spectral vegetation indexes derived from reflectance measurements in the visible and near infrared spectral regions, and allow to analyse the spatial and temporal variability of the phenological cycle at different spatial resolutions, even in remote forests, where field phenological monitoring is seldom performed [Moulin et al., 1997; Myneni et al., 1997; Schwartz and Reed, 1999; Ebata and Tateishi, 2001; Jonsson and Eklundh, 2002; Zhang et al., 2003; Cook et al., 2005; Ahl et al., 2006; Beck et al., 2006; Delbart et al., 2006; White and Nemani, 2006; Beck et al., 2007; Fisher and Mustard, 2007; Studer et al., 2007; Soudani et al., 2008]. In particular, the MODerate resolution Imaging Spectroradiometer (MODIS) on board NASA's Terra and Aqua platforms, with a ground spatial resolution of 250 m, offer a unique opportunity to monitor vegetation phenology in heterogeneous landscapes, such as the mountainous environments in the Alps. MODIS Terra and Aqua record images of the entire Earth's surface every 1 to 2 days in 36 spectral bands at different spatial resolution. Terra's orbit around the Earth is timed so that it passes from north to south across the equator in the morning, while Aqua passes south to north over the equator in the afternoon, and the images acquired by the two sensors are therefore separated by about 3 hours. A major advantage of MODIS imagery over many other sources of satellite imagery for phenological monitoring is that it provides images of the entire globe with high temporal resolution and high spatial resolution. For this reason MODIS Terra data were frequently employed to analyze phenology across different geographic regions and ecosystems. Although MODIS Terra images have been a long exploited for phenological mapping [e.g., Ahl et al., 2006; Beck et al., 2006, 2007; Soudani et al., 2008; Busetto et al., 2010], very few studies focused on the comparison of Aqua and Terra data for vegetation monitoring. For example, Yang et al. [2006] evaluated that there are no significant discrepancies between Terra and Aqua 8-day reflectances averaged over large areas, although at smaller scales large differences can arise due to the random nature of residual atmospheric effects and that, overall, differences in vegetation indices can be introduced from the limited accuracy of atmospheric correction of satellite data. However, no study has been carried out to compare the performance of MODIS Terra and MODIS Aqua for phenological monitoring.

The objective of this study is to evaluate the performances of Terra and Aqua MODIS for monitoring the phenological cycle of larch forests and grassland ecosystems in mountainous areas. The accuracy of MODIS 250 m Terra and Aqua phenological metrics was evaluated for larch forests through comparison with field data collected in different years and the derived phenological maps were used to evaluate the interannual phenological variability at regional scale. Regional maps of start and end of season were finally analyzed to identify the relationships between phenology and air temperatures. This allowed a quantification of the response of larch and grassland to interannual climatic variability in a sensitive environment such as the Alps.

Materials and methods

Study area and phenological field observations

The study was conducted on European Larch forests (*Larix decidua* Mill.) and grassland ecosystems in the Aosta Valley (Northwestern Italy). Aosta Valley is a typical alpine region with considerable variations in elevation, terrain morphology and primary and secondary topographic attributes. European Larch is a deciduous conifer widely distributed in this area and throughout the Alps [Ozenda, 1985] which grows over a wide altitudinal range (Fig. 1) and shows easily detectable phenological phases. Grassland ecosystems considered in this study are high-altitude unmanaged prairies broadly corresponding to the "taiga-tundra" ecotone, which have been regarded as highly sensitive to environmental change, and particularly to climate warming, since most of the species grows at their limits of tolerance [Fortin et al., 2000; Holtmeier and Broll, 2005].

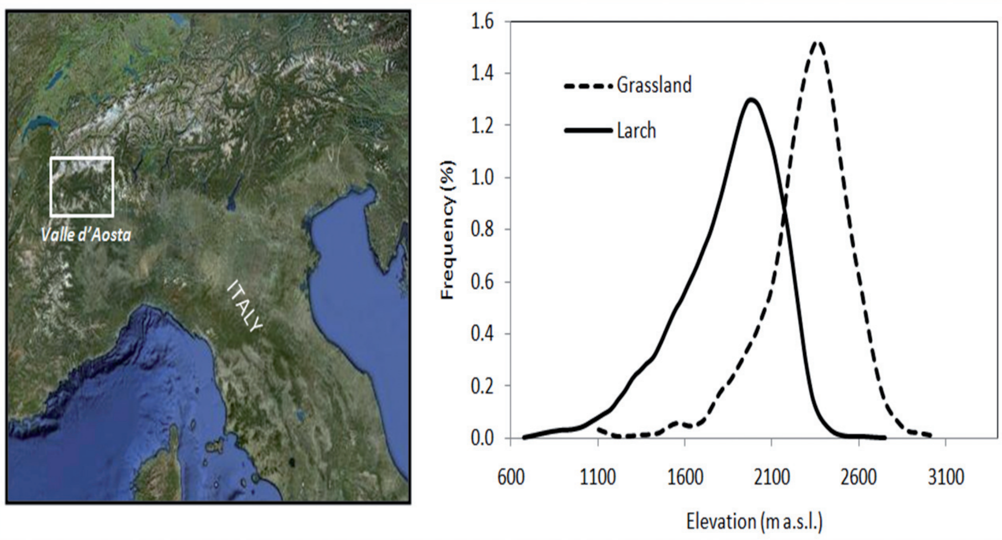

Figure 1 - Location and altitudinal distribution of grasslands and larch forests analyzed in this study (a.s.l. stands for above sea level – data derived from the "Carta Natura" map).

Weekly phenological observations were conducted in spring and autumn from 2005 to 2009 in eight different homogeneous larch communities within the Aosta Valley. Ten trees were randomly selected in three plots located in the lower, medium and upper altitudinal portions of the slope and, for both springtime and autumn phases, a score ranging from 1 to 5 was assigned to each tree at each sampling date, on the basis of its phenological development [Migliavacca et al., 2008]. During springtime the score was assigned on the basis of the analysis of needles elongation and unfolding, while during autumn the score was assigned on the basis of the analysis of crown discolouration (from green to yellow and finally to bronze). The average phenological stage at plot level was defined as the mean score value of the 10 plants observed. The start of the growing season (SOS) at plot level was assumed to coincide with the date at which the linear interpolation of the scores obtained at the different dates reached the value of 2, which corresponds to the completion of the bud-burst phase. The end of the growing season (EOS) at plot level was instead assumed to coincide with the date at which the linear interpolation of the scores reached the value of 3, which coincides to the complete yellowing of tree crowns. The SOS and EOS at site level were finally computed as the mean of the dates computed for its three plots and then compared with MODIS data [Colombo et al., 2009; Busetto et al., 2010].

Modelling phenology from MODIS data

MODIS 16 days composite NDVI (Normalised Difference Vegetation Index) data with 250 m spatial resolution acquired from Terra and Aqua platforms (Product MOD13Q1 – v005 and MYD13Q1, respectively) in the 2003-2009 period were used to estimate the dates of green-up of larch and grassland in the study area using the method proposed in Busetto et al. [2010]. MODIS data were re-projected to a UTM-WGS84 reference system with the MODIS Reprojection Tool software, using a nearest-neighbour resampling algorithm (https://lpdaac.usgs.gov/lpdaac/tools/modis_reprojection_tool). MODIS pixels corresponding to the two ecosystem types analyzed were then identified by intersecting the MODIS acquisition grid with the 1:10000 "Carta Natura" Map, derived from visual interpretation of aerial orthophotos, and retaining only the pixels which showed a fractional cover greater than 0.8 for larch or grasslands.

The NDVI time series of the retained pixels were then smoothed applying the algorithm proposed in Chen et al. [2004]. The algorithm is based on the iterative application of a Savitzky and Golay smoothing filter and allows the retrieval of high-quality NDVI time series, well adapted to the upper envelope of the original data. The time series were then corrected for the effect of snow using the method proposed by Beck et al. [2006; 2007], which substitutes winter values with a theoretical winter "snow free" NDVI value ($NDVI_w$). $NDVI_w$ was computed by first extracting the NDVI values recorded in snow-free conditions (according to the MODIS Snow Cover Flag) in the autumn and early winter of each year, and then computing the mean of the minimum values extracted in each year. The smoothed and snow-corrected NDVI time series of each pixel and year were then fitted using a double-logistic curve. The double logistic is well suited for phenological monitoring from remote sensing data, since it allows asymmetry in the NDVI temporal evolution of spring and autumn [Beck et al., 2006; Fisher et al., 2006] [Eq.1]:

$$NDVI(i,t) = NDVI_w(i) + (NDVI_{MAX}(i) - NDVI_w(i)) \cdot \left(\frac{1}{1 + e^{-mS \cdot (t - S)}} + \frac{1}{1 + e^{-mA \cdot (t - A)}} \right) \quad [1]$$

where *NDVI (i,t)* is the NDVI of pixel with spatial location *i* at day of the year (DOY) t, $NDVI_{MAX}(i)$ is the maximum NDVI during the year, *S* and *A* are the DOYs of maximum

slope of the curve respectively in spring and autumn, while *mS* and *mA* are the slopes of the curve at DOYs S and A, respectively.
The start and end of season dates for both larch and grassland of the selected pixel and year were then computed as the DOYs corresponding to the first and to the last zeroes of the third derivative of the fitted curve, which correspond to the dates of transition between the linear and nonlinear portions of the sigmoid curve [Potts et al., 1993]. This allowed the production of yearly maps of SOS and EOS at regional level for both larch forests and grasslands.

Comparison of Terra and Aqua SOS and EOS estimates
The comparison between Terra and Aqua SOS and EOS estimates on larch forests was conducted by comparing the dates estimated from data acquired by the two platforms and start and end of season dates collected in-field in the eight monitoring sites between 2005 and 2009. Observations were conducted in all eight sites during 2005, while in the other years some of them were excluded because of logistical constraints. Overall, the number of validation points was 25 and 22 for SOS and EOS, respectively. The ground validation was conducted only on larch forests due to the lack of field data regarding the SOS and EOS dates for grassland ecosystems.
The accuracy of the estimated dates was evaluated by computing the correlation coefficient (r), the Mean Error (ME, days), the Mean Absolute Error (MAE, days) and the Root Mean Square Error (RMSE, days) between MODIS estimated dates and field data (Tab. 1).

Table 1 - Statistic terms used to determine the accuracy of the larch SOS and EOS dates estimated from MODIS Terra and Aqua data. $DOY_{OBS}(i)$ and $DOY_{EST}(i)$ are the observed and modeled SOS or EOS dates at monitoring site *i*, while σDOY_{OBS} and σDOY_{EST} indicate their standard deviations and $\sigma DOY_{OBS} DOY_{EST}$ indicate their covariance.

Statistic parameter	Acronym	Formula
Correlation coefficient	r	$\frac{\sigma DOY_{OBS} DOY_{EST}}{\sigma DOY_{OBS} \sigma DOY_{EST}}$
Mean Error	ME	$\frac{\sum_{i=1}^{n}\left(DOY_{OBS}(i) - DOY_{EST}(i)\right)}{n}$
Mean Absolute Error	MAE	$\sum_{i=1}^{n}\left\| DOY_{OBS}(i) - DOY_{EST}(i)\right\| = \frac{1}{n}\sum_{i=1}^{n}\left\| e_i \right\|$
Root Mean Square Error	RMSE	$\sqrt{\frac{\sum_{i=1}^{n}(DOY_{OBS}(i) - DOY_{EST}(i))^2}{n}}$

Finally, the accordance between Terra and Aqua estimates was also evaluated at regional level, by comparing the mean regional SOS and EOS dates estimated from the two platforms in the different years (2003-2009), for both larch and grassland ecosystems.

Analysis of the relationships between phenological and climatic temporal variability

The relationships between the interannual variability of the larch and grassland SOS and that of regional climate were investigated by comparing the mean yearly satellite-derived SOS anomalies with yearly air temperature anomalies in different periods of the year by empirical regression models.

The estimated SOS mean yearly anomaly at regional level $\left(\overline{\Delta SOS}_{EST}(y)\right)$ was computed for each year y as the mean of the anomalies estimated for year y in each pixel i $\left(\Delta SOS_{EST}(i,y)\right)$ [Eq. 2].

$$\overline{\Delta SOS}_{EST}(y) = \frac{1}{N}\sum_{i=1}^{n}\Delta SOS_{EST}(i,y) = \frac{1}{N}\sum_{i=1}^{n}\left(SOS_{EST}(i,y) - \overline{SOS}_{EST}(i)\right) \quad [2]$$

Where $SOS_{EST}(i,y)$ is the SOS date estimated in year y for pixel i, $\overline{SOS}_{EST}(i)$ is the 7-year mean SOS estimated for the same pixel i, while N is the number of pixels considered, which is equal to the number of pixels belonging to the considered ecosystem in the study area.

The determination of the yearly air temperature anomalies over the whole study area was instead conducted starting from daily air temperature (°C) data acquired at sixteen meteorological stations distributed on the Aosta Valley region. For each station and year, the anomaly of mean monthly temperatures (obtained as the mean of hourly values measured within the month) and of their running averages with periods of 2, 3 and 4 months $\Delta\overline{T}(y)_m$, with m indicating the time period considered) with respect to the corresponding 2003-2009 mean were computed according to:

$$\Delta\overline{T}(y)_m = \frac{1}{n}\sum_{i=1}^{n}\Delta T(i,y)_m = \frac{1}{n}\sum_{i=1}^{n}\left(T(i,y)_m - \overline{T}(i)_m\right) \quad [3]$$

where $T(i,y)_m$ is the mean temperature recorded at station i in year y in the time period indicated by m (e.g., mean temperature of February and March), $\overline{T}(i)_m$ is the mean temperature observed at the same station in period m over the 7 years, while n is the number of meteorological stations considered.

Results and discussion

Accuracy evaluation and regional level comparison

Results of the statistical analysis conducted to compare the larch SOS and EOS estimated from Terra and Aqua with field data are shown in Table 2.

Table 2 - Results of the statistical comparison between Terra and Aqua and field observed larch SOS and EOS dates (p<0.001).**

	r	ME	MAE	RMSE
SOS AQUA	0.83**	1.3	7.74	9.02
SOS TERRA	0.87**	1.9	6.8	7.93
EOS AQUA	0.78**	-3.47	4.8	5.78
EOS TERRA	0.76**	1	4.1	5.2

The estimates of SOS and EOS computed from Aqua and Terra were very similar and their accuracy is comparable to the one obtained in recent remote sensing studies based on images acquired from the Terra satellite [e.g. Delbart et al., 2006; Beck et al., 2007; Soudani et al., 2008; Busetto et al., 2010]. The Wilcoxon signed ranked test between the residuals of Terra (e.g. SOS Terra - SOS observed) and Aqua did not show statistically significant differences in the mean of the two populations. This suggests that, although Terra and Aqua observations differ for viewing geometry and atmospheric conditions due to their different orbits, they can be used to map the start and end of the growing season in larch forests with similar accuracies. However, in the senescent phase, even though Aqua and Terra correlation coefficients are similar, the larger mean error of Aqua may indicate a slightly better performance of Terra in estimating the end of the growing season.
A preliminary analysis conducted on the time series of the MODIS Vegetation Indices Usefulness Index (http://datamirror.csdb.cn/modis/resource/doc/MOD13_UserGuide.pdf) showed that in our study area the quality of Terra data during the growing season months is slightly better than that of Aqua (data not shown). Valle d'Aosta is typically characterized by the presence of convective clouds in the hours of maximum solar radiation and, since Terra imagery is acquired earlier than Aqua (i.e. at 10:30 am local solar time), it may be that Terra dataset is overall less subject to cloud contamination. This suggests that Terra NDVI time series may be better suited to monitor the larch phenological cycle in mountainous alpine environment and may explain the slightly better accuracy of Terra phenological estimates.

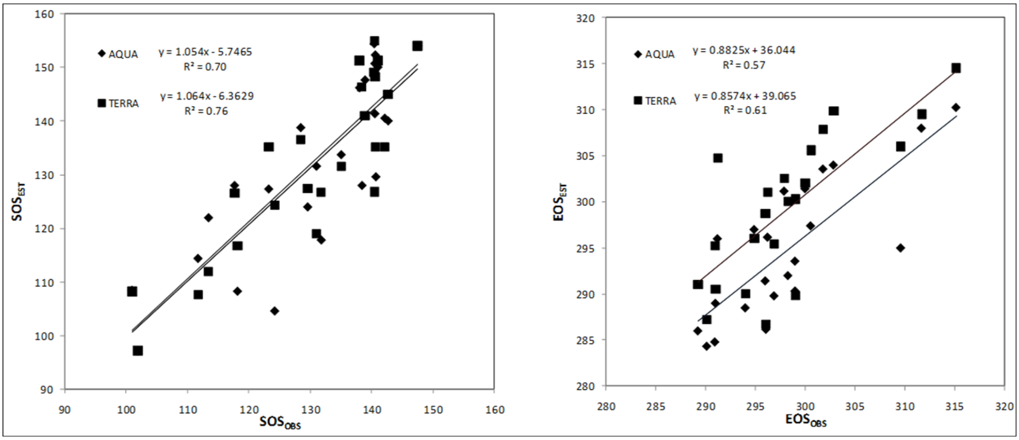

Figure 2 - Comparison of start (left) and end (right) of season dates computed from MODIS Terra and Aqua with field data.

The analysis at regional level showed that there is a strong correlation between the mean SOS dates detected from MODIS Terra and Aqua in the different years, for both larch and grassland ecosystems (Fig. 3). While the larch EOS estimated from the two platforms are still well related, the correlation is strongly reduced in grassland ecosystems. The lack of correlation between Terra and Aqua MODIS in grassland may be due to different factors, such as random change of external atmospheric effects, reflectance anisotropy or may be induced from fast dynamics of land surface characteristics. During the end of the season, grasslands may be in fact covered from patchy snow and rapid changes may occur in few hours [e.g. Parajka and Blosch, 2006]. This change in the target reflectance properties may be recorded differently from Terra and Aqua data, leading to pretty strong differences in the NDVI measured by the two sensors. However the reasons of this poor correlation is still not clear and further investigations should be conducted to examine this issue.

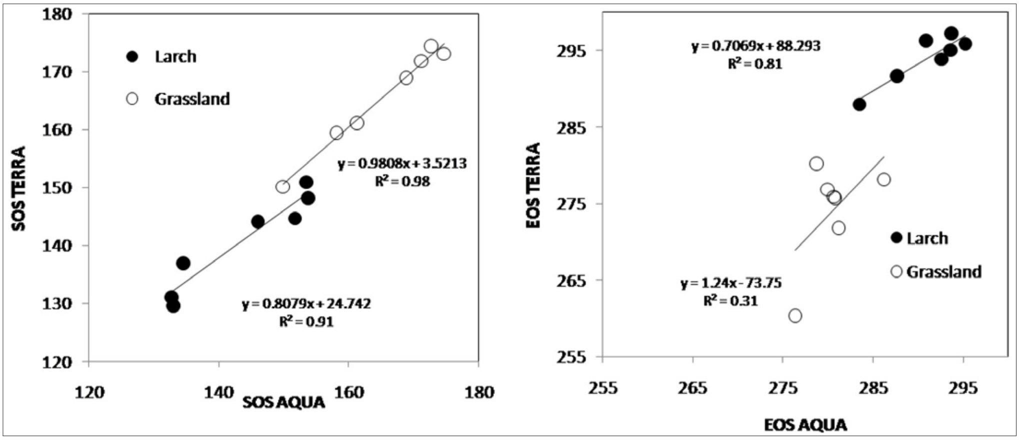

Figure 3 - Comparison of start (left) and end (right) of the growing season of larch and grassland detected from Terra and Aqua MODIS data.

Phenological interannual variability

As observed in recent studiesthe yearly phenological maps derived from MODIS data highlights strong spatial variability of the phenological dates in the Aosta Valley as a function of elevation and of its effects on air temperature [Colombo et al., 2009; Busetto et al., 2010]. As regards the interannual variability, the analysis of the regional anomalies computed from Terra data over the analyzed period shows that the variability of SOS and EOS in the two ecosystems considered is similar (Fig. 4). Very similar results were obtained starting from Aqua data (data not shown). MODIS derived regional anomalies highlight a strong interannual variability of larch and grassland SOS, although no statistically significant trends can be observed in the last decade.

The analysis of the anomalies clearly indicates a strong interannual variability with an earlier SOS of about 10 days in 2003, 2005 and 2007, and a delay of more than a week in 2004 and 2008, reflecting the interannual variability of the air temperature. The interannual variations of the EOS were instead found to be generally weaker, in particular for grassland ecosystems.

Variations of such magnitude can lead to strong effects on forest primary production and thus on carbon sequestration. For example, Picard et al. [2005] suggested that an advance in the start of the growing season of 16 days can lead to an increment of 34% of Net Primary Production of Siberian deciduous forests, while Churkina et al. [2005] found a rate of 3.4 gCm^{-2} day^{-1} and 7.9 gCm^{-2} day^{-1} for evergreen needleleaf forests and herbaceous grassland, respectively.

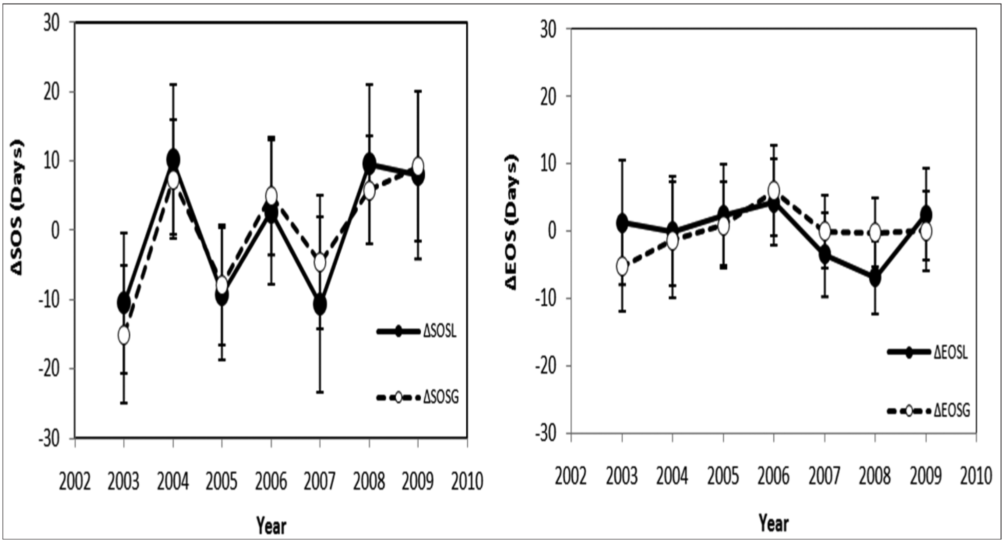

Figure 4 - Mean regional anomalies (± 1SD1 standard deviation) of SOS (left) and EOS (right) with respect to the 2003-2009 mean (computed from MODIS Terra results). ΔSOSL (ΔEOSL) and ΔSOSG (ΔEOSG) refer to larch and grassland anomalies, respectively.

However, regarding the relationship between growing season length and productivity, different studies have indicated contradictory results. Dunn et al. [2007] could not identified in a boreal conifer stand a significant relationship between growing season length and net ecosystem productivity, while Sacks et al. [2007] observed in a subalpine conifer forest that the annual Net Ecosystem Production decreases in years with an early spring. Finally, Piao et al. [2008] discussed the relationship between lengthening of the growing season in higher latitude ecosystems due to autumn warming and the net ecosystem production, while Richardson et al. [2010] evaluated the influence of spring and autumn phenological transitions on forest ecosystem productivity using 153 site-years of data from 21 FLUXNET sites [Baldocchi et al., 2008].

Figure 5 shows the relationship between air temperature and larch and grasslands regional mean Terra's SOS anomalies. A strong negative relationship was found between April-May-June air temperature and SOS for both larch forests and grasslands, demonstrating that air temperature is a key driver of vegetation green up at the regional scale of observation. The slope of the linear regression lines was almost identical for the two ecosystems, indicating that the mean SOS of larch and grassland in the Aosta Valley advances (or delays) by about 10 days for each degree of increase (or decrease) in air temperature in the spring period. Results of the linear regression analysis between air temperature anomalies and the yearly anomalies derived from Aqua data showed similar results, although the strength of the relationship was weaker (data not shown).

The strong response of MODIS-derived SOS at regional level to spring temperature variations highlights and allows to quantify the influence of climate on this phenological variable. The magnitude of the response identified in this study is in accordance with results of previous studies based on analysis of satellite and field data [e.g. Walkovszky, 1998; Chmielewski and Rotzer, 2001; Menzel et al., 2006].

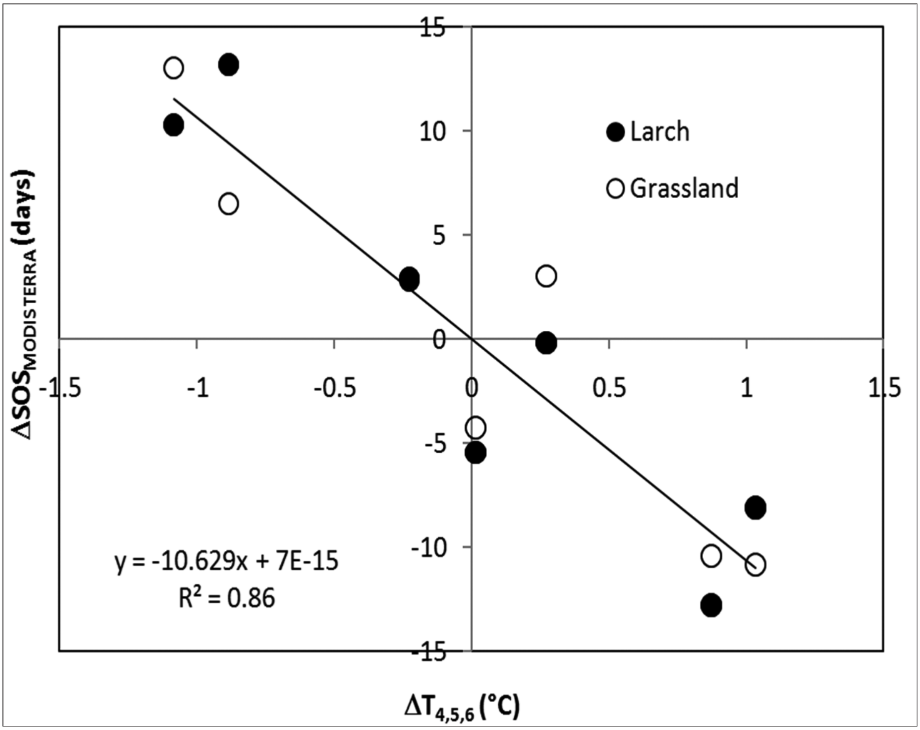

Figure 5 - Regression model relating mean yearly regional anomalies of MODIS Terra start of season for larch/grassland and mean yearly air temperature regional anomalies (April, May and June).

Conclusions

In this paper we evaluated the performances of Terra and Aqua MODIS 16-day composite NDVI data with 250 m spatial resolution for monitoring the phenological cycle of larch forests and grassland ecosystems in mountainous areas. Comparison with field data acquired in larch forests showed that MODIS Terra and MODIS Aqua estimates of start of season are highly accurate, providing a mean absolute error of less than a week, which is acceptable for an accurate monitoring of the vegetation phenological cycle. Overall, MODIS Terra estimates of the end of the larch growing season seem to be slightly more accurate than those obtained with MODIS Aqua. At regional level it was observed a strong correlation between the larch and grassland SOS dates estimated from Terra and Aqua data, while for the end of the season a lower correlation was found, in particular for grassland ecosystems.
MODIS derived SOS dates of larch and grasslands highlighted a strong interannual variability in the last seven years. The mean SOS in larch forests occurred around DOY 150, about 20 days before the average SOS DOY observed for grasslands, due to the different altitudinal range of these ecosystems (i.e. grasslands occupy higher elevation areas), while grassland senescence occurs about 10 days earlier with respect to larch forests. A strong similarity was observed in the inter-annual variability of the phenological cycle in the two ecosystems, indicating that the effect of interannual air temperature variability is approximately the same for larch and grasslands ecosystems. Differences in mean SOS dates of up to two weeks

were found in the different years as a consequence of climatic variability. Mean yearly regional anomalies of MODIS Terra start of season for larch/grassland and mean yearly air temperature regional anomalies indicate that an increase of 1°C in April, May and June air temperature leads to about 10 days anticipation of the start of the growing season.
In summary, this study demonstrates that MODIS data may be very useful for phenological monitoring and that a combined analysis of satellite images and local meteorological measurements may allow quantifying the response of the phenological cycle to climatic variability in mountainous regions. Field validation campaigns and collection of webcam images should be however carried out to validate the MODIS phenological estimation on grassland ecosystems before a possible extension of the proposed monitoring methodology over the European Alps. Moreover, further studies aimed to compare Terra and Aqua NDVI products are still necessary to evaluate their performance for phenological monitoring in different regions and ecosystems. Finally, further investigations may be addressed on the use of combined Terra and Aqua daily dataset, that may help to better evaluate fast dynamics in the senescence phase.

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References

Ahl D.E., Gower S.T., Burrows S.N., Shabanov N.V., Myneni R.B., Knyazikhin Y. (2006) - *Monitoring spring canopy phenology of a deciduous broadleaf forest using MODIS*. Remote Sensing of Environment, 104: 88-95. doi: http://dx.doi.org/10.1016/j.rse.2006.05.003.

Baldocchi D. (2008) - *Breathing of the terrestrial biosphere: lessons learned from a global network of carbon dioxide flux measurement systems*. Aust. J. Bot. 56: 1-26. doi: http://dx.doi.org/10.1071/BT07151.

Beck P.S.A., Atzberger C., Hogda K.A., Johansen B., Skidmore A.K. (2006) - *Improved monitoring of vegetation dynamics at very high latitudes: A new method using MODIS NDVI*. Remote Sensing of Environment, 100: 321-334. doi: http://dx.doi.org/10.1016/j.rse.2005.10.021.

Beck P.S.A., Jonsson P., Hogda K.A., Karlsen S.R., Eklundh L., Skidmore A.K. (2007) - *A ground-validated NDVI dataset for monitoring vegetation dynamics and mapping phenology in Fennoscandia and the Kola peninsula*. International Journal of Remote Sensing, 28: 4311-4330. doi: http://dx.doi.org/10.1080/01431160701241936.

Busetto L., Colombo R., Migliavacca M., Cremonese E., Meroni, M. Galvagno M., Rossini M., Siniscalco C., Morra di Cella U., Pari E. (2010) - *Remote sensing of Larch phenological cycle and analysis of relationships with climate in the Alpine Region*. Global Change Biology, 16: 2504-2517.

Chen J., Jonsson P., Tamura M., Gu Z. H., Matsushita B., Eklundh L. (2004) - *A simple method for reconstructing a high-quality NDVI time-series data set based on the Savitzky-Golay filter*. Remote Sensing of Environment, 91: 332–344. doi: http://dx.doi.org/10.1016/j.rse.2004.03.014.

Chmielewski F.M., Rotzer T. (2002) - *Annual and spatial variability of the beginning of growing season in Europe in relation to air temperature changes*. Climate Research, 19: 257-264. doi: http://dx.doi.org/10.3354/cr019257.

Churkina G., Schimel D., Braswell BH, Xiao X.M. (2005) - *Spatial analysis of growing season length control over net ecosystem exchange*. Global Change Biology, 11:1777–1787. doi: http://dx.doi.org/10.1111/j.1365-2486.2005.001012.x.

Colombo R., Busetto L., Migliavacca M., Cremonese E. , Meroni M., Galvagno M., Rossini M., Siniscalco C., Morra di Cella U. (2009). *On the spatial and temporal variability of Larch phenological cycle in mountainous areas*. Italian Journal of Remote Sensing , 41(2): 79-96. doi: http://dx.doi.org/10.5721/ItJRS20094126.

Cook B.I., Smith T.M., Mann M.E. (2005) - *The North Atlantic Oscillation and regional phenology prediction over Europe*. Global Change Biology, 11: 919-926, doi: http://dx.doi.org/10.1111/j.1365-2486.2005.00960.x.

Delbart N., Le Toan T., Kergoat L., Fedotova V. (2006) - *Remote sensing of spring phenology in boreal regions: A free of snow-effect method using NOAA-AVHRR and SPOT-VGT data (1982-2004)*. Remote Sensing of Environment, 101: 52-62. doi: http://dx.doi.org/10.1016/j.rse.2005.11.012.

Delbart N., Picard G., Le Toans T., Kergoat L., Quegan S., Woodward I., Dye D., Fedotova V. (2008) - *Spring phenology in boreal Eurasia over a nearly century time scale*. Global Change Biology, 14: 603-614. doi: http://dx.doi.org/10.1111/j.1365-2486.2007.01505.x.

Dunn A. L., Barford C. C., Wofsy S. C., Goulden M. L., Daube B. C. (2007) - *A long-term record of carbon exchange in a boreal black spruce forest: means, responses to interannual variability, and decadal trends*. Glob. Change Biol., 13: 577-590. doi: http://dx.doi.org/10.1111/j.1365-2486.2006.01221.x.

Ebata M., Tateishi R. (2001) - *Phenological stage monitoring in Siberia using NOAA/AVHRR data*. In: CRS 2001 - 22nd Asian Conference on Remote Sensing. pp Page, Singapore.

Fisher J.I., Mustard J.F. (2007) - *Cross-scalar satellite phenology from ground, Landsat, and MODIS data*. Remote Sensing of Environment, 109: 261-273. doi: http://dx.doi.org/10.1016/j.rse.2007.01.004.

Fisher J.I., Mustard J.F., Vadeboncoeur M.A. (2006) - *Green leaf phenology at Landsat resolution: Scaling from the field to the satellite*. Remote Sensing of Environment, 100: 265-279. doi: http://dx.doi.org/10.1016/j.rse.2005.10.022.

Fortin M.J., Olson R.J., Ferson S., Iverson L., Hunsaker C., Edwards G., Levine D., Butera K., Klemas V. (2000) - *Issues related to the detection of boundaries*. Landscape Ecol., 15: 453–466. doi: http://dx.doi.org/10.1023/A:1008194205292.

Goetz S.J., Prince S.D. (1996) - *Remote sensing of net primary production in boreal forest stands*. Agricultural and Forest Meteorology, 78: 149-179. doi: http://dx.doi.org/10.1016/0168-1923(95)02268-6.

Holtmeier F.K., Broll G. (2005) - *Sensitivity and response of northern hemisphere altitudinal and polar treelines to environmental change at landscape and local scales*. Global Ecol. Biogeogr., 14: 395–410. doi: http://dx.doi.org/10.1111/j.1466-822X.2005.00168.x.

Jonsson P., Eklundh L. (2002) - *Seasonality extraction by function fitting to time-series of satellite sensor data*. IEEE Transactions on Geoscience and Remote Sensing, 40: 1824-1832. doi: http://dx.doi.org/10.1109/TGRS.2002.802519.

Lieth H. (1974) - *Phenology and seasonality modeling*. Springer, Heidelberg.

Menzel A, Sparks T., Estrella N., Kochz E., Aasa A., Ahas R., Alm-Kübler K., Bissolli P., Braslavska O., Briede A., Chmielewski F.M., Crepinsek Z., Curnel Y., Dahl A., Defila C., Donnelly A., Filella Y., Jatczak K., Mage F., Mestre A., Nordli Ø., Penuelas J., Pirinen P., Remisovà V., Scheifinger H., Striz M., Susnik A., Van Vliet A., Wielgolaski F.E., Zachz S., Zust A. (2006) -*European phenological response to climate change matches the warming pattern*. Global Change Biology, 12: 1969–1976. doi: http://dx.doi.org/10.1111/j.1365-2486.2006.01193.x.

Migliavacca M., Cremonese E., Colombo R., Busetto L., Galvagno M., Ganis L., Meroni M., Pari E., Rossini M., Siniscalco C., Morra di Cella U. (2008) - *European larch phenology in the Alps: can we grasp the role of ecological factors by combining field observations and inverse modelling?* International Journal of Biometeorology, 52: 587-605. doi: http://dx.doi.org/10.1007/s00484-008-0152-9.

Moulin S., Kergoat L., Viovy N., Dedieu G. (1997) - *Global-scale assessment of vegetation phenology using NOAA/AVHRR satellite measurements*. Journal of Climate, 10, 1154-1170. doi: http://dx.doi.org/10.1175/1520-0442(1997)010<1154:GSAOVP>2.0.CO;2.

Myneni R.B., Keeling C.D., Tucker C.J., Asrar G., Nemani R.R. (1997) - *Increased plant growth in the northern high latitudes from 1981 to 1991*. Nature, 386: 698-702. doi: http://dx.doi.org/10.1038/386698a0.

Ozenda P. (1985) -*La végétation de la chaine alpine dans l'espace montagnard européen, Masson, France*.

Parajka J., Blosch G. (2006) - *Validation of MODIS snow cover images over Austria*. Hydrol. Earth Syst. Sci., 10: 679–689, doi: http://dx.doi.org/10.5194/hess-10-679-2006.

Piao S., Ciais P., Friedlingstein P., Peylin P., Reichstein M., Luyssaert S., Margolis H., Fang J., Barr A., ChenA., Grelle A., Hollinger D.Y., Laurila T., Lindroth A., Richardson A.D., Vesala T. (2008) - *Net carbon dioxide losses of northern ecosystems in response to autumn warming*. Nature 451: 49-52. doi: http://dx.doi.org/10.1038/nature06444.

Picard G., Quegan S., Delbart N., Lomas M.R., Le Toan T., Woodward F.I. (2005) - *Bud-burst modelling in* Siberia *and its impact on quantifying the carbon budget*. Global Change Biology, 11: 2164-2176. doi http://dx.doi.org/10.1111/j.1365-2486.2005.01055.x.

Potts J.T., Shi X.R.R., Raven P.B. (1993) - *Carotid baroreflex responsiveness during dynamic exercise in humans*. American Journal of Physiology, 265, H1928-H1938.

Richardson A.D., Black T.A., Ciais P., Delbart N., Friedl M.A., Gobron N., Hollinger D.Y., Kutsch W.L., Longdoz B., Luyssaert S., Migliavacca M., Montagnani L., Munger J.W., Moors E., Piao S., Rebmann C., Reichstein M., Saigusa N., Tomelleri E., Vargas R., Varlagin A. (2010) - *Influence of spring and autumn phenological transitions on forest ecosystem productivity*. Philosophical Transactions of the Royal Society, Series B, 365: 3227-3246. doi: http://dx.doi.org/10.1098/rstb.2010.0102.

Running S.W., Nemani R.R. (1991) - *Regional hydrologic and carbon balance responses of forests resulting from potential climate change*. Climatic Change, 19, 349-368. doi: http://dx.doi.org/10.1007/BF00151173.

Sacks W. J., Schimel D. S., Monson R. K. (2007) - *Coupling between carbon cycling and climate in a high-elevation, subalpine forest: a model-data fusion analysis*. Oecologia 151: 54-68. doi: http://dx.doi.org/10.1007/s00442-006-0565-2.

Schwartz M.D. (1992) - *Phenology and springtime surface layer change*. Monthly Weather

Review, 120, 2570-2578. doi: http://dx.doi.org/10.1175/1520-0493(1992)120<2570:PASSLC>2.0.CO;2.

Schwartz M.D., Reed B.C. (1999) -*Surface phenology and satellite sensor-derived onset of greenness: an initial comparison*. International Journal of Remote Sensing, 20, 3451-3457. doi: http://dx.doi.org/10.1080/014311699211499.

Schwartz M.D., Reed B.C., White M.A. (2002) - *Assessing satellite-derived start-of-season measures in the conterminous USA*. International Journal of Climatology, 22: 1793-1805. doi: http://dx.doi.org/10.1002/joc.819.

Sellers P.J., Berry J.A., Collatz G.J., Field C.B., Hall F.G. (1992) - *Canopy reflectance, photosynthesis, and transpiration .3. A reanalysis using improved leaf models and a new canopy integration scheme*. Remote Sensing of Environment, 42: 187-216. doi: http://dx.doi.org/10.1016/0034-4257(92)90102-P.

Soudani K., le Maire G., Dufrene E., Francois C., Delpierre N., Ulrich E., Cecchini S. (2008) - *Evaluation of the onset of green-up in temperate deciduous broadleaf forests derived from Moderate Resolution Imaging Spectroradiometer (MODIS) data*. Remote Sensing of Environment, 112: 2643-2655. doi: http://dx.doi.org/10.1016/j.rse.2007.12.004.

Studer S., Stockli R., Appenzeller C., Vidale P.L. (2007) - *A comparative study of satellite and ground-based phenology*. International Journal of Biometeorology, 51: 405-414. doi: http://dx.doi.org/10.1007/s00484-006-0080-5.

Walkovszky A (1998) - *Changes in phenology of the locust tree (Robinia pseudoacacia L) in Hungary*. International Journal of Biometeorology, 41: 155-160. doi: http://dx.doi.org/10.1007/s004840050069.

White M.A., Nemani R.R. (2006) - *Real-time monitoring and short-term forecasting of land surface phenology*. Remote Sensing of Environment, 104: 43-49, 10.1016/j.rse.2006.04.014. doi: http://dx.doi.org/10.1016/j.rse.2006.04.014.

Yang W., Shabanov N.V, Huang D, Wang W., Dickinson R.E., Nemani R.R., Knyazikhin Y., Myneni R.B. (2006) - *Analysis of leaf area index products from combination of MODIS Terra and Aqua data*. Remote Sensing of Environment, 104: 297-312. doi: http://dx.doi.org/10.1016/j.rse.2006.04.016.

Zhang X.Y., Friedl M.A., Schaaf C.B., Strahler A.H., Hodges J.C.F., Reed B.C., Huete A. (2003) - *Monitoring vegetation phenology using MODIS*. Remote Sensing of Environment, 84: 471-475. doi http://dx.doi.org/10.1016/S0034-4257(02)00135-9.

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