Remote Sensing Based Monitoring of Snow-Vegetation Relationships in the European Alps

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Abstract

The response of vegetation phenology and greening to the inter-annual variations of seasonal snow and meteorological factors differ between topographies and climatic subregions in alpine regions. These relationships are essential for human well-being, but a deeper understanding of the most significant controls relating to elevation and geographical subregions is still lacking. This thesis builds time-series vegetation index-derived land surface phenology and greenness mapping and satellite-derived snow cover phenology and gridded snow accumulation metrics for the period of 2003–2014 and analyses snow-vegetation relationships in the European Alps.

Snow-vegetation relationships were analyzed across naturally vegetated areas for seven vegetation types to retrieve geographical heterogeneity, namely elevations and climatic subregions, for more than a decade. In addition to investigating the spatiotemporal change of snow and vegetation metrics, the relative effects of snow factors on land surface phenology and greenness were also identified. These time-series land surface phenology and greenness metrics enabled the detection of the impacts of climate factors (i.e., temperature, precipitation, and relative sunshine duration) and non-climatological effects (such as topography) on alpine vegetation phenology and greening change.

In the European Alps, correlations of snow cover duration with the start or length of season were found to be more pronounced in the northern subregions, at high elevations, and on the north- and west-facing terrain – or more generally, in regions with longer snow cover duration. The correlation differences between climatic subregions are more pronounced at low elevations than at high elevations. In the Swiss Alps, the relationships of snow cover duration or snow accumulation to the start or the length of the alpine growing season was found to be stronger at high elevations than at lower elevations. The relationship between start or length of the growing season and snow cover duration or snow accumulation is strongest in natural grasslands and sparsely vegetated areas. Start of season was influenced primarily by snow cover duration and secondarily by snow accumulation, while length of season was equally affected by snow cover duration and snow accumulation across different elevations. Further, in the alpine grassland of the Swiss Alps, the start of the season was found to be positively correlated with snow cover melt date, but poorly correlated

with spring meteorological metrics after snowmelt. End of season is mainly positively correlated with autumn air temperature below 2000 meters above sea level but negatively correlated with autumn precipitation above 2000 meters. Land surface greenness shows significant positive correlations with snow accumulation and snow cover melt. The areas, sensitive to seasonal snow and meteorological factors, are more pronounced in northern and eastern regions and at higher elevations above 1500 meters above sea level.

This thesis suggests that alpine ecosystems may, therefore, be particularly sensitive to the future change of cover and accumulation of snow and climate warming scenarios at high elevations mainly dominated by grassland. Future variations of snow cover and accumulation could reshape the features and dynamics of alpine ecosystems, such as species composition and their topographic distribution, as a result of response to the new environment if alpine climate perturbations become permanent.

In conclusion, by using time-series remote sensing for alpine vegetation phenology and productivity mapping, this thesis provides a framework and contribution to spatial variation and temporal snow-vegetation relationship monitoring, and to the identification of the effects of seasonal snow and meteorological drivers of change on alpine vegetation phenology and productivity, depending on elevations at landscape level.

Future research directions proposed include calibration and validation of satellite-derived land surface phenology using field-observed and herbarium phenology records for improved ground truthing and spatial resolution. Furthermore, identifying the controls that primarily determine vegetation phenology and productivity over large spatial scales requires thorough understanding of the geographical variation and relative importance of various environmental factors on land surface phenology and greenness. These open questions still need detailed assessment, which will permit better quantification of vegetation responses to the changing climate.

Zusammenfassung

Die Reaktion von Vegetationsphänologie und Greening auf jährliche Schwankungen von Schnee und meteorologischen Faktoren unterscheidet sich durch die Topographie und die klimatischen Teilregionen in alpinen Gebieten. Obwohl sie für das menschliche Wohlbefinden unerlässlich sind, fehlt noch immer ein tieferes Verständnis der wichtigsten einflussnehmenden Prozesse im Bezug auf die Höhenlage und auf geografische Teilregionen. Die vorliegende Arbeit erstellt auf Basis von Vegetationsindizes Zeitreihen der Landoberflächenphänologie, der Greenness, der satellitengestützten Schneebedeckungsphänologie und der Schneeakkumulation in den europäischen Alpen im Zeitraum von 2003 – 2014. Die Beziehung Schnee-Vegetation wurde für sieben Vegetationstypen in naturbelassenen Gebieten analysiert, um die geografische Heterogenität, hervorgerufen durch Höhenlagen und klimatische Teilregionen, zu bestimmen.

Es wurde entdeckt, dass in den europäischen Alpen die Korrelation der Schneebedeckungsdauer mit Beginn und Dauer der Vegetationsperiode in nördlichen Teilregionen, in höheren Lagen und im nach Norden und Westen ausgerichteten Gelände, oder allgemeiner, in Regionen mit längerer Schneebedeckungsdauer, ausgeprägter ist. Die Unterschiede der Korrelationen zwischen den klimatischen Teilregionen sind in niedrigen Lagen stärker ausgeprägt als in hohen. In den Schweizer Alpen wurde festgestellt, dass die Abhängigkeit von Schneebedeckungsdauer und Schneeakkumulation zu Beginn und Dauer der alpinen Vegetationsperiode in hohen Lagen stärker ist als in niedrigen. Die Abhängigkeit zwischen Beginn und Dauer der Vegetationsperiode und der Dauer der Schneebedeckung und der Schneeakkumulation ist am stärksten in natürlichen Graslandschaften und nur spärlich bewachsenen Gebieten. Der Beginn der Vegetationsperiode wurde hauptsächlich durch die Dauer der Schneebedeckung und sekundär durch die Schneeakkumulation beeinflusst, während die Dauer der Vegetationsperiode in verschiedenen Höhenlagen gleichermassen durch die Dauer der Schneebedeckung und die Schneeakkumulation beeinflusst wurde. Desweiteren fand die vorliegende Doktorarbeit, dass im alpinen Grasland der Schweizer Alpen der Beginn der Vegetationsperiode signifikant positiv mit dem Schmelzzeitpunkt der Schneedecke korreliert, aber schlecht mit den meteorologischen Messgrössen im Frühling nach der Schneeschmelze. Das Ende der Vegetationsperiode ist unter 2000

Meter über dem Meeresspiegel hauptsächlich positiv mit der Lufttemperatur im Herbst korreliert, aber negativ mit den Niederschlägen im Herbst in Regionen über 2000 Meter. Das Grün der Landoberfläche zeigt signifikante positive Korrelationen mit der Schneeakkumulation und der Schmelze der Schneebedeckung. Die nördlichen und östlichen Regionen sowie die Lagen über 1500 Meter über dem Meeresspiegel reagieren empfindlicher auf saisonalen Schnee und meteorologische Einflüsse.

Die vorliegende Arbeit legt daher nahe, dass alpine Ökosysteme besonders empfindlich reagieren auf zukünftige Änderungen der Schneebedeckung und -akkumulation sowie der Klimaerwärmung in hohen, hauptsächlich von Grasland dominierten Lagen. Falls zukünftige Schwankungen der Schneebedeckung und -akkumulation zu dauerhaften Veränderungen im alpinen Klima führen, könnten sich die Eigenschaften und Dynamiken alpiner Ökosysteme, wie z.B. die Artenzusammensetzung und ihre topographische Verteilung, als Reaktion auf die neuen Bedingungen verändern.

Zusammenfassend stellt diese Doktorarbeit durch die Verwendung von Fernerkundungs-basierten Zeitreihen zur Bestimmung der alpinen Vegetationsphänologie und der Produktivität, ein Framework und einen Beitrag zur Überwachung der räumlichen Variation und des zeitlichen Schnee-Vegetations-Verhältnisses, als auch zur Bestimmung der Effekte saisonalen Schnees und meteorologischer Treiber auf Veränderungen der alpinen Vegetationsphänologie und –produktivität auf Landschaftsebene in Abhängigkeit von der Höhe, zur Verfügung.

Zukünftige Forschungsrichtungen beinhalten die Kalibrierung und Validierung der satellitengestützten Landoberflächenphänologie unter Verwendung von Feldbeobachtungen und Herbariumphänologieaufzeichnungen für eine verbesserte Kalibrierung und eine höhere räumliche Auflösung. Darüber hinaus erfordert die Bestimmung der primären grossräumigen Einflussfaktoren auf die Vegetationsphänologie und die Produktivität ein tiefgehendes Verständnis der geografischen Veränderungen und der relativen Bedeutung der verschiedenen Umweltfaktoren auf die Landoberflächenphänologie und das Greening.

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List of Abbreviations

AP	Average of mean autumn precipitation
AT_{max}	Average of max autumn temperature
AT_{min}	Average of min autumn temperature
AT_{mean}	Average of mean autumn temperature
ARSD	Average of mean autumn relative sunshine duration
AVHRR	Advanced very high resolution radiometer
DEM	Digital elevation model
EOS	End of season
EVI	Enhanced vegetation index
GIMMS	Global inventory modeling and mapping studies
HISTALP	Historical Instrumental Climatological Surface Time Series of The Greater Alpine Region
Landsat ETM	Landsat Enhanced Thematic Mapper
FSF	First snow fall
LAI	Leaf area index
LAI_{mean}	Mean LAI between SOS and EOS
Landsat TM	Landsat thematic mapper
Landsat ETM	Landsat enhanced thematic mapper
LSD	Last snow day
LSP	Land surface phenology
m asl	Metres above sea level
MODIS	Moderate resolution imaging spectroradiometer
MP	Average of mean summer precipitation
MRSD	Average of mean summer relative sunshine duration
MT_{max}	Average of max summer temperature
MT_{min}	Average of min summer temperature
MT_{mean}	Average of mean summer temperature
NDVI	Normalized difference vegetation index
$NDVI_{mean}$	Mean NDVI between SOS and EOS
$NDVI_{peak}$	Peak NDVI between SOS and EOS
P	Precipitation
POS	Peak of season
$P_{\_melt7}$	Average value of Precipitation in 7-days after SCMD
$P_{\_melt14}$	Average value of Precipitation in 14-days after SCMD
$P_{\_melt21}$	Average value of Precipitation in 21days after SCMD
$P_{\_melt28}$	Average value of Precipitation in 28-days after SCMD
$RSD_{\_melt7}$	Average value of Relative Sunshine Duration in 7-days after SCMD
$RSD_{\_melt14}$	Average value of Relative Sunshine Duration in 14-days after SCMD
$RSD_{\_melt21}$	Average value of Relative Sunshine Duration in 21days after SCMD
$RSD_{\_melt28}$	Average value of Relative Sunshine Duration in 28-days after SCMD
SA	Snow accumulation (mean SWE from January to April)

SCD	Snow cover duration
SCMD	Snow cover melt day
SCM	Snow cover maps
SCOD	Snow cover onset day
SD	Standard deviation
SWE	Snow water equivalent
SWE_m	Mean SWE of the corresponding SCD in each WY
SWE_{acc}	Mean SWE in the accumulation period (from January to April)
SP	Average of mean spring precipitation
SRSD	Average of mean spring relative sunshine duration
ST_{max}	Average of max spring temperature
ST_{min}	Average of min spring temperature
ST_{mean}	Average of mean spring temperature
SOS	Start of season
T_a	Air temperature
T_{max_melt7}	Average value of max Temperature in 7-days after SCMD
T_{max_melt14}	Average value of max Temperature in 14-days after SCMD
T_{max_melt21}	Average value of max Temperature in 21days SCMD
T_{max_melt28}	Average value of max Temperature in 28-days after SCMD
T_{mean_melt7}	Average value of mean Temperature in 7-days after SCMD
T_{mean_melt14}	Average value of mean Temperature in 14-days after SCMD
T_{mean_melt21}	Average value of mean Temperature in 21-days after SCMD
T_{mean_melt28}	Average value of mean Temperature in 28-days after SCMD
T_{min_melt7}	Average value of min Temperature in 7-days after SCMD
T_{min_melt14}	Average value of min Temperature in 14-days after SCMD
T_{min_melt21}	Average value of min Temperature in 21-days after SCMD
T_{min_melt28}	Average value of min Temperature in 28-days after SCMD
UTM	Universal Transverse Mercator
WP	Average of mean winter precipitation
WT_{max}	Average of max winter temperature
WT_{min}	Average of min winter temperature
WT_{mean}	Average of mean winter temperature
WRSD	Average of mean winter relative sunshine duration
WSL	Swiss Federal Institute for Forest, Snow and Landscape Research

Chapter 1

Introduction

1.1 Remote sensing for tracking alpine vegetation phenology

1.1.1 Background

Plant phenology is the study of the timing of recurring biological events in the life cycle of organisms as affected by the environment (Lieth 1974). Monitoring vegetation phenology is not only important to understand the response of vegetation to short- and long-term climate change, but also to determine the feedback mechanisms that plant response may generate on the environment and climate (Dannenberg *et al*. 2018; Flynn and Wolkovich 2018; Fu *et al*. 2015; Keenan 2015; Morisette *et al*. 2009; Pastor-Guzman *et al*. 2018; Peñuelas *et al*. 2009). Optical remote sensing provides remarkable data for quantifying one aspect of plant leafing phenology: multispectral sensors have systematically tracked the greenness of vegetation, and how it varies through time, at millions of locations across the entire planet for over 40 years. These time-series of vegetation greenness can be used retrospectively to quantify the timing of greening-up and senescence of vegetation (referred to as land surface phenology; e.g., time-series normalized difference vegetation index (NDVI), see Figure 1.1).

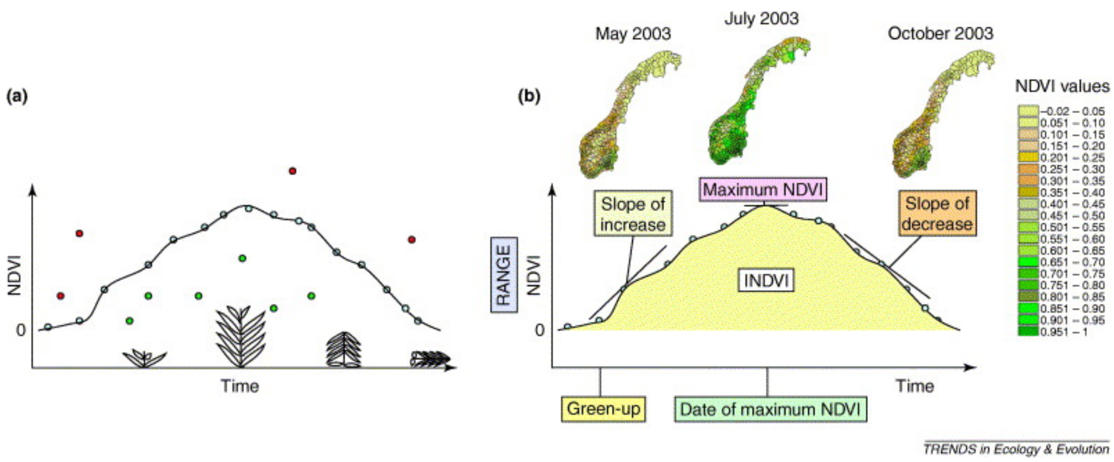

Figure 1.1 NDVI time-series. (a) Presentation of the three types of NDVI data that can be collected: data collected during a cloudy day (green circles), a clear day (blue circles), and 'false high' NDVI values (red circles) owing to transmissions errors. Because of this diversity in the quality of information contained in NDVI values, the time-series needs to be smoothed. A typical smoother (black line) will rebuild the NDVI profile based mainly on clear-day estimates. The NDVI time-series over a year typically shows an increase that corresponds with the start of vegetation growth, the NDVI then peaks, establishing a plateau (which corresponds to a period of high photosynthetic activity), and then finally decreases,

corresponding with the start of vegetation senescence. (b) Presentation of the different indices (the slopes of increase (spring) and decrease (fall), the maximum NDVI value, the Integrated NDVI (INDVI, i.e. the sum of NDVI values over a year), the date when the maximum NDVI value occurs, the range of annual NDVI values, and the date of green-up (i.e. the beginning of the growing season)) that could be derived from NDVI time series over a year. Moreover, maps presenting NDVI values (ranging from 0 to 1) for Norway in May, July and October 2003 are also shown. Those data have been provided by the Global Inventory Modeling and Mapping Studies (GIMMS) group (http://ltpwww.gsfc.nasa.gov/gimms/htdocs/; the pixel size being 64 km^2). [Modified after permission from Pettorelli et al. (2005), p. 507].

1.1.2 Monitoring leafing phenology by remote sensing

Recent studies have used long-term field observations of the timing of flowering, leafing out, and leaf fall in response to evaluate how plant species are responding to inter-annual climate variability and global warming (Cleland *et al*. 2006; Fu *et al*. 2014; Parmesan 2007; Seyednasrollah *et al*. 2018; Vitasse *et al*. 2018; Walther *et al*. 2002; Wang *et al*. 2017). However, these studies focused on few species (Chen *et al*. 2015a; Pellerin *et al*. 2012) and have limited spatial coverage (Fisher *et al*. 2006; Klosterman *et al*. 2018; Melaas *et al*. 2016; Miller-Rushing *et al*. 2006; Panchen *et al*. 2012; Studer *et al*. 2007; Willis *et al*. 2017). Remote sensing provides remarkable long-term data on the phenology of vegetation greenness but few studies have exploited this data to evaluate changes of greenness in response to climate change in real-world ecosystems over large spatial scales. Vegetation greenness has been monitored routinely for almost two decades by calculating the NDVI (Tucker 1979) or enhanced vegetation index (EVI) (Huete *et al*. 2002) from data collected from satellite-based optical sensors including advanced very high resolution radiometer (AVHRR), moderate resolution imaging spectroradiometer (MODIS), satellite for observation of Earth (SPOT), Landsat thematic mapper/ enhanced thematic mapper (TM/ETM) (Fisher *et al*. 2006; Pettorelli *et al*. 2005) and Landsat 8 (Melaas *et al*. 2018). Thus vegetation greenness is being recorded regularly within small pixels across the whole globe, allowing land surface phenology to be tracked (e.g., White *et al*. (2009), Trujillo *et al*. (2012), Oehri *et al*. (2017)) at a global scale, and consistently tracked over timescales relevant to understanding responses to a changing climate

(Stöckli and Vidale 2004; Trujillo *et al*. 2012; Yu *et al*. 2013).

1.1.3 Monitoring alpine vegetation phenology by satellite derived data

The study area in Chapter 2 of this thesis is the central European Alps region, whose borders are defined by the Alpine Convention (http://www.alpconv.org/, accessed July 2015). This region is centrally located on the European continent and covers 168,252 km^2 (Figure 1.2), i.e., 88.2% of the entire Alps (5.8°E–14.2°E, 43.8°N–48.2°N). The area is dominated by a typical alpine climate (Brunetti *et al*. 2009a), and commonly separated into four climatic subregions (Auer *et al*. 2007): north-west (NW; temperate westerly, oceanic features; 53,691 km^2, 32% of total area), north-east (NE; temperate westerly, continental features; 23,547 km^2, 14%), south-east (SE; Mediterranean subtropical, continental features; 15,082 km^2, 9%) and south-west (SW; Mediterranean subtropical, oceanic features; 75,932 km^2, 45%). The delineation of climatic subregions was defined according to the statistical regionalization of different climate elements, such as precipitation and temperature, as obtained from Historical Instrumental Climatological Surface Time Series of The Greater Alpine Region (HISTALP) (Auer *et al*. 2007). The subregions are assumed to reflect different snow-vegetation correlation regimes. The average annual accumulative precipitation (between 2003-2014) ranges between 1100 and 1400 mm, with maximum values occurring at lower elevations of the SE. The mean annual temperature (between 2003-2014) ranges from -5 °C to 12 °C in lower elevational zones across the study region. The Alps are subject to strong topographic variability (Auer *et al*. 2007; Scherrer *et al*. 2004b). The area is characterized by extensive lowlands, deeply incised valleys and highest peaks at an elevation of more than 4,800 m above sea level (asl). Natural vegetation (NV) covers 68.5% of the study area (Figure 1.2). The predominant NV cover types in the study region are Natural Grasslands (NG, 15.5%) and forests (64.1% of NV, including Broad-leaved Forest (BF), Coniferous Forest (CF) and Mixed Forest (MF)).

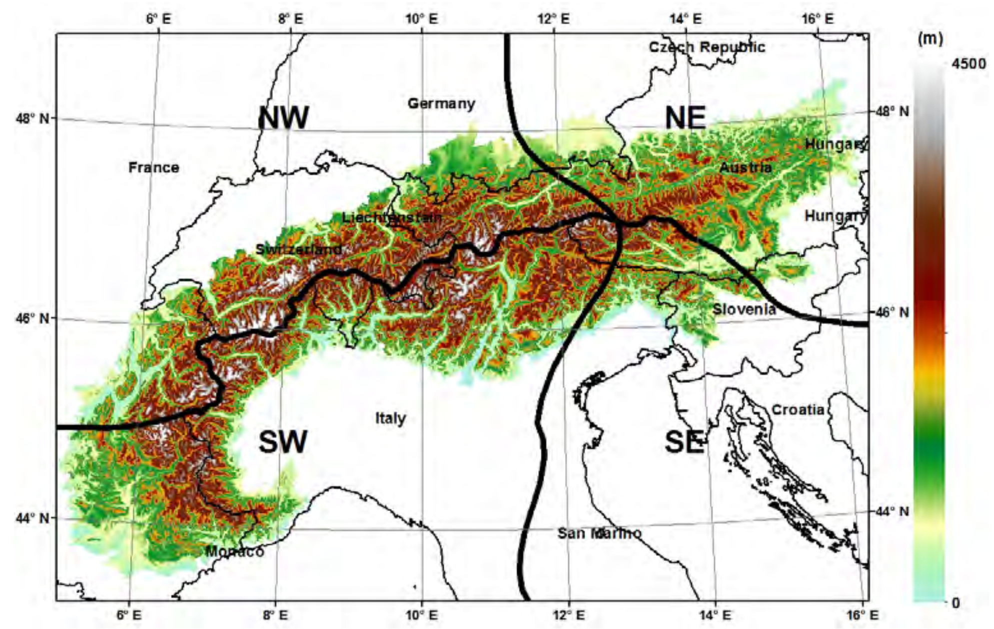

Figure 1.2 Topography of the study regions. The black lines indicate the subdivision into four main climate subregions according to Auer *et al*. (2007).

The study area in Chapter 3 and 4 of this thesis, the Swiss Alps (6.8°E–10.5°E, 45.8°N–47.4°N), encompass an area of 25 194 km^2 (Figure 1.3). These areas were selected for analysis due to their typical mountain character with complicated topography (Jonas *et al*. 2008; McVicar *et al*. 2010; Scherrer *et al*. 2004a), as well as long-term changes of snow attributed to climate changes (Beniston *et al*. 2003b; Marty *et al*. 2017; OcCC-Consortium 2007). The study region was separated into the Northern Swiss Alps (NSA; 10 867 km^2, 43.1% of total area), the Eastern Swiss Alps (ESA; 5825 km^2, 23.1%), the Southern Swiss Alps (SSA; 3667 km^2, 14.6%), and the Western Swiss Alps (WSA; 4834 km^2, 19.2%) according to the subdivision of biogeographical regions (Gonseth *et al*. 2001). NSA, WSA and ESA are subject to temperate westerly and oceanic features, while SSA experiences Mediterranean subtropical and oceanic features (Auer *et al*. 2007). At particular times, the NSA often show different climatic conditions compared to the SSA (Laternser and Schneebeli 2003). The climate of the four subregions has differed in past decades and is expected to differ in the projected future (Rammig *et al*. 2010). The subregions are assumed to reflect different ecological and climatological regimes.

In Chapter 3, this thesis focuses on 6 NV types (Figure 1.3), excluding the areas that experienced land cover changes (2.5% of NV in 2000) between 2000-2012, based on the CORINE Land Cover 2000 and 2012 seamless vector data (http://land.copernicus.eu/, accessed May 2017). NV types in this statistical analysis cover 60.0% of the study area and include BF (6.8% of NV), MF (8.8% of NV), CF (35.7% of NV), MH (7.1% of NV), NG (32.0% of NV) and SV (10.1% of NV). The NV types grow at elevations up to 3000 m asl. The absence of permafrost is below 2580 m asl (Luetschg *et al*. 2004), and the alpine–nival ecotone is around 3000 m asl (Gottfried *et al*. 2011).

In Chapter 4, this thesis focuses on NG regions (covering 19.2% of the study area), based on the CORINE Land Cover 2000 seamless vector data (http://land.copernicus.eu/, accessed December 2017). NG includes pastures and meadows (Pasolli *et al*. 2015) and ranges from 1000 to 3000 m asl (Figure 1.3).

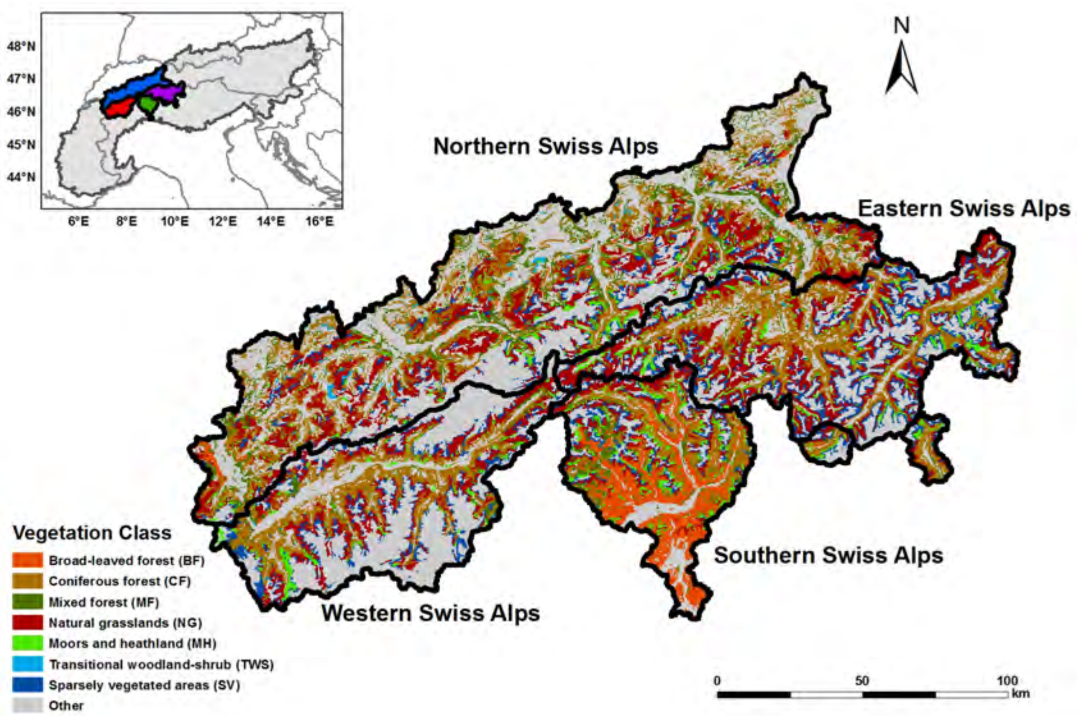

Figure 1.3 Location and natural vegetation types of the Swiss Alps (separated as NSA, ESA, SSA and WSA).

MODIS MOD13Q1-version 005 NDVI data were used to derive yearly LSP metrics for SOS, EOS and LOS on a pixel-level basis. NDVI is one of the most widely used indices for the monitoring of vegetation phenological events at various scales (e.g., Fisher *et al*. (2006), Piao *et al*. (2006), Cleland *et al.* (2007)). A total of

276 MODIS/Terra Vegetation Indices 16-Day L3 Global 250-m SIN Grid products were used in this thesis. The available 276 MOD13Q1 images were 16-day composites spanning 2003 to 2014, with 250 m spatial resolution and corresponding quality and day-of-observation information data.

The MODIS NDVI products were transformed from the native sinusoidal projection into the UTM 32 projection. Quality Assurance (QA) of the MODIS NDVI values and Maximum Value Composite (MVC) datasets over the 16 day period accounted for the use of MOD13Q1 Band 2 and 10, which contain detailed QA (better than "Lowest quality", and "Lowest quality" (QA flag value ≤ 12) were selected, based on the quality statistical results) and MVC information (16-bit binary) to generate higher quality, cloud free NDVI products. Figure 1.4 illustrates NDVI in one pixel and the corresponding quality record (QA flag value ≤ 12 was defined as 1).

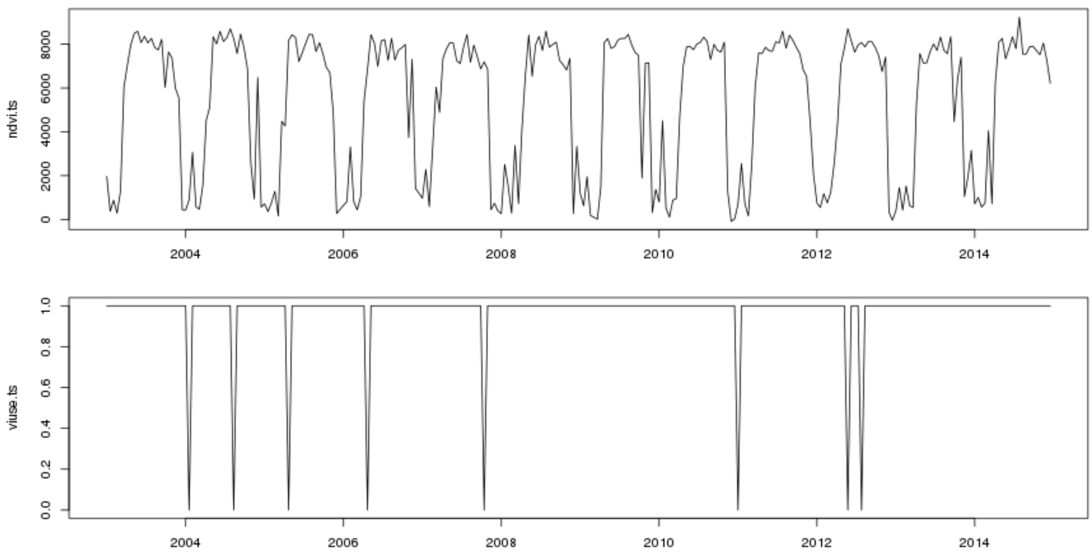

Figure 1.4 Illustration of NDVI in one pixel and the correpending quality record.

To each annual time series of NDVI data, this thesis first applied harmonic analysis to interpolate between two observations, taking into account the day of observation as provided within MOD13Q1 data. To derive SOS timing from annual NDVI time series, the day when NDVI reaches half its annual range was selected. This relative threshold method - called $\text{Midpoint}_{\text{pixel}}$ - is based on the comprehensive inter-comparison of SOS metrics by White *et al*. (1997) and makes it possible to account for spatial variability in NDVI dynamics within the region (see Figure 1.5). The EOS is then defined as the day at which NDVI reaches the midpoint again in the calendar year, and the LOS is simply the number of days between SOS and EOS. SOS and EOS are always expressed in day of (calendar) year (DOY), and LOS in days.

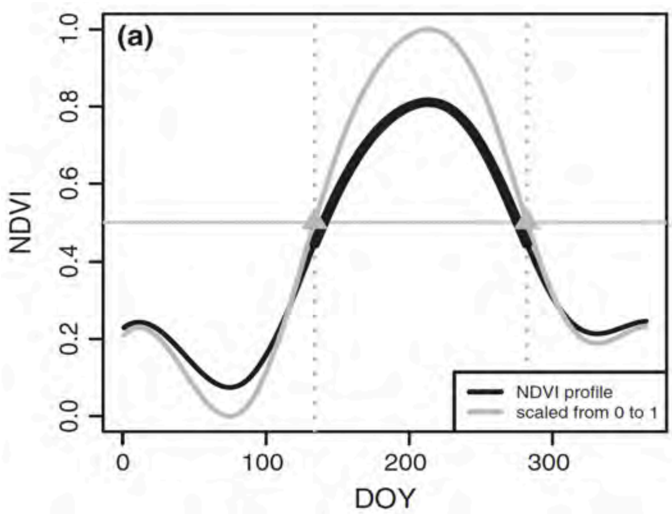

Figure 1.5 Illustration of midpoint$_{pixel}$. The black bold line highlights the growing season as extracted from our algorithm. The grey triangles represent start-of-season (SOS) and end of season (EOS) dates, respectively. [Modified after permission from Garonna *et al.* (2014), p. 3460].

Additionally, in Chapter 4, the POS and the NDVI$_{max}$ were derived between SOS and EOS according to the definition from Zhang *et al.* (2003). POS is expressed in DOY. The amount of pixels with LSP metrics takes 96.3% of NG areas. Both NDVI and LAI correlate well with the productivity and greenness of vegetation (Asam *et al.* 2013; Myneni *et al.* 1997a; Pasolli *et al.* 2015; Pettorelli *et al.* 2005). To compute the greenness metrics, the NDVI and LAI products, provided by the Institute for Applied Remote Sensing of EURAC research, were employed. These data comprise an NDVI and LAI time series at a 250-m/4-days resolution in the Alps covering the years 2003-2014. The NDVI and LAI values are determined for NG according to the CORINE 2006 land cover classification. LAI is closely correlated with total biomass of grassy species (Halabuk *et al.* 2013). The LAI maps are produced with an innovative algorithm developed by EURAC based on radiation transfer modeling (Pasolli *et al.* 2015). This algorithm exploits the 250 m MODIS surface reflectance data and thus produces LAI at a higher resolution concerning the MODIS standard product (1-km resolution). The NDVI and LAI images were re-sampled at a daily resolution. The changed NG areas between 2000 and 2006 were removed according to the CORINE

Land Cover 2000 and 2006 seamless vector data. Then, the $NDVI_{mean}$ and LAI_{mean} as the metrics of the greenness of the NG growing season were calculated between SOS and EOS. The amount of $NDVI_{mean}$ pixels takes 93.7% of NG areas, and the amount of LAI_{mean} pixels takes 68.5% of NG areas.

1.2 Monitoring the timing and accumulation of alpine snow

1.2.1 Background

With timing and accumulation of snow being among the important climate drivers, seasonal thawing and snowmelt affect the potential production and length of growing season for vegetation at mid-northern latitudes (Walker *et al*. 2014). Alpine seasonal snow plays a significant role in the global climate system (Brigham *et al*. 2018; IPCC 2007), and a major role in regulating mountain ecosystems (Jonas *et al*. 2008; Vitasse *et al*. 2017). Annual change of snowmelt or snow cover may induce strong ecosystem responses. Together with other environmental factors, snow is one of the essential environmental parameters controlling high-elevation vegetation phenology (Cornelius *et al*. 2013; Wipf *et al*. 2009). Figure 1.5 is an example of the overview of the snow cover landscape in one corner of the European Alps.

An increase in annual mean temperatures of about 1.1 °C has been observed in the European Alps over the past 100 years (Böhm *et al*. 2001). The expected continuation of this warming (IPCC 2018) is likely to result in more frequent early snowmelt events (Foppa and Seiz 2012b). For instance, winter warming could result in snow fall reduction, or reduction in the duration of snow cover, thereby increasing soil freezing (Groffman *et al*. 2006) and root mortality (Peng *et al*. 2010b; Wahren *et al*. 2005). The timing and accumulation of snow (Beniston *et al*. 2003a; Dorjia *et al*. 2018; Hüsler *et al*. 2014; Trujillo *et al*. 2012) have been reported to change with elevation. For a long time, the timing and accumulation of snow has been referenced as one of the important drivers of mountainous ecosystems across topographic gradients (Vitasse *et al*. 2017; Wipf and Rixen 2010).

Figure 1.5 Overview photography of snow covered landscape in the European Alps (photo taken on 12 May 2016 by Jing Xie).

1.2.2 Seasonal snow in alpine regions

The timing and accumulation of snow cover are known to be subject to interdependent and interconnected relationships. For instance, the date of snow disappearance shows a strong correlation with the maximum snowpack accumulation (Trujillo *et al*. 2012). In combination with spring temperatures, the winter snow depth determines the time of snow melting (Richardson *et al*. 2013). Snow depth is closely related to snow water equivalent (Grippa *et al*. 2005a) and usually used to estimate this metric (Jonas *et al*. 2009; Magnusson *et al*. 2014). Moreover, snow cover duration is closely linked to both the start day and melt day of snow cover in high elevational regions with continuous snow cover (Hüsler *et al*. 2014). However, the characteristic and magnitude of the correlation between snow timing and snow accumulation across elevation still need detailed understanding.

No single ecological factor can offer a significant statistical explanation to mountainous vegetation ecology (Löffler 2005). The ecosystem in snow sensitive regions, where weak or no interdependence between timing and accumulation of snow exists, needs further assessment through the use of multiple snow metrics. Thus, in particular, the question of the relative importance of the timing and accumulation of snow, which is significant to a mountainous ecosystem, remains to be answered.

1.2.3 Monitoring the timing and accumulation of alpine snow

In Chapter 2 and Chapter 3, this work defines the SCD as the total number of snow-covered days in each Water Year (WY, running from 01 October to 30 September of the following year) (Hüsler *et al*. 2014), the FSF as the date of first snow fall in each WY, the LSD as the last snow-covered date in each WY, and the SWE_m as the average value of SWE of the corresponding SCD in each WY. These snow metrics can provide information about the current status of timing of snow cover and accumulation of seasonal snow characteristics and were used to examine the spatiotemporal variation of snow conditions in the European Alps for the period 2002-2014.

In Chapter 4, this work defines the SWE_{acc} as an average value of SWE from January 1^{st} to April 30^{th} at a pixel. SCMD is defined as the first date after February 15^{th} with a snow-covered fraction below 33% at a pixel. The unit of SWE_{acc} is millimeters (mm), and SCMD is expressed in DOY. These snow metrics provide useful information about the status of accumulation and melt of seasonal snow characteristics and can be used to examine the spatiotemporal snow variation in the Swiss Alps over the period 2002-2014.

In Chapter 2 and 3 MODIS snow products with a spatial resolution of 250 m were used to derive SCP for 12 WY (running from 01 October to 30 September of the following calendar year) between 2002-2014 for the European Alps region, including cloud removal. FSF, LSD and SCD were derived from snow maps obtained from MODIS/Terra data using a novel algorithm developed by EURAC (European Academy, Bolzano, Italy) in order to take into account the specific characteristics of mountain areas. The two main characteristics of the algorithm are the improved ground resolution of 250 m and a tailored topographic correction (Notarnicola *et al.* 2013a, b). The study area covers the alpine arc and SCD, FSF and LSD have been derived on a yearly basis for the WY period from 2002-2014.

The daily availability of snow maps allowed the calculation of SCD without gaps (Figure S1 of 3.8 Supporting Information). The FSF was defined as the first date in the WY when a pixel is snow covered. For each pixel of the snow map, the implemented algorithm extracted the first date when there is snow. With the proposed approach, the FSF calculation was also taking into account the sporadic snowfall in the early autumn. Consequently, it did not always refer to the starting date of the continuous winter snow covered period. The LSD is the last date in the WY when a pixel is snow covered, and it provides useful information about the melting process. To calculate LSD, the algorithm extracted, from the time series of snow maps of every WY, the last day in which the pixels were snow covered. Furthermore, in order to eliminate erroneous pixels due to misclassification, the final maps of FSF and LSD were filtered to remove pixels where i) the FSF date was in the range between DOY 91 (1 April) and DOY 181 (30 June) and ii) the SCD was <10. These parameters provide information about the current status of snow cover characteristics and were used to examine the spatiotemporal variation of snow cover condition.

To derive the accumulation of snow metrics, the SCM at 250-m/daily resolution was employed (Notarnicola *et al*. 2013a, b) and the SWE grids at 1-km/daily resolution (Jonas *et al*. 2009; Magnusson *et al*. 2014). SCM were obtained from MODIS images with a tailored topographic correction and improved ground resolution of 250 m in order to take into account the specific characteristics of mountainous areas (Notarnicola *et al*. 2013a, b). Daily SWE grids, which were generated on the basis of 298 observational snow monitoring sites in Switzerland using a distributed snow hydrological model *(Griessinger et al. 2016; Magnusson et al*. 2014), were resampled with 250 m resolution in order to match the SCM.

The LSD can provide useful information about the melting process, given that multiple late season transient snow patterns and snowfall occur during snowmelt seasons (Crawford *et al*. 2013; Hüsler *et al*. 2014) across elevations. Moreover, a pixel of the SWE grid is involved in the calculation of SWE_m only if the corresponding SCM pixel is identified as snow cover. The detailed calculations of SCD and SWE_m are presented in Figure S1 of 3.8 Supporting Information.

1.3 Remote sensing for monitoring snow-vegetation relationships

1.3.1 Background

Given the recent trend (IPCC 2014) in global warming and that warming is expected to continue in the next decades (IPCC 2018), reports have indicated considerable activity and shifts in the Earth's ecosystem (Graven *et al.* 2013; Myneni *et al.* 1997b; Parmesan 2006; Parmesan and Yohe 2003; Peñuelas and Filella 2001; Root *et al.* 2003; Testa *et al.* 2018; Xu *et al*. 2013). Phenological shifts and the change of productivity have been referred to as 'significant and observable tracks in ecosystem response to climate change' (Menzel *et al*. 2006; Trujillo *et al*. 2012; White *et al*. 2009; Workie and Debella 2018), and as key determinants of coupled carbon exchange (Mack *et al*. 2004; Richardson *et al*. 2013; Ward *et al*. 2017) and land surface water fluxes (Barrio *et al*. 2013; Cleland *et al*. 2007; Richardson *et al*. 2010). These variations influence the distribution and abundance of species (Chuine and Beaubien 2001; Jonas *et al*. 2008) and their genetic makeup (Diez *et al*. 2012; Fox 2003; Primack *et al*. 2009), and may also threaten species which have synchronized life cycles (Post *et al*. 2009; Thomas *et al*. 2004). Thus, studying the phenology and productivity of vegetation is critical for terrestrial ecologists to allow better predictions of the influence of climate change on land surface ecosystems.

Recent climate warming was reported to have led to considerable activity and shifts in phenology across ecosystems (Graven *et al*. 2013; Myneni *et al*. 1997b; Parmesan 2006; Parmesan and Yohe 2003; Peñuelas and Filella 2001; Root *et al*. 2003; Xu *et al*. 2013). Specifically, the differences in the atmospheric heating of snow-covered and snow-free ecosystems in spring are larger than that in autumn (Euskirchen *et al*. 2007). The spring phenology is, thus, particularly sensitive to the change of climate factors (Bennie *et al*. 2010; Chuine *et al*. 2010; Flynn and Wolkovich 2018; Fu *et al*. 2015; Piao *et al*. 2006). The inter-annual variations of climatic and climate-relative factors induce strong responses in the vegetation phenology (Jonas *et al*. 2008; Sharifi *et al*. 2018; Wipf and Rixen 2010). As a consequence, quantifying the influence of climate and climate-related factors on vegetation phenology and productivity is crucial to understanding the mechanism by which ecological dynamics respond to environmental stimuli in mountainous regions under further increases in climate warming.

1.3.2 Snow-vegetation relationships in alpine regions

The firm link between phenological changes and seasonal temperature variability suggests that broad-scale and long-term observations of phenology could serve as a proxy for global climate change over space and time (Garonna *et al.* 2016; Garonna *et al.* 2018; Myneni *et al.* 1997b; White *et al*. 1997). For instance, advances of spring phenology were reported to show biological responses to warmer spring temperatures (Delbart *et al*. 2008; Flynn and Wolkovich 2018; Fu *et al*. 2014; Menzel *et al*. 2006; Parmesan 2006; Peñuelas and Filella 2001) with estimates ranging from 0.23 days (Parmesan and Yohe 2003) to 0.55 days (Root *et al*. 2003) per year across groups of species. Therefore, much attention focused on the detection of temperature-induced trends in vegetation phenology. Furthermore, air temperature is the primary environmental control regulating the spring phenology in temperate and boreal trees (Linkosalo *et al*. 2009), and recent climatic warming is already resulting in an advancement of the vegetation phenology (Delbart *et al*. 2008; Garonna *et al*. 2016; Menzel *et al.* 2006; Schwartz *et al*. 2006). These changes may, in turn, affect the long-term distribution of plant species (Chuine 2010). Therefore, phenology of vegetation in European Alps may be mainly influenced by temperature.

With snow cover being among important climate-related drivers, alpine snow cover plays a significant role in the global climate system (IPCC 2007, 2014) and is one of the essential environmental parameters controlling high-elevation vegetation phenology (Badeck *et al*. 2004; Cornelius *et al*. 2013; Keller *et al*. 2005; Wipf and Rixen 2010; Wipf *et al*. 2009). Changes in snow cover have been reported to influence the land surface energy balance significantly (Chen *et al*. 2015b; Chen *et al*. 2015c; Euskirchen *et al*. 2007) and water cycling (Barnett *et al*. 2005; Rawlins *et al*. 2006), which have reverse implications for spring phenology (Dorrepaal 2003; Goulden ML 1998; Monson *et al*. 2006). Seasonal thawing and snow melt affect the potential production and growing season length of vegetation at mid-northern latitudes (Walker *et al*. 2014). Plants adapted to changes in the duration of snow cover can show distinct responses to snow melt advancement or delay (Keller and Körner 2003; Wipf and Rixen 2010; Wipf *et al*. 2006). Furthermore, snow cover can regulate the growth of alpine vegetation and block off sunlight needed for photosynthesis (Jonas *et al*. 2008). Snow protects vegetation from dry and severe cold conditions and simultaneously supplies moisture (Buckeridge and Grogan 2008; Desai *et al*. 2016; Ide and Oguma 2013; Inouye 2008; Schimel *et al*. 2004). Thus, snow might be the most important controlling factor of spring phenology at high elevations. Changes in seasonal patterns of snow are related to plant photosynthesis and growth in the snow-free season (Galvagno *et al*. 2013; Rossini *et al*. 2012), thus influencing ecosystem functioning (Saccone *et al*. 2012). However, combined with the winter and spring temperature, the magnitude of the influence of snow cover phenology on spring phenology is not yet well known.

Recent studies reported that senescing autumn phenology can result in an extension of the growing period (Garonna *et al*. 2014; Zhu *et al*. 2012) and therefore plays an indispensable role in regulating carbon cycling in temperate vegetation (Piao *et al*. 2008; Richardson *et al*. 2010). Autumn phenology was found to show positive significant relationship with autumn air temperature, precipitation, and photoperiod (Gill *et al*. 2015; Jeong *et al*. 2011; Liu *et al*. 2016; Ren *et al*. 2017; Sun *et al*. 2014). Several studies report weak or insignificant relationship between air temperature and autumn senescence (Menzel *et al*. 2006; Pudas *et al*. 2008). Besides, recent experimental results show that warmer summers affect autumn senescence (Gunderson *et al*. 2012; Marchin *et al*. 2015).

Variations in seasonal snow may interact with air temperature and therefore affect greenness, duration, and the peak biomass of plant growth (Legay *et al*. 2013; Yu *et al*. 2013). Winter warming could result in snowfall reduction, or shorter duration of snow cover, thereby increasing soil freezing (Groffman *et al*. 2006) and root mortality (Peng *et al*. 2010a; Wahren *et al*. 2005), which in turn leads to a reduction of vegetation growth (Grippa *et al*. 2005b). For instance, in the forested regions of the Sierra Nevada region, maximum snow accumulation was reported to show significant positive relationships with the inter-annual variability of the maximum greening of forests between 2000-2600 m asl (Trujillo *et al*. 2012). In the grasslands of China, winter snow depth shows a significant positive correlation with May–June greenness (Peng *et al*. 2010a). However, in the High Arctic, Cooper *et al*. (2011) reported that a late snow melt delays the development of plants and results in lower success of reproduction. Remote sensing of vegetation provides information on the activity and dynamics of montane ecosystems over time and across large areal extent (Pettorelli *et al*. 2005). To date, the relative role of winter, spring, and summer meteorological factors and the possible lag effects of accumulation and melt of snow involved in the variability of vegetation greenness remain to be investigated.

Furthermore, snowpack characteristics are different with the variation of geographic factors such as climatic conditions and elevations (Dedieu *et al*. 2014; Gobiet *et al*. 2014; Xie *et al*. 2017). Vegetation distribution is subject to meteorological and geological conditions (Ide and Oguma 2013). From previous studies, a consistent message has emerged: the influence of climate and climate-relative factors on the growth of vegetation are different between climatic regions (Dye and Tucker 2003; Peng *et al*. 2010b), and between land cover types such as tundra (Dorrepaal 2003; Wahren *et al*. 2005; Wipf *et al*. 2006; Wipf *et al*. 2009), grass and meadow (Cornelius *et al*. 2013; Zeeman *et al*. 2017) and forest (Hu *et al*. 2010; Jönsson *et al*. 2010) and so forth, as well as between elevations (Trujillo *et al*. 2012; Walker *et al*. 2014; Xie *et al*. 2017). There, it is necessary to identify the regions that are most sensitive to interannual variations in climate and climate-relative factors for the further understanding of ecosystem responses to climate change.

However, changes in seasonal snow cover may interact with air temperature and thus affect plant growth (Yu *et al*. 2013). Warming temperatures are likely to cause reduced snowfall and early snowmelt in spring (Barnett *et al*. 2005; Foppa and Seiz 2012a). Moreover, together with reduced snow cover, increased air temperature may lead to intensified water stress and ultimately constriction of vegetation growth (IPCC 2007). For instance, winter warming could result in snowfall reduction, or reduction in the duration of snow cover, thereby increasing soil freezing (Groffman *et al*. 2006) and root mortality (Peng *et al*. 2010b; Wahren *et al*. 2005), which in turn leads to a delay in the start of the growing season and a reduction of the vegetation growth (Grippa *et al*. 2005a). These changes might lead to an earlier spring season, consequently resulting in an advancement and extension of the carbon uptake period (Desai *et al*. 2016). However, the relative effect of climate and climate-relative factors on the variation of spring, autumn, and length of phenology, and productivity of growing season at the ecosystem scale, across elevational gradients in mountain regions, is still waiting to be addressed.

As a consequence, understanding the elevational variation of the influence of seasonal snow and meteorological factors on land surface phenology and greening, and predicting future trajectories of spring phenological shifts are important aspects of montane ecological studies. Satellite observations can provide accurate data for spatiotemporal research in phenological and ecological responses to environmental changes, with the advantages of comprehensive ground coverage and regularly repeated observations at large scales (Pettorelli *et al*. 2005), although atmospheric interference and a lack of biome-scale ground phenological data challenge the application of satellite-derived phenological metrics (Badeck *et al*. 2004). The European Alps, with a key focus on the Swiss Alps, were selected as study areas for their strong topographic variability (Auer *et al*. 2007; Scherrer *et al*. 2004a) with a typical mountainous climate (Brunetti *et al*. 2009b), as well as climate warming over the past (Böhm *et al*. 2001) and next decades (Gobiet *et al*. 2014).

1.4 Key challenges for snow-vegetation research

In the European Alps, the mean temperatures have increased by about 1.1 °C over the past 100 years (Böhm *et al*. 2001). Furthermore, higher-than-average warming is expected to occur till 2050, with approximately 0.25 °C per decade, and by the end of 2100 with roughly 0.36 °C per decade (Gobiet *et al*. 2014). Given the recent trend in global warming, the ecosystem in the European Alps was reported to be particularly sensitive to interannual variations in climatic drivers such as temperature and solar radiation (Beniston *et al*. 2003b; Gobiet *et al*. 2014) and climate-relative factors such as rain and snow (Jonas *et al*. 2008; Xie *et al*. 2017).

Snow cover plays a vital role in alpine ecosystems and has a large impact on alpine land surface phenology and productivity in various ways. However, our knowledge about the relationships of snow cover with alpine land surface phenology is limited, particularly the dependence of these relationships on elevation. In particular, the effect of snow cover changes on the variation of alpine phenological events at the ecosystem scale, across elevational gradients, is not well known yet. While plot-scale ground monitoring can accurately report on plant phenology at small scales (Fisher *et al*. 2006), satellite observations can also provide accurate observations of snow-vegetation relationships at large scales. Quantification of the relation between snow cover and alpine land surface phenology is crucial to understanding the mechanism of vegetation dynamics in alpine regions. Monitoring of alpine land surface phenology is necessary to assess the impact of seasonal snow extension and ongoing climate change. Therefore, the effects of snow cover on alpine land surface phenology and greenness may vary with elevation among vegetation types, terrain aspects and specific regions.

Timing and accumulation of snow are among the most important phenomena influencing vegetation phenology in mountainous ecosystems. However, our knowledge of their influence on alpine land surface phenology is still limited, and it remains unclear that which of these is the most significant snow metric. Snow metrics are known to be subject to interdependent and interconnected relationships. However, the characteristic and magnitude of the correlation between snow timing and snow accumulation across elevation still need detailed understanding. Furthermore, while the snow cover duration is highly correlated with the start and the length of a phenological cycle, the relationship between snow accumulation and alpine land surface phenology needs still to be addressed. Specifically, the amount of snow accumulation and the character of its influence on mountainous land surface phenology require further investigation across elevations. In addition, no single ecological factor can offer a significant statistical explanation to mountainous vegetation ecology (Löffler 2005). The ecosystem in snow sensitive regions, where weak or no interdependence between timing and accumulation of snow exists, needs further assessment through the use of multiple snow metrics. Thus, the question of the relative importance of the timing and accumulation of snow, which is significant to a mountainous ecosystem, remains to be answered. As a consequence, it is necessary to investigate the relationship of the change in timing and accumulation of snow with land surface phenology at different elevations and subregions, and to identify the key snow metrics for land surface phenology in mountainous regions. These investigations may facilitate the understanding of the mechanisms of vegetation response to snow cover and accumulation in mountainous ecosystems, as well as the magnitude of the relative importance between these snow metrics to land surface phenology, given the impact of climate change in mountainous regions.

In alpine grasslands, fewer studies on land surface phenology and greenness exist than in temperate vegetated regions and forested ecosystems (Fabio *et al*. 2008; Richardson *et al*. 2010; Richardson *et al*. 2013). In particular, the relationships of alpine grassland ecosystems with seasonal snow and meteorological factors across complex topography need further investigation (Xie *et al*. 2018; Xie *et al. 2017).* Alpine grasslands are the very areas most sensitive to the variation of duration and accumulation of snow cover (Xie *et al*. 2018; Xie *et al*. 2017). Together with other meteorological factors, the accumulation and melt of snow have multiple impacts on the land surface phenology and greenness in various ways in alpine grasslands. However, our knowledge about the elevation-dependent character and magnitude of these effects is still limited and requires further investigation. In particular, the effects of snow accumulation and melt, combined with spring meteorological factors and their relative influence on spring land surface phenology, are not yet well understood in alpine grassland. So far, most existing studies have been based on limited field-observation or experimental data in their investigation of the influence of snow accumulation and melt, and meteorological factors on spring land surface phenology.

Recent studies reported that senescing autumn phenology can result in an extension of the growing period (Garonna *et al*. 2014; Zhu *et al*. 2012) and therefore plays an indispensable role in regulating carbon cycling in temperate vegetation (Piao *et al*. 2008; Richardson *et al*. 2010). In alpine grasslands, the elevation-dependent influence of these meteorological factors on autumn land surface phenology is not yet well understood.

Variations in seasonal snow may interact with air temperature and therefore affect greenness, duration, and the peak biomass of plant growth (Legay *et al*. 2013; Yu *et al*. 2013). Remote sensing of vegetation provides information on the activity and dynamic of mountainous ecosystems over time and across large areal extent (Pettorelli *et al*. 2005). To date, the relative role of winter, spring, and summer meteorological factors, and the possible lag effects of accumulation and melt of snow involved in the variability of vegetation greenness remain to be investigated. Meteorological factors (Auer *et al*. 2007; Xie *et al*. 2017), snow accumulation and snowmelt (Beniston *et al*. 2003a; Hüsler *et al*. 2014; Trujillo *et al*. 2012; Wipf and Rixen 2010), as well as phenological events (Benadi *et al*. 2014; Cornelius *et al*. 2013; Defila and Clot 2005; Lambert *et al*. 2010; Schuster *et al*. 2014) have been reported to differ with changing environmental conditions and topography. Therefore, the effect of snow accumulation and snow melt on the land surface phenology and greenness in alpine grasslands across elevations and between subregions, in combination with other meteorological factors, needs to be investigated.

1.5 Aims of the thesis

Studying alpine land surface phenology is a key topic for alpine ecosystem research and its management decisions in planning and conservation at landscape and ecological levels. Since land surface phenology mapping and monitoring in mountainous regions are often lacking spatial explicitness and restricted by complex topography, there is a need to fill this gap. Optical remote sensing offers versatile capabilities for addressing this.

The aims of this thesis are to advance the use of satellite-derived data as a tool for snow-vegetation research covering different spatiotemporal scales. It focuses on the European Alps, with particular emphasis on the Swiss Alps, where data availability was adequate to map several snow and phenology metrics. The particular research goals are to:

- map the snow cover phenology, snow accumulation, and land surface phenology at large scale to assess elevation-dependent relationships of snow cover phenology and snow accumulation with land surface phenology over the period of 2003-2014.
- evaluate the relative influence of snow cover phenology and snow accumulation on land surface phenology at alpine vegetated regions between 2004 and 2014.
- examine the effects of climatological factors and seasonal snow on the land surface phenology and productivity in the alpine natural grassland between 2004 and 2014.

This thesis is the first systematic attempt to track elevational variation in mid spatial resolution (i.e. 250-m) land surface phenology and greenness metrics derived from remote sensing data, and to test their relationships with seasonal snow and climatic factors for the entire European Alps and specifically, for the Swiss Alps. In this thesis, the Ph.D. candidate conceived the study and designed the analyses under the supervision of Mathias Kneubühler and Michael E. Schaepman. The Ph.D. candidate collected and performed the data analyses of land surface phenology (i.e., start of season, end of season, and length of season), land surface greenness (normalized difference vegetation index and leaf area index), snow cover phenology (i.e., first snow fall, last snow day, and snow cover duration), snow accumulation (i.e., mean snow water equivalent of the snow cover duration and mean snow water equivalent from January to April), snow cover melt day, and meteorological factors and carried out interpretation of results. In addition, this thesis is the first work to investigate the association of first snow fall and last snow day with end of season and start of season and to analyse the relative contribution of timing and accumulation of snow on alpine land surface phenology.

1.5.1 Hypotheses and research questions

The general hypotheses are:

I. Effects of snow cover on alpine land surface phenology vary among vegetation types, terrain aspects and specific regions, as well as with elevation.
II. Snow cover plays a more important role than snow accumulation in alpine land surface phenology in the Swiss Alps.
III. The importance of snow melt timing on spring phenology (SOS) increases with elevation.
IV. Autumn phenology is more driven by temperature than precipitation or sunshine duration.
V. Effects of snow and temperature on greening metrics during the growing season vary among regions and elevations.

Three research questions (RQ) were formulated as follows:

RQ1: How does the snow timing influence alpine land surface phenology changes with topography, and which regions are more affected by snow timing?

RQ2: How do the timing and accumulation of snow relatively influence alpine land surface phenology with elevation?

RQ3: How do seasonal snow and meteorological factors influence the land surface phenology and productivity in alpine grassland?

1.5.2 Structure of the thesis

Chapter 1 provides definitions and the state of the art of the thesis, and presents its objectives and research questions.

Chapter 2 studies the relationship between snow cover phenology (first snow fall, last snow day, and snow cover duration) and land surface phenology (start, end, and length of season) in the European Alps using satellite-derived metrics for the period of 2003–2014. This chapter then tests the dependency of inter-annual differences of snow cover phenology and land surface phenology with elevation (up to 3000 m asl) for seven natural vegetation types, four main climatic subregions and four terrain expositions. Hypothesis I is analysed in this Chapter using MODIS13Q1 in the European Alps.

Chapter 3 analyzes timing (snow cover duration and last snow day) and accumulation (mean snow water equivalent within snow cover duration) of snow, and land surface phenology (start and length of season) in the Swiss Alps over the period 2003–2014. This chapter then goes on to examine elevational and regional variations in the relationships between snow and phenology metrics, using multiple linear regression and relative weight analyses, and subsequently identifies the most important of the above snow metrics to inter-annual variations in alpine land surface phenology of natural vegetation types. Hypothesis II was evaluated in this Chapter in the Swiss Alps.

Chapter 4 utilises data on land surface phenology (start, end, and peak of season), greenness metrics (the maximum and mean normalized difference vegetation index and mean leaf area index within the length of season), snow cover melt date, snow accumulation (mean snow water equivalent from January 1st to April 30th), and meteorological factors such as air temperature, relative sunshine duration, and precipitation in the Swiss Alps over the period 2003–2014 to investigate the relationships between inter-annual changes of land surface phenology and greenness metrics, and seasonal snow and meteorological metrics across elevations, for the four specific subregions of the alpine grassland. This Chapter tests Hypothesis III, IV and V across alpine grassland in the Swiss Alps.

Finally, **Chapter 5** summarizes and discusses the main findings of the thesis and provides concluding remarks and an outlook on possible future research directions.

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Chapter 2

Altitude-dependent influence of snow cover on alpine land surface phenology

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Author contributions

Jing Xie conceived the study and designed the analyses under the supervision of Mathias Kneubühler and Michael E. Schaepman. Jing Xie collected and performed the data analyses of land surface phenology and snow cover phenology metrics. Jing Xie, Mathias Kneubühler and Michael E. Schaepman carried out interpretation of results jointly, and Jing Xie prepared the initial manuscript. Jing Xie, Irene Garonna, and Rogier de Jong computated and interpretated the land surface phenology metrics. Claudia Notarnicola and Ludovica De Gregorio provided the snow cover phenology metrics. Jing Xie, Mathias Kneubühler, Irene Garonna, Rogier De Jong, and Michael E. Schaepman edited the final version of the manuscript.

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RESEARCH ARTICLE

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Altitude-dependent influence of snow cover on alpine land surface phenology

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Key Points:

- Snow cover duration shows strong correlation with start and length of the alpine growing season at high altitudes (above 2000 m)
- The correlation differences between climatic subregions and terrain aspects are more pronounced below 2000 m than above
- The correlation between start and length of the growing season and snow cover duration is strongest in natural grasslands

Supporting Information:

- Supporting Information S1
- Figure S1
- Table S1

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Abstract Snow cover impacts alpine land surface phenology in various ways, but our knowledge about the effect of snow cover on alpine land surface phenology is still limited. We studied this relationship in the European Alps using satellite-derived metrics of snow cover phenology (SCP), namely, first snow fall, last snow day, and snow cover duration (SCD), in combination with land surface phenology (LSP), namely, start of season (SOS), end of season, and length of season (LOS) for the period of 2003–2014. We tested the dependency of interannual differences (Δ) of SCP and LSP metrics with altitude (up to 3000 m above sea level) for seven natural vegetation types, four main climatic subregions, and four terrain expositions. We found that 25.3% of all pixels showed significant ($p < 0.05$) correlation between ΔSCD and ΔSOS and 15.3% between ΔSCD and ΔLOS across the entire study area. Correlations between ΔSCD and ΔSOS as well as ΔSCD and ΔLOS are more pronounced in the northern subregions of the Alps, at high altitudes, and on north and west facing terrain—or more generally, in regions with longer SCD. We conclude that snow cover has a greater effect on alpine phenology at higher than at lower altitudes, which may be attributed to the coupled influence of snow cover with underground conditions and air temperature. Alpine ecosystems may therefore be particularly sensitive to future change of snow cover at high altitudes under climate warming scenarios.

1. Introduction

Vegetation phenology has been referenced as an important and observable track in ecosystem response to climate change [*Menzel et al.*, 2006] and as a key determinant of coupled water and land surface carbon exchange [*Barrio et al.*, 2013; *Richardson et al.*, 2010], as well as of species distributions [*Chuine and Beaubien*, 2001]. Furthermore, interannual variability in vegetation phenology affects the exchange of energy, water, and carbon between the vegetation and the atmosphere [*White et al.*, 2009]. With snow cover phenology (SCP) being among important climate drivers, changes in SCP have been reported to significantly influence the global energy balance [*Chen et al.*, 2015a, 2015b; *Euskirchen et al.*, 2007] and water cycling [*Barnett et al.*, 2005; *Rawlins et al.*, 2006], which has in turn implications on land surface phenology (LSP) [*Dorrepaal et al.*, 2003; *Monson et al.*, 2006; *Shimamura et al.*, 2006]. For instance, seasonal thawing and snowmelt affect the potential production and growing season length of vegetation at midnorthern latitudes [*Walker et al.*, 2014]. Plants adapted to changes in the duration of snow cover (such as snowbed or fellfield) can show distinct responses to snowmelt advancement or delay [*Keller and Körner*, 2003; *Wipf and Rixen*, 2010; *Wipf et al.*, 2006].

Alpine snow cover plays a significant role in the global climate system [*Intergovernmental Panel on Climate Change (IPCC)*, 2007] and a major role in regulating mountain ecosystems [*Jonas et al.*, 2008]. The dates of alpine plant growth respond to the change of climate and climate-related drivers such as snow cover [*Jonas et al.*, 2008; *Wipf and Rixen*, 2010]. Snow cover can regulate the growth of alpine vegetation and block off sunlight needed for photosynthesis. On the other hand, snow protects vegetation from dry and severe cold conditions and simultaneously supplies moisture [*Desai et al.*, 2016; *Ide and Oguma*, 2013; *Inouye*, 2008]. Annual change of snowmelt or snow cover may induce strong ecosystem responses. Together with other environmental factors, snow is one of the essential environmental parameters controlling high-altitude vegetation phenology [*Cornelius et al.*, 2013; *Wipf et al.*, 2009]. For instance, the first and last snow days were observed to be highly correlated with the end and start of growing season at high-altitude drier regions in Nepal Trans Himalaya [*Paudel and Andersen*, 2013].

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An increase in annual mean temperatures of about 1.1°C has been observed in the European Alps over the past 100 years [*Böhm et al.*, 2001]. The expected continuation of this warming is likely to result in more frequent early snowmelt events [*Foppa and Seiz*, 2012]. The resulting reduction in snow cover may intensify water stress and ultimately constrains vegetation growth [*IPCC*, 2007]. Interacting with air temperature, variations in seasonal snow cover may affect plant growth [*Yu et al.*, 2013]. For instance, winter warming could result in snow fall reduction, or reduction in the duration of snow cover, thereby increasing soil freezing [*Groffman et al.*, 2006] and root mortality [*Peng et al.*, 2010; *Wahren et al.*, 2005], which in turn leads to a delay in the start of the growing season and a reduction of the vegetation growth [*Grippa et al.*, 2005]. Changes in seasonal patterns of snow are related to plant photosynthesis and growth in the snow-free season [*Galvagno et al.*, 2013; *Rossini et al.*, 2012], thus influencing ecosystem functioning [*Saccone et al.*, 2012]. Therefore, quantifying the relationship between snow cover and alpine phenology is crucial to understanding the mechanism of vegetation dynamics in alpine regions and monitoring of alpine phenology is necessary to assess the impact of seasonal snow extension and ongoing climate change.

Numerous studies have focused on snow-vegetation interaction in alpine environments [*Abeli et al.*, 2011; *Badeck et al.*, 2004; *Desai et al.*, 2016; *Jonas et al.*, 2008;, *Keller et al.*, 2005; *Paudel and Andersen*, 2013; among others]. Recently, a number of studies have focused on the relationship between snow and vegetation in different regions [e.g., *Dye and Tucker*, 2003, *Peng et al.*, 2010], investigating the effect of snow on tundra [e.g., *Dorrepaal et al.*, 2003; *Wahren et al.*, 2005; *Wipf et al.*, 2006, 2009], grass, and meadow [e.g., *Cornelius et al.*, 2013; *Zeeman et al.*, 2017] and forest [e.g., *Jönsson et al.*, 2010; *Hu et al.*, 2010; *Trujillo et al.*, 2012]. Efforts have been made to investigate the effects of changing snow cover on alpine vegetation phenology by means of direct snow manipulation experiments [*Cornelius et al.*, 2013; *Wipf and Rixen*, 2010]. A majority of former snow-vegetation field experiments and studies in the Alps focused primarily on small-scale measurements [e.g., *Abeli et al.*, 2011; *Julitta et al.*, 2014; *Keller et al.*, 2005; *Saccone et al.*, 2012; *Wipf et al.*, 2009]. However, the effect of snow cover changes on variation of alpine phenological events at the ecosystem scale across altitudinal gradients is not well known yet. While plot-scale ground monitoring can accurately report on plant phenology at small scale [*Fisher et al.*, 2006], satellite observations can also provide accurate observations of snow-vegetation relations at large scale. Remote sensing data are increasingly important in spatiotemporal research of phenological and ecological responses to environmental changes [*Pettorelli et al.*, 2005] with the advantages of comprehensive ground coverage and regularly repeated observations at large scale, although atmospheric interference and a lack of biome-scale ground phenological data challenge the application of satellite-derived phenological metrics [*Badeck et al.*, 2004].

As a consequence, understanding the altitude-dependent influence of SCP on LSP and predicting future trajectories of phenological shifts are important aspects of alpine ecological studies. Obviously, snowpack characteristics are related to geographic factors such as climatic conditions, altitude, location, and slope orientation [*Dedieu et al.*, 2014; *Gobiet et al.*, 2014]. Furthermore, plant species habitats are subject to meteorological and geological conditions [*Ide and Oguma*, 2013]. Therefore, we hypothesize that effects of snow cover on alpine phenology vary among vegetation types, terrain aspects, and specific regions with altitude. Furthermore, identifying the most sensitive regions to interannual variations in snow cover is important to understanding ecosystem responses to climate change. In this study, we examined the potential impacts of interannual snow cover variations on alpine phenology using remote sensing data and focusing on natural vegetation types and geographical factors. The goals of this study are (i) to investigate how snow cover phenology (SCP) and land surface phenology (LSP) in the Alps varied between 2003 and 2014, (ii) to check for altitude-dependent changes in SCP and LSP, and (iii) to test temporal correlation between SCP and LSP metrics for the whole Alps, for specific subregions, and with variation in altitude and across different terrain aspects.

2. Material and Methods

2.1. Study Area Description

The study area is the central European Alps region, whose borders are defined by the Alpine Convention (http://www.alpconv.org/, accessed February 2017). This region is centrally located on the European continent and covers 168′252 km^2 (Figure 1a), i.e., 88.2% of the entire Alps (5.8°E–14.2°E, 43.8°N–48.2°N). The area is dominated by a typical alpine climate [*Brunetti et al.*, 2009] and commonly separated into four climatic

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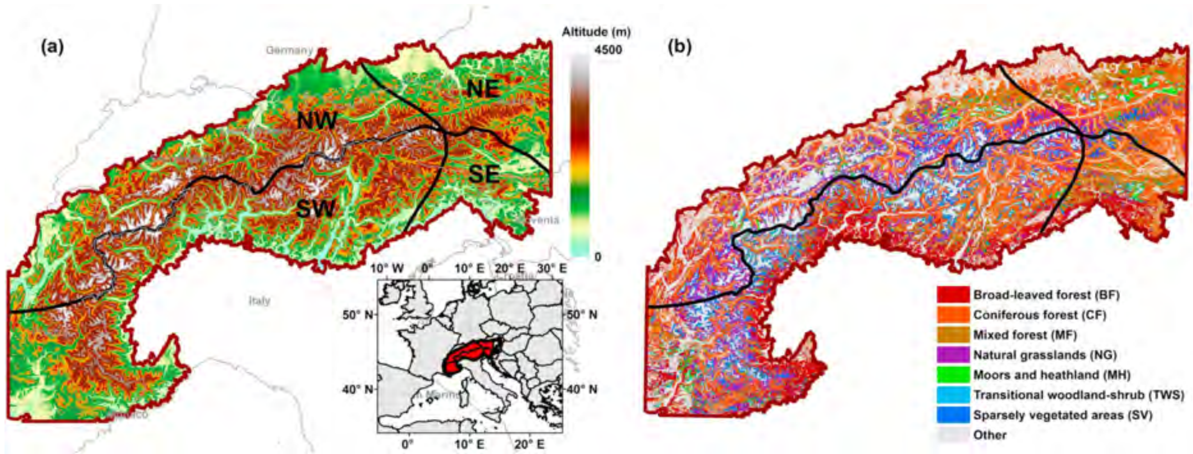

Figure 1. (a) Altitudes and (b) natural vegetation types of the study region. The dark red area (inset) delineates the study area; the black lines indicate the subdivision into four subregions (NW, NE, SW, and SE) following *Auer et al.* [2007].

subregions [*Auer et al.*, 2007]: north-west (NW; temperate westerly, oceanic features; 53′691 km^2, 32% of total area), north-east (NE; temperate westerly, continental features; 23′547 km^2, 14%), south-east (SE; mediterranean subtropical, continental features; 15′082 km^2, 9%) and south-west (SW; mediterranean subtropical, oceanic features; 75′932 km^2, 45%). The delineation of climatic subregions was defined according to the statistical regionalization of different climate elements such as precipitation and temperature as obtained from Historical Instrumental Climatological Surface Time Series of The Greater Alpine Region (HISTALP) [*Auer et al.*, 2007]. The subregions are assumed to reflect different snow-vegetation correlation regimes. The mean annual accumulative precipitation (between 2003 and 2014) ranges between 1100 and 1400 mm, with maximum values occurring at lower altitudes of the SE. The mean annual temperature (between 2003 and 2014) ranges from −5°C to 12°C in lower altitudinal zones across the study region. The Alps are subject to strong topographic variability [*Auer et al.*, 2007; *Scherrer et al.*, 2004]. The area is characterized by extensive lowlands, deeply incised valleys, and highest peaks ranging to more than 4800 m above sea level (asl). Natural vegetation (NV) covers 68.5% of the study area (Figure 1b). The predominant NV cover types in the study region are natural grasslands (15.5% of NV) and forests (64.1% of NV, including broad-leaved forest, coniferous forest, and mixed forest).

2.2. Snow Cover Phenology (SCP)

Moderate Resolution Imaging Spectroradiometer (MODIS) snow data products with a spatial resolution of 250 m were used to derive snow cover phenology (SCP) for 12 water years (WY, running from 1 October to 30 September of the following calendar year) between 2002 and 2014 for the European Alps region, including cloud removal. First snow fall (FSF) was defined as the first date in the WY when a pixel is snow covered; last snow day (LSD) is the last date in the WY when a pixel is snow covered; snow cover duration (SCD) is the total number of dates in the WY when pixels are snow covered. *Paudel and Andersen* [2013] calculated the first snow appearance day and the last snow free day given several snow cycles in Nepal Trans Himalaya. For the intermittent snow cover and potential late season transient snow fall events which occur often in the Alps [*Hüsler et al.*, 2014], we adopted the methodology used by *Paudel and Andersen* [2013] mostly for its simplicity in the calculation of the FSF and LSD. FSF, LSD, and SCD were derived from snow maps obtained from MODIS/Terra data using a novel algorithm developed by European Academy of Bolzano, Italy, in order to take into account the specific characteristics of mountain areas. The two main characteristics of the algorithm are the improved ground resolution of 250 m and a tailored topographic correction [*Dietz et al.*, 2012; *Notarnicola et al.*, 2013a, 2013b].

The daily availability of snow maps allowed the calculation of SCD without gaps (Figure S1 in the supporting information). For each pixel of the snow map, the implemented algorithm extracted the first date as FSF when there is snow. With the proposed approach, the FSF calculation was also taking into account the

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sporadic snowfall in the early fall. Consequently, it did not always refer to the starting date of the continuous winter snow covered period. LSD provides useful information about the melting process. To calculate LSD, the algorithm extracted from the time series of snow maps of every WY the last day in which the pixels were snow covered. Furthermore, in order to eliminate erroneous pixels due to misclassification, the final maps of FSF and LSD were filtered to remove pixels where (i) the FSF date was in the range between day of (calendar) year (DOY) 91 (1 April) and DOY 181 (30 June) and (ii) the SCD was <10. The same approach was used to extract FSF and LSD dates. Full details about the SCP derivation procedure are provided in Text S1 in the supporting information.

The uncertainty layer was used primarily during the validation of our snow products when we compared the snow maps with ground data [*Notarnicola et al.*, 2013a, 2013b]. This was done especially in difficult cases such as snow in forest and snow under critical illumination conditions [*Thirel et al.*, 2012]. From this comparison, it emerged as well that the uncertainty layer can provide some false alarm especially in certain cloud condition which may be spectrally similar to snow cover. For this reason, we introduced a further check based on the temporal variability of the pixel in the determination of the snow phenology. This is done for the snow cover duration, thanks to a moving window used to calculate the number of days with snow cover (Figure S1).

2.3. Land Surface Phenology (LSP)

MODIS MOD13Q1-version 005 normalized difference vegetation index (NDVI) data were used to derive yearly LSP metrics for start of season, endof season, and length of season (SOS, EOS and LOS, respectively) on a pixel-by-pixel basis. NDVI is one of the most widely used indices for monitoring of vegetation phenological events at various scales [*Cleland et al.*, 2007; *Fisher et al.*, 2006; *Piao et al.*, 2006]. The available MOD13Q1 images for the study period of 2003–2014 (276 in total) were 16 day composites with 250 m spatial resolution and included corresponding quality and day-of-observation information. Several studies mention that snow in vicinity of green vegetation may lead to errors when detecting vegetation greenness [*Jönsson et al.*, 2010; *Quaife and Lewis*, 2010]. Therefore, snow dynamics might relate to or influence satellite monitoring of vegetation phenology [*Jönsson et al.*, 2010; *White et al.*, 2009]. These MODIS NDVI images were transformed from the native sinusoidal projection into the universal transverse Mercator 32 projection. For quality assurance (QA) of the MODIS NDVI values and maximum value composite (MVC) data sets, we used MOD13Q1 Bands 2 and 10, which contain detailed QA (flag values of Band $2 \leq 12$ were selected based on the quality statistical results), and MVC information (16 bit binary) to generate higher-quality, cloud-free NDVI images.

To each annual time series of NDVI data, we first applied harmonic analysis to interpolate between observations, and taking into account the day of observation within each compositing window. Among the different SOS indicators that have been used in previous LSP literature, we chose the Midpoint-pixel method based on the comprehensive study of *White et al.* [2009], who found it to be better related to phenological observations across North America than other commonly used indicators. This method was also used in previous studies over Europe at coarser resolution [*Garonna et al.*, 2014]. Midpoint-pixel is a relative threshold method which defines SOS as the day when NDVI reaches half its annual range (i.e., the midpoint). The EOS was then defined as the day at which NDVI reaches the midpoint again in the calendar year, and the LOS is the number of days between SOS and EOS. SOS and EOS are always expressed in day of (calendar) year (DOY) and LOS in days.

2.4. Land Cover Data, Digital Terrain Model, and Climatologies

The CORINE Land Cover 2000 seamless vector data of the Copernicus Land Monitoring Service (http://land.copernicus.eu/, accessed February 2017) were used to stratify our results. This product is derived without the input of NDVI data, which was a crucial criteria in our choice of a land cover product to stratify our results. We assumed that every pixel belongs to one single vegetation type (reference land cover) and no changes in vegetation cover in the study region occurred over the study period of 2003–2014. Seven vegetated land cover types (i.e., broad-leaved forest (BF), coniferous forest (CF), mixed forest (MF), natural grasslands (NG), moors and heathland (MH), transitional woodland-shrub (TWS), and sparsely vegetated areas (SV)) were identified to assess the correlation of snow cover variation with alpine phenology. Topographic information at a 1 arc sec scale (30 m) obtained from the European Environment Agency was used to generate a digital elevation model (DEM) and to derive terrain information, which includes north facing (NF), east (EF), south (SF), and west facing (WF) terrain aspects. Gridded data sets with 8 km resolution of monthly precipitation

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[*Efthymiadis et al.*, 2006] and temperature [*Chimani et al.*, 2013] from 2003 to 2014 were collected from HISTALP (http://www.zamg.ac.at/, accessed February 2017). All data products were resampled to a 250 m grid to match the spatial resolution of the SCP and LSP metrics, except for the climatology maps (1 km grid).

2.5. Altitude-Dependent Analysis

The altitude-dependent analysis consisted of selecting distinct zones within a 100 m altitudinal band with an altitudinal resolution of 50 m (up to 3000 m asl, corresponding to the altitude range experiencing seasonal snow and natural vegetation cover) across the entire study area. SCP and LSP metrics were averaged within each 100 m altitudinal band, for each of the 12 years of the study period. Following this step, the existence of potential changes in SCP and LSP (significance defined as $p < 0.001$) were examined by altitudinal band (100 m) using a simple linear regression. The trends of SCP and LSP were calculated by employing a simple linear regression (significance defined as $p < 0.05$) on a pixel basis over time. Interannual differences (Δ) of SCP and LSP were described for each pixel as the value of the current year minus the value of the preceding year. We assumed that alpine phenology correlates with time and duration of snow cover. Correlation coefficients between interannual differences of preseason (running from 1 October to the following SOS) snow cover (ΔLSD and ΔSCD) and alpine phenology (ΔSOS and ΔLOS) were obtained using Spearman's correlation. Spearman's correlation between ΔFSF and ΔEOS was also employed to identify the correlation between the first day of snow fall and end of season in the same season. The 250 m grids of SCP and LSP and the statistical results were intersected with the 250 m DEM, terrain aspect, subregions, and vegetation type-maps. Pixels with (i) SCD lower than 10 days or larger than 360 days, (ii) less than 1% proportion of each vegetation type, and (iii) a percentage of significant correlation lower than 5% were masked out at each altitudinal band. SCP and LSP metrics were investigated for different terrain aspects (i.e., NF, EF, SF, and WF) along the altitudinal bands. Altitude-dependent mean and trends of winter (December, January, and February) precipitation and temperature were used to analyze the meteorological environment of the four study regions. Image data processing was performed with ArcGIS (v10.0, Environmental Systems Research Institute, USA), ENVI/IDL (v4.8, EXELIS Inc., McLean, VA, USA), and statistical analysis was performed using R (v3.2.3).

3. Results

3.1. Characterization and Temporal Changes in Snow Cover Phenology (SCP) and Land Surface Phenology (LSP) Metrics Between 2003 and 2014

The distribution of natural vegetation types in the Alps and its variation with altitude are presented in Figure 2a. High altitudes (>2000 m asl) are dominated by natural grasslands (NG) and sparsely vegetated areas (SV). At midaltitudes (1000–2000 m asl), NG and forest (broad-leaved forest (BF), coniferous forest (CF), and mixed forest (MF)) are the major vegetation types, together with moors and heathland (MH) and transitional woodland-shrub (TWS). The low altitudes (<1000 m asl) are mainly covered by forest (BF, CF, and MF). Most of the natural vegetation grows between 500 and 2500 m asl (Figure 2b). The amount of natural vegetation in the western subregions (27.9% in north-west (NW) and 47.8% in south-west (SW)), being influenced by oceanic climate features, is higher than in the eastern Alps (14.2% in north-east (NE) and 10.0% in south-east (SE)), which are subject to a more continental climate regime. The altitudinal range of natural vegetation (mainly between 600–2200 m asl) is smaller in the eastern Alps (NE and SE) than in the western Alps (NW and SW).

At the same high altitude, the mean snow cover duration (SCD) is higher in the northern Alps than in the southern Alps, and in the eastern as compared to the western Alps (Figure 2c). The first snow fall (FSF) is earlier, while the last snow day (LSD) is later in the northern than in the southern Alps. At altitudes lower than 1500 m asl, the start of season (SOS) is earlier, the end of season (EOS) is later, and the length of season (LOS) is shorter in the northern than in the southern Alps. Above 1500 m asl, the opposite is true. The SOS is earlier, the EOS is later, and the LOS is longer in the western than in the eastern Alps. The spatial patterns of SCP (i.e., FSF, LSD, and SCD) and LSP (i.e., SOS, EOS, and LOS) among the four main climatic subregions of the Alps are shown in Figures S2 and S3.

Simple linear regression results show significant ($p < 0.001$) change in SCP and LSP with altitude. On average, FSF advances 1.28 (±0.01) days/50 m from 1000 to 3000 m asl, LSD delays 3.21 (±0.12) days/50 m, and SCD increases 5.65 (±0.14) days/50 m from 0 to 3000 m asl. SOS delays 1.65 (±0.04) days/50 m, and LOS shrinks

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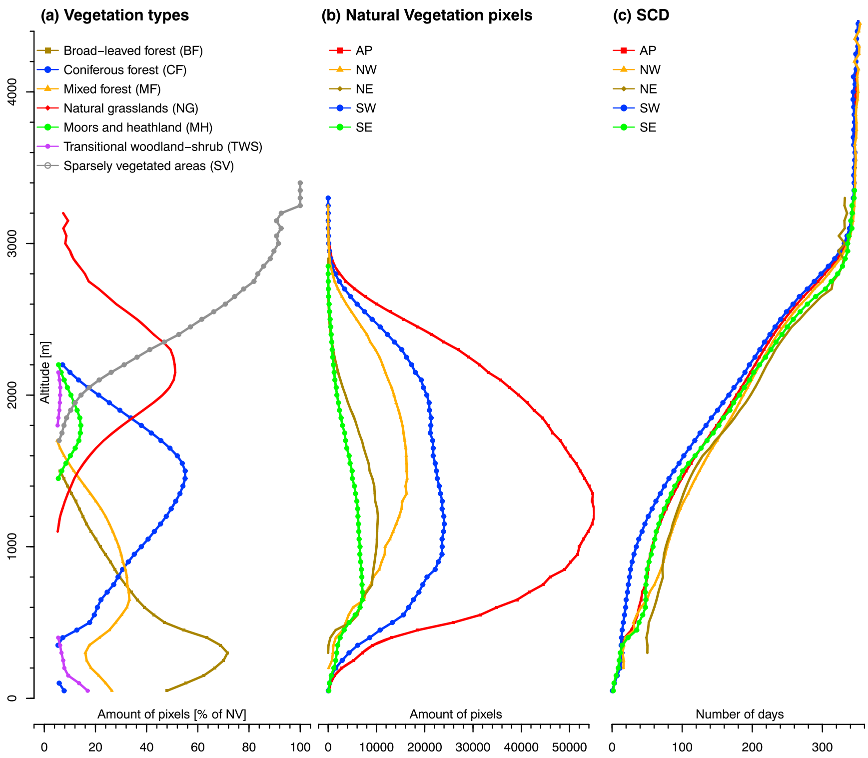

Figure 2. (a) Altitude-dependent distribution and percentage of natural vegetation types (% of NV], (b) altitude-dependent amount of natural vegetation pixels for the entire study area (AP) and the four subregions (NW, NE, SW, and SE), and (c) altitude-dependent amount of days of mean annual SCD for the entire study area (AP) and the four subregions (NW, NE, SW, and SE).

1.65 (±0.07) days/50 m from 500 to 3000 m asl with altitude increase for the entire study area. EOS advances 0.91 (±0.02) days/50 m from 1500 to 3000 m asl but shows no consistent trends in forest dominated altitudes below 1500 m. There are no apparent differences in SCP and LSP change with altitude between the four subregions (Table S1 in the supporting information), except for the SW, where the SOS shows a slight delay (0.49 days/50 m between an altitudinal range of 500–3000 m asl) compared to the other subregions.

Over the 12 investigated years, less than 3% of all pixels show a significant trend ($p < 0.05$) in SCP and LSP metrics across the entire study area. More precisely, 2.9% of pixels showed a significant delay in FSF (average of 0.98 d/yr), 1.0% of pixels showed a delay in LSD (average of 0.99 d/yr), and 2.0% of pixels showed an extension of SCD (average of 0.98 d/yr). For LSP, SOS advanced for 2.0% of pixels (averaging 0.40 d/yr), EOS delayed for 3.2% of pixels (averaging 2.17 d/yr), and LOS extended for 3.2% of pixels (averaging 2.53 d/yr) across the entire study area. These trends are similar across the four subregions (Table S2). The temporal trends and corresponding percentage of pixels with significance of SCP and LSP are presented in Figures S2 and S3.

Neither winter temperature nor precipitation shows significant trends for the period 2002–2014. The mean winter (December, January, and February) temperature showed no significant trend ($p < 0.05$), and 10.0% of the study area showed an average increase of 12.69 mm/yr in winter precipitation over the study period. The mean winter temperature and precipitation changes with altitude are presented in Figure S4.

3.2. Correlation Between ΔSCP and ΔLSP Across the Alps and in Subregions

Figure 3 shows the spatial patterns of the correlation coefficient R between ΔSCD and ΔSOS and between ΔSCD and ΔLOS across the entire study area. We found 25.3% of the considered pixels to have a significant correlation ($p < 0.05$) between ΔSCD and ΔSOS across the entire study area (Figure 3a), with a mean correlation of $R = 0.59$. The vast majority of pixels with a significant correlation between ΔSCD and ΔSOS show

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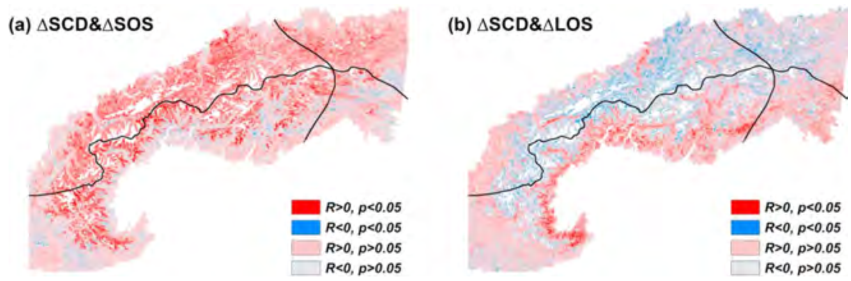

Figure 3. Correlation analysis between (a) ΔSCD and ΔSOS and (b) ΔSCD and ΔLOS across the entire study area.

positive correlation (i.e., 23.3%), and 2.0% show negative correlation between the two variables. Pixels with a negative correlation coefficient were mainly found in the southern Alps (SW and SE). Both the extent and magnitude of the correlations found were higher in the northern than in the southern subregions (Table 1). For instance, the average *R* across the southern Alps was 0.48, as opposed to 0.68 in the northern Alps (Table 1). The ΔSOS of the high altitudinal vegetation types (NG, MH, and SV) have stronger correlation with ΔSCD and a higher corresponding percentage of significant pixels than in the case of the low altitudinal forest (BF, CF, and MF) (Table 1). A total of 41.4% NG, 34.0% MH, and 42.2% SV show strong correlation ($R > 0.68$) between ΔSOS and ΔSCD, especially 48.0%, 43.3% and 48.1% of these vegetation types present in NW. Less than 10% BF shows significant correlation between ΔSCD and ΔSOS in the entire study area, but a higher amount of 23.3% in NE (Table 1).

Pixels of NV (15.3%) (10.0% show negative and 5.3% show positive correlation) were found to have a significant correlation between ΔSCD and ΔLOS for the entire study region (Figure 3b). Stronger mean negative correlations (−0.52 in NW and −0.49 in NE) were found in the northern Alps, compared to the mean correlations (0.08 in SW and 0.19 in SE) found in the southern Alps. More pixels with significant correlation were found in the western (16.1% in SW and 16.6% in NW) than in the eastern Alps (12.0% in NE and 13.3% in SE). Most pixels with a positive correlation were found in the southern Alps. The correlation between ΔSCD and ΔLOS of the high altitudinal vegetation types (NG and SV), as well as the corresponding percentage of significant pixels, is higher than for low altitudinal vegetation types (BF, CF, and MF) (Table 1), except for BF in SW.

Concerning LSD, only 8.8% of all pixels show a significant correlation ($p < 0.05$) between ΔLSD and ΔSOS and 8.3% of all pixels between ΔLSD and ΔLOS, respectively. Both ΔSOS and ΔLOS show low correlation with ΔLSD in middle and low altitudinal regions ($|R| < 0.1$, below 2000 m asl) and low to moderate correlations in high altitudinal regions ($|R| < 0.4$, above 2000 m asl) across the entire study area. Also, only 7.8% of all pixels show a significant correlation ($p < 0.05$) between ΔFSF and ΔEOS ($|R| < 0.1$, above 1000 m asl; $|R| < 0.3$, below 1000 m asl). The correlation of ΔSCD with ΔSOS and ΔLOS illustrates the importance of the influence of SCD on alpine phenology. Therefore, further analysis focuses on the correlation of ΔSCD with ΔSOS and ΔLOS, given the weak correlations and low percentage of significant pixels between ΔLSD and ΔSOS/ΔLOS, and between ΔLSD and ΔFSF/ΔEOS. The spatial pattern of the correlation coefficient *R* between ΔSCP and

Table 1. Mean Significant Correlation Coefficient *R* Between ΔSCD and ΔSOS and Between ΔSCD and ΔLOS for Seven Vegetation Types (BF, CF, MF, NG, MH, TWS, and SV) and Corresponding Amount of Significant Pixels (% of Total) for the Entire Study Area (AP) and the Four Subregions (NW, NE, SW, and SE)

	ΔSOS and ΔSCD (*R*; % of Total)					ΔSCD and ΔLOS (*R*; % of Total)				
Vegetation Class (% Cover)	AP	NW	NE	SW	SE	AP	NW	NE	SW	SE
BF (15.0)	0.20;9.9	0.48;14.0	0.68;23.3	0.02;8.9	0.14;8.8	0.51;18.6	0.17;11.1	0.05;8.7	0.57;21.2	0.34;13.7
CF (32.9)	0.55;22.1	0.68;28.9	0.56;23.4	0.46;18.4	0.02;12.3	−0.29;12.1	−0.49;14.2	−0.47;12.2	−0.07;10.7	0.14;11.0
MF (16.1)	0.45;18.7	0.65;25.8	0.68;27.5	0.06;12.1	−0.12;10.3	0.17;13.8	−0.16;12.1	−0.42;11.0	0.48;17.0	0.45;14.1
NG (17.4)	0.70;41.4	0.73;48.0	0.73;34.3	0.67;37.6	0.68;35.8	−0.52;17.8	−0.68;20.7	−0.67;13.3	−0.34;16.4	−0.35;16.0
MH (5.2)	0.68;34.0	0.73;43.4	0.72;31.6	0.62;31.0	0.65;28.1	−0.57;16.3	−0.67;21.8	−0.65;13.0	−0.45;15.8	−0.54;12.8
TWS (4.1)	0.53;24.1	0.70;32.8	0.64;32.2	0.52;24.0	0.15;13.9	−0.01;15.2	−0.48;14.1	−0.52;13.7	0.02;15.3	0.25;14.5
SV (9.3)	0.71;42.3	0.73;48.1	0.71;26.5	0.70;41.3	0.64;27.3	−0.61;20.5	−0.69;23.1	−0.64;12.8	−0.56;20.0	−0.44;14.4
NV	0.59;25.3	0.70;34.9	0.64;26.6	0.51;21. 6	0.25;14.2	−0.15;15.3	−0.52;16.6	−0.49;12.0	0.08;16.1	0.19;13.3

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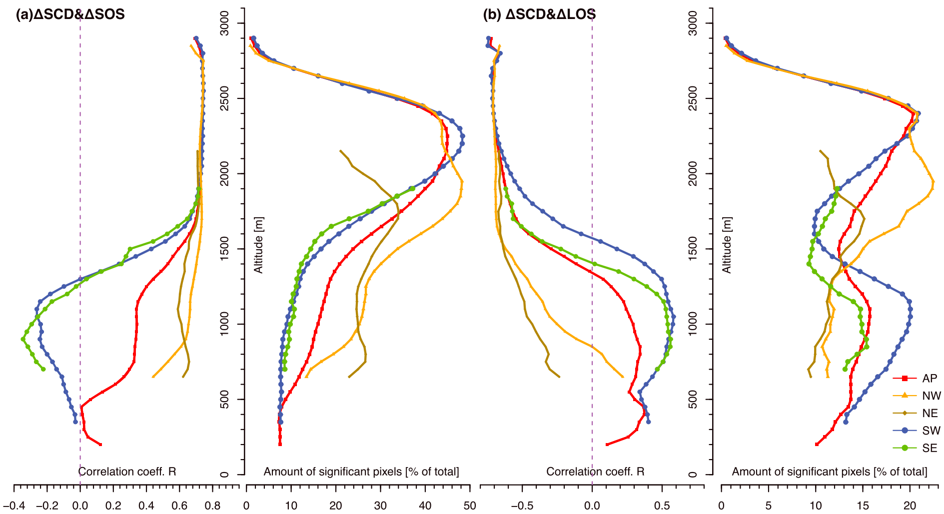

Figure 4. Altitudinal variation in (a, left, and b, left) correlation coefficient R and (a, right, and b, right) corresponding amount of pixels (% of total) with a significant correlation between ΔSCD and ΔSOS (Figure 4a) and ΔSCD and ΔLOS (Figure 4b) across the entire study area (AP) and averaged by subregion (NW, NE, SW, and SE). The dashed purple lines represent a correlation coefficient of 0. The corresponding figures for seven natural vegetation types (BF, CF, MF, NG, MH, TWS, and SV) across the entire study area (AP) and the four subregions (NW, SE, SW, and NE) are presented in Figures S6 and S7.

ΔLSP and the corresponding significant pixels across the entire study area for the period of 2003–2014 are summarised in Figure S5.

3.3. Correlation Between ΔSCP and ΔLSP With Variation in Altitude

In the period of 2003–2014, the correlations between ΔSCD and ΔSOS and between ΔSCD and ΔLOS were strongest at high altitudes ($>$ 2000 m asl) (Figure 4). All four subregions show the same pattern: a strong positive correlation ($R > 0.7$) between ΔSCD and ΔSOS and a strong negative correlation ($R < -0.6$) between ΔSCD and ΔLOS. However, the differences among the four subregions are clearly present in middle and low altitudinal zones (Figure 4). Subregional differences in all correlations were only present at mid and low altitudes.

More precisely, above 1800 m asl, where vegetation is predominantly MF, NG, and SV and where SCD is greater than 150 days, the correlation coefficient R of ΔSCD and ΔSOS is greater than 0.70 (Figure 4a). At these altitudes, about 30–50% of natural vegetation areas have a high positive correlation for the entire study region, with almost no differences between the four subregions. In altitudinal regions above 1800 m asl, the positive correlation between ΔSCD and ΔSOS turns to stable and appears largely the same between the four subregions. At high altitudes, the percentage of pixels with significant positive correlation peaks around 2300 m asl, before dramatically declining with altitude where SCD exceeds 220 days. The positive values of the correlation coefficient R of ΔSCD and ΔSOS slightly increase with altitude from 600 to 1800 m. asl in the northern Alps (NW and NE). From 1300 to 1800 m asl in the southern Alps (SW and SE), the correlation coefficient R of ΔSCD and ΔSOS strongly increases with altitude. Around 1300 m above sea level (asl) in the southern Alps, where vegetation is dominated by forest (BF, CF, and MF), the negative correlation turns to positive with increasing altitude. The strongest negative ($R < -0.3$) correlations of ΔSCD and ΔSOS are observed at low altitudes (800 to 1200 m asl) in the southern Alps, where the SCD is less than 60 days.

Concerning the correlation between ΔSCD and ΔLOS in the altitudinal zones dominated by NG and SV (above 2250 m asl, where SCD is greater than 280 days), high negative values of the correlation coefficient R around -0.65 can be observed (Figure 4b). Natural vegetation pixels at these high altitudes show high negative correlations between ΔSCD and ΔLOS for the entire study region and no differences between the four subregions. Above 2250 m asl, the negative correlation between ΔSCD and ΔLOS turns to stable and appears

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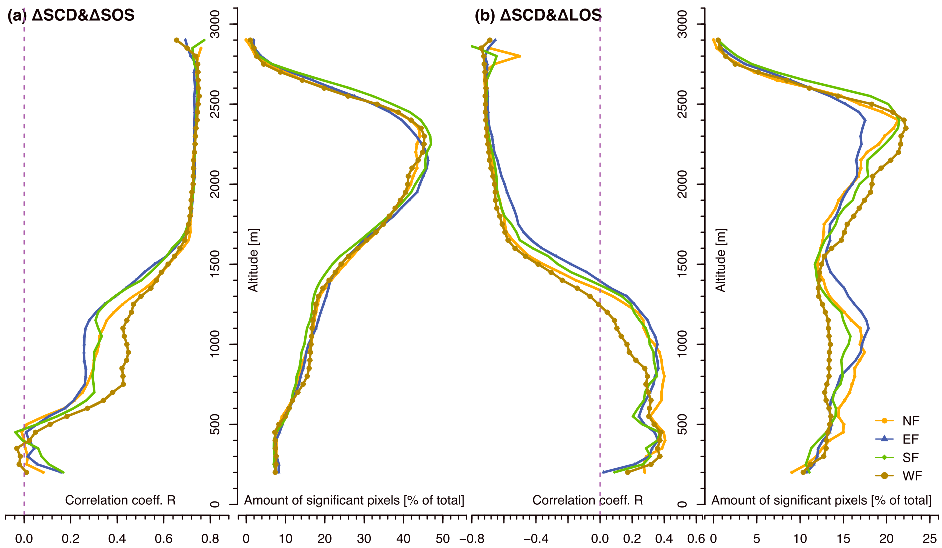

Figure 5. Altitudinal variation in (a, left, and b, left) correlation coefficient R and (a, right, and b, right) corresponding amount of pixels (% of total) with a significant correlation between ΔSCD and ΔSOS (Figure 5a) and ΔSCD and ΔLOS (Figure 5b) for north (NF), west (WF), south (SF), and east facing (EF) terrains of natural vegetation (NV) across the entire study area (AP). The dashed purple lines represent correlation coefficients of 0.

almost the same between the four subregions. The percentage of significant pixels of negative correlation peaks around 2400 m asl but declines with altitude where SCD becomes more than 240 days. In altitudinal regions dominated by forest (BF, CF, and MF), the correlation between ΔSCD and ΔLOS turns from positive to negative at 800 m asl in NW, at 1550 m asl in SW, and at 1400 m asl in SE with increasing altitude. A positive correlation between ΔSCD and ΔLOS was mainly found at middle and low altitudes (<1500 m asl with SCD less than 100 days) in the southern Alps (SW and SE).

3.4. Correlation Between ΔSCP and ΔLSP With Variation in Terrain Aspect

At high altitudes above 1900 m asl, where the dominant vegetation types are MF, NG, and SV, there is no apparent difference in the correlation between ΔSCD and ΔSOS among the four main terrain aspects (Figure 5a). At low and middle altitudes (below 1800 m asl), there are differences in the correlation between ΔSCD and ΔSOS among the four aspects: north and west facing terrain aspects show slightly higher positive correlation values than south and east facing terrain aspects. The corresponding percentage of pixels with a significant correlation is similar among the four terrain aspects but differs with altitude.

The same pattern is true for the correlation coefficient *R* between ΔSCD and ΔLOS and the corresponding percentage of significant pixels, which show no major difference among the four terrain aspects above 2400 m asl (Figure 5b). Slightly higher negative correlations between ΔSCD and ΔLOS can be found for north and west facing terrain compared to south and east facing terrain for altitudes ranging from 1400 to 2200 m asl across the entire study area. Low altitudes (<1000 m asl) only show slight differences among the four terrain aspects.

In general, the differences in correlations between ΔSCD and ΔSOS and between ΔSCD and ΔLOS and the corresponding percentage of significant pixels between the four terrain aspects are more pronounced at low and middle altitudes and they tend to become smaller and even disappear toward high altitudes for the entire study area (Figure 5) and the four subregions (Figure S8). For each vegetation type, highest *R* values and corresponding percentage of pixels with significant correlation are present in west and north facing terrains, as compared to south and east facing terrains for the entire study area and the four subregions (Table S3).

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4. Discussion

4.1. Characterization and Temporal Changes in Snow Cover Phenology (SCP) and Land Surface Phenology (LSP) Metrics Between 2003 and 2014

Our results indicate that SCP metrics (i.e., first snow fall (FSF), last snow day (LSD), and snow cover duration (SCD)) vary considerably between the four subregions (north-west (NW), north-east (NE), south-west (SW), and south-east (SE)) of the Alps. The findings that the SCD in the SW is lower than in the NE and that regional differences in SCD disappear at higher altitudes are in agreement with *Hüsler et al.* [2014], who reported that the northern Alps had above-average SCD as compared to the southern Alps. These regional differences of SCD are presumably due to different climatic influences, such as a stronger dependency of snow cover on precipitation at higher altitudes, and a higher sensitivity of snow cover to temperature in lower regions [*Hüsler et al.*, 2014]. Our results show earlier FSF and later LSD in regions with longer SCD in the northern Alps (with more precipitation in winter) and at high altitudes (with lower freezing temperature in winter) over the past decade (Figures 2c and S2). LSP (i.e., start of season (SOS), end of season (EOS), and length of season (LOS)) shows regular distribution with coupling to SCP across study area (Figures S2 and S3). Namely, a later SOS, an earlier EOS, and a shorter LOS often occur in climatic subregions with longer SCD, and vice versa.

SCP and LSP metrics both showed significant relationship with altitude (Table S1), confirming the dependency of both snow cover and phenology on altitude [*Gottfried et al.*, 2012]. The finding that SCD increases by 5.65 (±0.14) days/50 m within 50 to 3000 m asl is in agreement with findings by *Hüsler et al.* [2014] where an increase of 5.0 days/50 m with a standard deviation of 12.5 days for the entire Alps is reported. Based on a study performed in the Berchtesgaden National Park, *Cornelius et al.* [2013] suggests that about 50% of all phenological events are significantly influenced by altitude. Despite differences in research methods and scale in our study, we find LSP to be strongly dependent on altitude across the entire Alps except for some forest-dominated low-altitude areas. This is reflected in the SOS delay with increasing altitude found across the entire study area. Our estimate of 1.65 (±0.04) days/50 m between 500 and 3000 m asl is in line with field observations by *Cornelius et al.* [2013], who found delays of 1.90 days/50 m between 680 and 1425 m asl in the northern part of the Berchtesgaden National Park in the Alps. Moreover, the linear delays of SOS with altitude in this study are similar with 1.35 days/50 m in New Hampshire [*Richardson et al.*, 2006] and 1.7 days/50 m in North Carolina [*Hwang et al.*, 2011]. In contrast to other studies over the southern Appalachians [*Hwang et al.*, 2011] and the eastern United States [*Elmore et al.*, 2012], we found that EOS advances 0.91 (±0.02) days/50 m between 1500 and 2500 m asl and LOS shrinks 2.09 (±0.07) days/50 m between 500 and 3000 m asl across our entire study area.

In our results, we found no significant trend in SCP and LSP metrics between 2003 and 2014. This was also the case for SCP over the period of 1990–2011 in previous studies [*Hüsler et al.*, 2014; *Marty*, 2008]. This is in contrast to *Chen et al.* [2015a], who reported that SCD has become shorter across European Alps from 2001 to 2014, as well as other studies reporting significant trends in recent decades in LSP over this region [*Defila and Clot*, 2005; *Stöckli and Vidale*, 2004]. However, these studies [*Defila and Clot*, 2005; *Stöckli and Vidale*, 2004] consider much longer time extents as compared to the 12 years of our study.

4.2. Correlation Between ΔSCP and ΔLSP Across the Alps and in Subregions

The finding that SCD is positively correlated with SOS but is negatively correlated with LOS across entire Alps (Figure 3 and Table 1) is a clear indication that snow cover duration influences the start and the length of vegetation phenology in alpine regions and thus plays a role in dynamic of alpine ecosystem. These results are in agreement with previous studies that demonstrated that prolonged snow cover results in a delayed and reduced growing season [*Cooper et al.*, 2011; *Jonas et al.*, 2008; *Julitta et al.*, 2014], whereas a shortened snow cover duration mostly advances and prolongs plant growth time [*Galvagno et al.*, 2013; *Wipf and Rixen*, 2010; *Wipf et al.*, 2009]. Furthermore, *Dorrepaal et al.* [2003] stated that increased winter snow cover had a positive effect on the production of *Sphagnum fuscum* in Abisko, Sweden. *Yu et al.* [2013] found that both winter and spring snow depths have an impact on SOS timing. These studies partially confirm that snow cover affects alpine phenology.

Our study includes LSD and FSF metrics, which do not necessarily represent the last and first date of the continuously snow covered winter period but allow us to account for potential late season transient snowfall events occurring in the Alps. Our results (section 3.2) indicate that last snow day and first snow fall have

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no influence on alpine phenology. In another study over the Nepal Trans Himalayan region, *Paudel and Andersen* [2013] used similar metrics but reported high correlations between last snow-free day and SOS over large areas and between first snow day and EOS at very high altitudes. This can be due to other factors such as different climatological and meteorological conditions. More precisely, our results only show low correlation coefficients ($|R| < 0.3$) between ΔLSD and ΔSOS and between ΔLSD and ΔLOS and a small amount of corresponding significant pixels (<8% of total) across the entire study area. The correlations of ΔLSD with ΔSOS and ΔLOS at high altitudes ($0.3 < |R| < 0.4$) are slightly higher than the correlations at mid and low altitudes ($|R| < 0.3$). Moreover, our results show no correlation between ΔFSF and ΔEOS. This may be due to the fact that the FSF and LSD are most meaningful in regions with continuous seasonal snow cover, other than in regions with multiple late season transient snowfall [*Hüsler et al.*, 2014]. Therefore, we conclude that SCD, rather than LSD or FSF, correlates with alpine phenology and largely affects it across altitude. Furthermore, late season transient snowfall events may only have limited influence on the growth of alpine vegetation and the dynamics of alpine ecosystem.

Our results show that the correlations between ΔSCD and ΔSOS and between ΔSCD and ΔLOS differ considerably between the four subregions (Figure 3 and Table 1), being generally stronger in the northern than in the southern Alpine subregions. These findings are in agreement with the fact that the correlation strength between SCD and onset of spring is dependent on the climate of a geographical region [*Jönsson et al.*, 2010]. We conclude that the correlation between SCD and alpine phenology is stronger in geographical regions with longer SCD than in regions with shorter SCD. Our study goes one step further in showing that the correlation between ΔSCD and ΔSOS and between ΔSCD and ΔLOS vary between vegetation types (Table 1). We found that ΔSCD has a strong positive correlation with ΔSOS and a negative correlation with ΔLOS for NG, MH, SV, and midaltitude TWS (Table 1 and Figures S6 and S7). These results indicate that a later start of growing season and a shorter length of growing season are always in parallel with a longer snow cover duration in high and middle altitudinal vegetation types, and vice versa. These findings support the suggestion by *Julitta et al.* [2014] that snow cover plays an important role in determining the start of phenological development in alpine grasslands and agree with the finding by *Galvagno et al.* [2013] that snow cover limits the length of the growing season in high-altitude grasslands. *Yu et al.* [2013] report that the winter snow depth has stronger effect on grasslands and shrubs than on broadleaf deciduous forests and needleleaf forests in temperate China, which is what we also find for the Alps. Our results provide evidence that SCD is correlated with forest phenology in middle and low altitudes across the Alps. Indeed, the phenology of forests (i.e., 10–22% of the total area of BF, CF and MF) and low-altitude TWS significantly correlates ($|R| < 0.5$) with snow cover duration at middle and low altitudes (Figures S6 and S7). Although temperature strongly regulates the start of the growing season of both temperate deciduous broadleaf and coniferous forest [*Yu et al.*, 2013], our results consequently support the suggestion that phenological events of most temperate tree species are not solely driven by air temperature [*Yu et al.*, 2013] but also by snow cover duration. Furthermore, in European Alps, the dynamic of forest ecosystem could be affected by the variation of interannual snow cover duration.

Our choice of land cover data set entails that changes in land cover type within the study period are not taken into account in our analysis. However, excluding pixels with land cover change between 2000 and 2012 had no significant influence on our results.

4.3. Correlation Between ΔSCP and ΔLSP With Variation in Altitude

Together with other environmental factors, snow is one of the essential environmental parameters controlling high-altitude alpine phenology [*Cornelius et al.*, 2013; *Wipf et al.*, 2009; *Zeeman et al.*, 2017]. The positive correlation between ΔSCD and ΔSOS and the negative correlation between ΔSCD and ΔLOS, both of which were found over high-altitude regions in Figure 4, indicate that the influence of snow cover duration on the start and length of alpine phenology is strong at high altitudes. Our results are in marked agreement with *Keller et al.* [2005], who concluded that SCD largely determines the length of the growing season of the vegetation in high altitude areas of the Swiss Alps. Our findings further agree with the fact that longer SCD reduce the length of the alpine phenology cycle [*Björk and Molau*, 2007; *Cooper et al.*, 2011]. Based on a study in the Swiss Alps, *Jonas et al.* [2008] reported that locations with late snowmelt typically experience a longer snow cover season and thus attract plant communities with shorter vegetation cycles. A study by *Abeli et al.* [2011] found the inflorescence production to be significantly correlated with snow cover persistence from 1980 to 2054 m asl in the North Apennines of Italy, thus emphasizing the importance of SCD. At high altitudes, mean

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annual SCD was longer than 180 d/yr. Meanwhile, the declining amount of pixels with significant correlation between ΔSCD and ΔSOS and between ΔSCD and ΔLOS with altitude above 2000 m asl is shown in Figure 4. These may underpin the role of extreme temperatures, beside SCD, as a limiting factor for alpine phenology in these areas.

At midaltitudes (1000–2000 m asl), the positive correlation between ΔSCD and ΔSOS above 1300 m asl and the negative correlation between ΔSCD and ΔLOS above 1500 m asl is higher in the northern than in the southern Alps (Figure 4). Hence, it may be concluded that the correlation of SCD with midaltitude alpine phenology is stronger in regions with longer SCD. In the southern Alps, the positive correlation between ΔSCD and ΔSOS shifts to negative around 1300 m asl and the negative correlation between ΔSCD and ΔSOS shifts to positive around 1500 m asl with increasing altitude. This change in correlation is similar to *Yu et al.* [2013], who found differing impacts of winter snow depth and spring snow depth on start of growing season. With increasing snow depth, the associated effect changed from delaying start of growing season to advancing start of growing season [*Yu et al.*, 2013]. We can conclude that the variation of the influence of snow cover duration on start and length of phenology with altitude is not only in magnitude but also in characteristic. Thus, the role of snow cover in alpine ecosystem might also vary with altitude. Furthermore, our results show that the altitude at which the change in correlation sign occurs are different among the four subregions. SCD in each subregion is different around these thresholds, possibly due to subregional climate.

At low altitudes (<1000 m asl), where SCD is lower than 50 days, negative correlations between ΔSCD and ΔSOS and positive correlations between ΔSCD and ΔLOS were mainly found in the southern Alps. There, a longer SCD results in an earlier start of the growing season and therefore a longer growing season, and vice versa. This may be due to the warmer climate at low altitudes, which changes sequestration rates of soil carbon due to changes in the insulating snow depth in forest ecosystems [*Monson et al.*, 2006]. Therefore, a longer snow cover period can provide longer frost protection for plants in winter [*Desai et al.*, 2016; *Hu et al.*, 2010] and may result in more soil moisture and nutrient mobilization at the start of the growing period [*Bergeron et al.*, 2007; *Dunn et al.*, 2007]. This could explain the observed negative correlation between ΔSCD and ΔSOS and the positive correlation between ΔSCD and ΔLOS in low-altitude regions dominated by forest (<1000 m asl) in the southern Alps.

Overall, our results show that the relationship between SCD and alpine phenology varies with low altitude and midaltitude. The correlation differences between climatic subregions of the Alps are pronounced at middle and low altitudes, yet become smaller with increasing altitude and eventually disappear toward high altitudes. Our findings are in agreement with the hypothesis that the role of snow cover in alpine ecosystem varies between altitudes, vegetation types, and climate subregions. Namely, the changing in role of snow cover is depending on climate and other environmental factors such as altitude.

4.4. Correlation Between ΔSCP and ΔLSP With Variation in Terrain Aspect

Our results show that SCD on north and west facing terrains is longer than on south and east facing terrains in all altitudes. This is in parallel with higher correlation between ΔSCD and ΔSOS and between ΔSCD and ΔLOS on north than on south facing terrains and on west than on east facing terrains. These results are in agreement with previous studies reporting that the distribution of snow cover and vegetation are closely linked with terrain aspect [*Gottfried et al.*, 2012; *Keller et al.*, 2005]. The smallest SCDs occur on south facing terrains due to the influence of direct solar energy [*Keller et al.*, 2005]. Similar results were found by *Ide and Oguma* [2013], where the ratio between snow-covered and snow-free pixels recorded by digital time-lapse cameras in the northern Japanese Alps declined earlier at sites on south facing terrain slopes, as compared to sites on slopes facing other directions. South facing terrains receive more direct solar radiation resulting in shorter SCD [*Marke et al.*, 2013] and longer photoperiod length for alpine plants. Thus, these results suggest that sunshine duration influences alpine phenology, on top of SCD and variation in terrain aspect.

Concerning differences between west and east facing terrain aspects with opposite exposure to dominant atmospheric circulation patterns in winter, our results show a lower SCD on east than on the west facing terrain aspects. This may explain the correlation between ΔSCD and ΔSOS and between ΔSCD and ΔLOS on east facing terrains being lower than on west facing terrains. In general, our results reveal that correlation differences between SCD and alpine phenology due to terrain aspects are more pronounced in middle and

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low altitudes. In our results, these correlation differences tended to decrease at high altitudes across the entire study area.

4.5. Implications on the Relationship Between Snow Cover and Alpine Phenology Under a Climate Warming Scenario

The European Alps are expected to be particularly sensitive to climate change [*Beniston et al.*, 2003; *Gobiet et al.*, 2014]. Compared to the background global average increase of 0.7 °C in the past 100 years [*IPCC*, 2007], annual mean temperatures have increased by about 1.1 °C in the European Alps over the same period [*Böhm et al.*, 2001]. Moreover, higher-than-average increases in temperature are expected for the next decades [*IPCC*, 2007]. However, in this study, no significant change was found in mean winter temperature and cumulative precipitation over the past decade (Figure S4), but this is likely an effect of the relatively short investigated period. Other sources indicated that warming is likely to occur at approximately 0.25°C per decade until 2050 and accelerate to 0.36°C per decade toward the end of the 21st century [*Gobiet et al.*, 2014]. These temperatures are likely to cause reduction in snow fall and earlier melting of snow in spring [*Barnett et al.*, 2005], with important consequences for SCP and LSP. Thus, shorter snow cover duration might lead to earlier start of season, consequently resulting in an advancement and extension of the carbon uptake period [*Desai et al.*, 2016].

The results presented in our study indicate a strong sensitivity of ecological processes to snow cover duration associated with altitude. Specifically, the correlation between ΔSCD and ΔSOS and between ΔSCD and ΔLOS in each of the four alpine subregions and across altitudinal bands support the following: (i) increased air temperature, together with reduced snow cover, may lead to increased water stress and ultimately constrains vegetation growth [*IPCC*, 2007], and (ii) variations in seasonal snow cover may interact with air temperature and thus affect plant growth [*Yu et al.*, 2013]. As differences in the atmospheric heating of snow-covered and snow-free ecosystems are larger in spring than in autumn [*Euskirchen et al.*, 2007], and given that we found a larger area with significant correlation between ΔSCD and ΔSOS than between ΔSCD and ΔLOS, the start of alpine phenology could become more sensitive to future warming than the overall length of the growing season. Our results indicate that alpine vegetation ecosystems are particularly sensitive to future changes in snow cover at middle and high altitudes. More precisely, our results suggest that the phenology of midaltitude forests in the northern Alps, as well as in high-altitude natural grassland, may be considerably affected by future potential changes in SCD.

Furthermore, phenological shifts can lead to variations in the distribution and abundance of plant species [*Jonas et al.*, 2008]. Our results suggest that the expected changes in snow cover in the Alps would impact vegetation phenology in this region, thus reshaping the topographical distribution, species composition, and performance of alpine vegetation. These changes in performance might themselves affect other alpine processes, such as bird and herbivore migration or wildfires. On a macrolevel, the variability of snow cover phenology also influences intraannual water exchanges and land surface carbon storage. Though it remains to be tested, our results suggest that changes are more pronounced in the northern Alps and for high-altitude and midaltitude grasslands, as compared to the southern Alps and low-altitude forests.

5. Conclusions

This study examined how the spatiotemporal variability of snow cover correlates with alpine land surface phenology. Based on the analysis between snow cover phenology (SCP) and land surface phenology (LSP) in the European Alps, our findings support the hypothesis that the influence of snow cover on alpine phenology is different between climatic subregions, natural vegetation types, and terrain aspects with varying altitudinal bands. In particular, we found that snow cover duration (SCD) plays a key role in the start and length of the growing season in middle and high altitudes across the European Alps. The correlation between SCD and start/length of the growing season varies considerably with altitude. This correlation is stronger in the northern and eastern Alps than in the southern and western Alps, and it peaks at high altitudes, where natural grassland and sparse vegetation areas dominate. The altitude-dependent correlation between SCD and start/length of growing season in north and west facing terrain aspects is higher than in south and east facing terrain aspects.

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We demonstrated that a change in SCD has a greater impact on alpine phenology at higher than at lower altitude, which may be due to a coupled influence of SCD with underground conditions and air temperature. Alpine phenology will react to changes in SCD with the predicted increase of global temperatures that influences and reshapes the alpine ecosystem. The magnitude of these responses will differ depending on vegetation types, climatic subregions, and topographical factors such as altitude and terrain aspect but will be more pronounced in regions with longer SCD and in higher altitudes.

Our study presented an overview on altitude-dependent correlation of snow cover with alpine phenology. Future work should address the relationship between alpine phenology and snow accumulation (e.g., winter solid precipitation, snow depth, or snow water equivalent) to explore the mechanisms driving snow-vegetation interactions in alpine regions. In addition, increased combination of ground and satellite observations for detailed long-term investigations should be envisaged.

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2.8 Supporting Information

Contents of this section

Figures S1 to S8

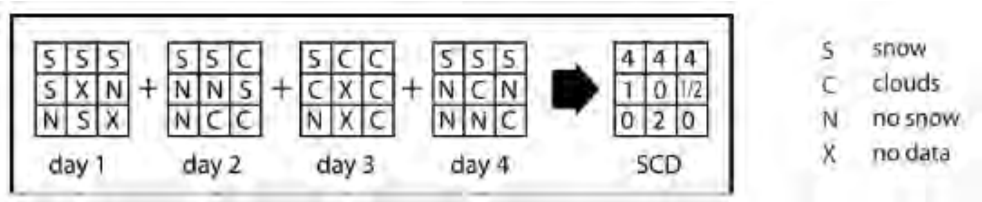

Figure S1: Illustration of the SCD algorithm; example of SCD calculation of four days.

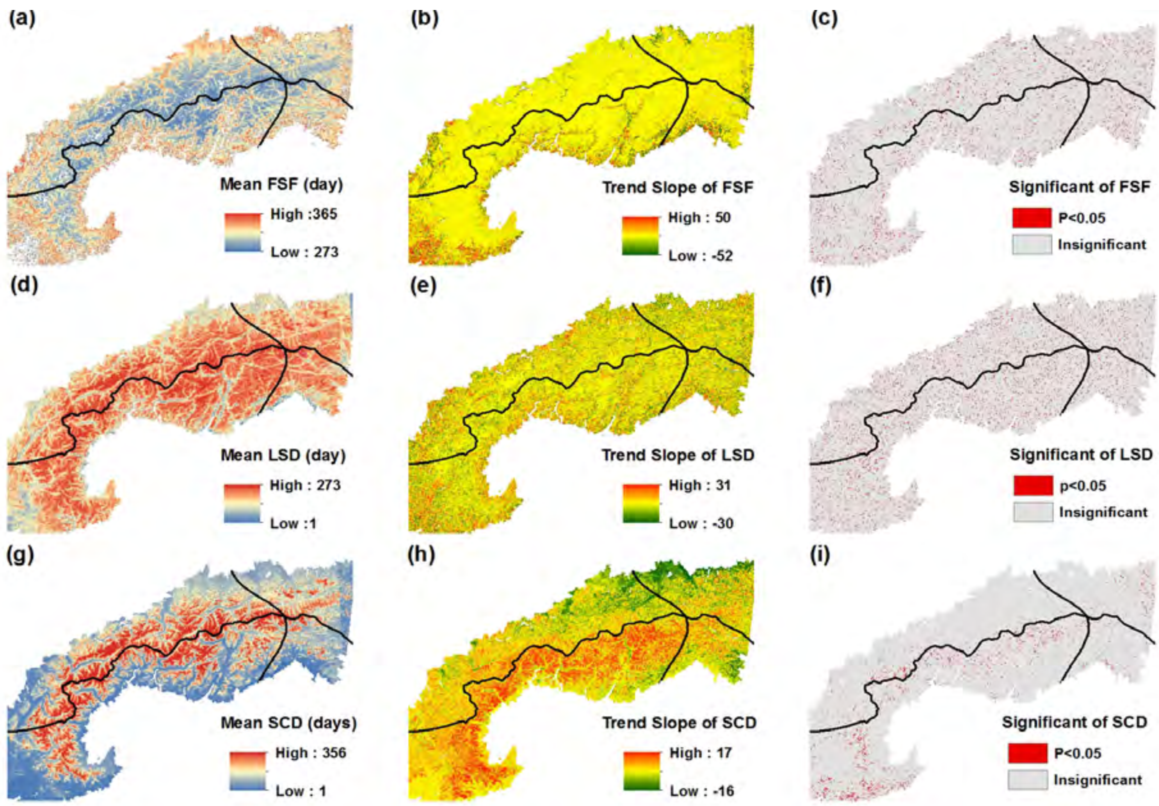

Figure S2: MODIS derived mean FSF (a) LSD (d) and SCD (g) for the period 2002-2014, their respective trends over the study period (b, e, h), and corresponding significant pixels (c, f, i).

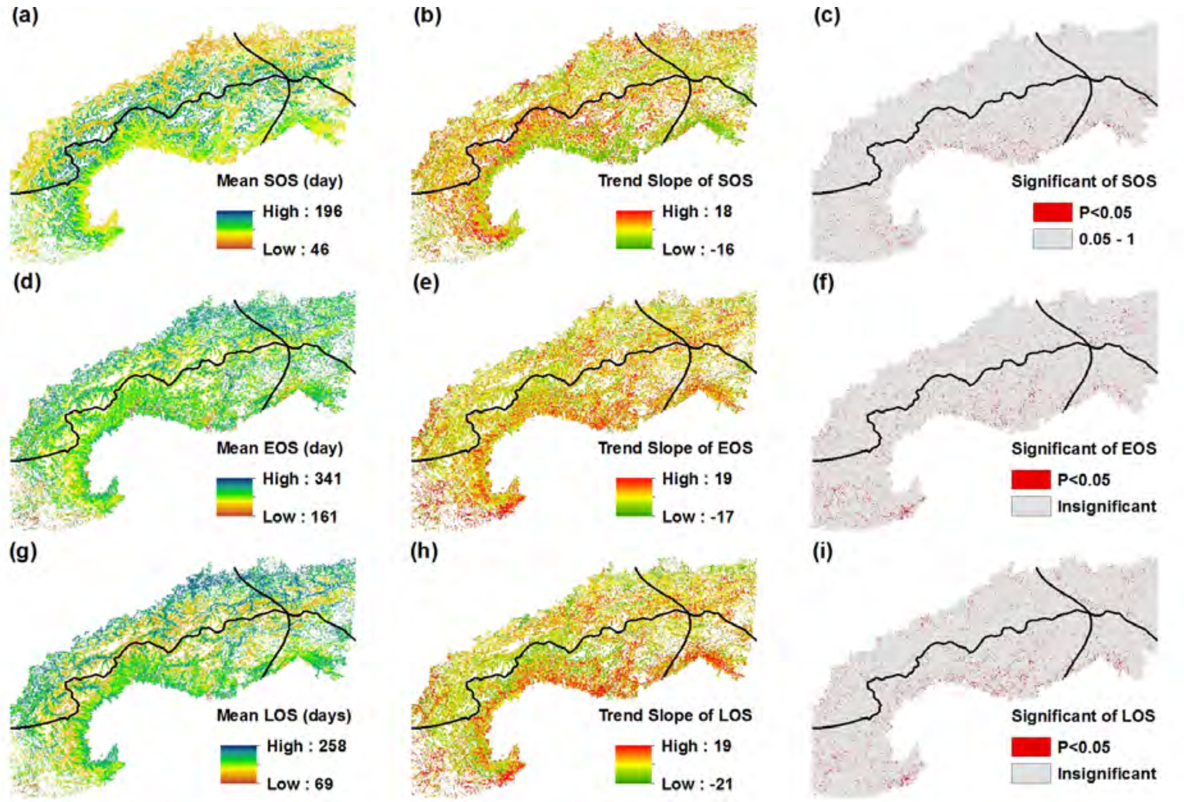

Figure S3: MODIS derived mean SOS (a), EOS (d) and LOS (g) for the period 2002-2014, their respective trends over the study period (b, e, h), and corresponding significant pixels (c, f, i).

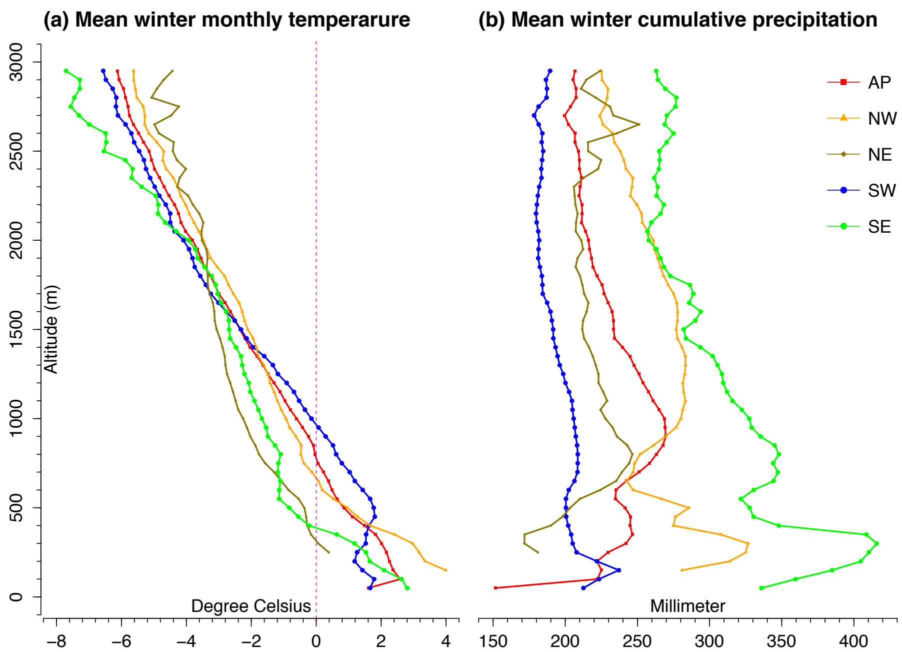

Figure S4: Variation in mean winter (December, January and February) temperature (a) and precipitation (b) with altitude for the entire study area (AP) and the four main subregions (NW, NE, SW, SE) for the period 2002-2014. Dashed purple lines denote a temperature of 0° C.

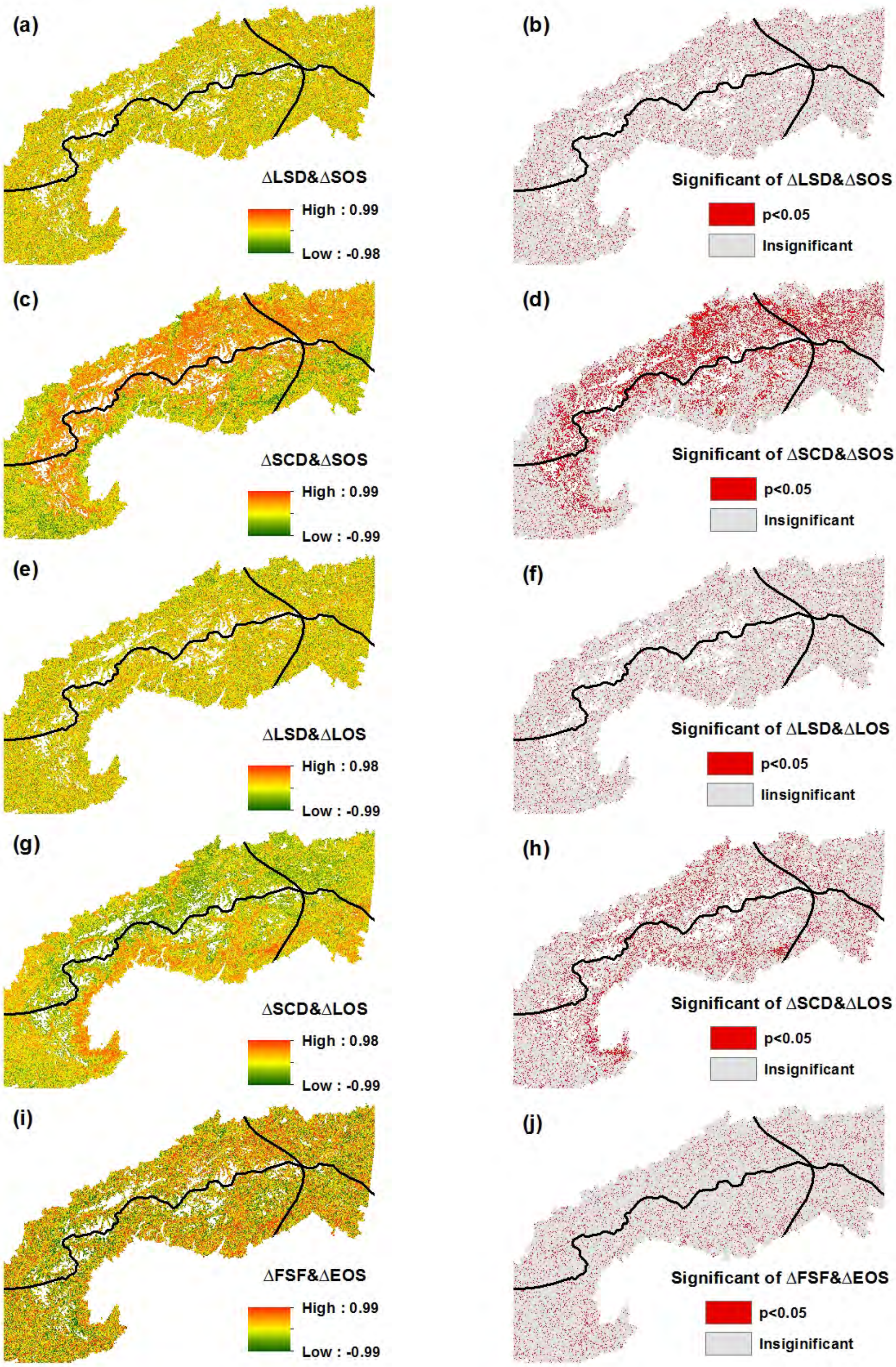

Figure S5: Spearman's rank correlation coefficient R and corresponding significant pixels for ΔLSD&ΔSOS (a, b), ΔSCD&ΔSOS (c, d), ΔLSD&ΔLOS (e, f), ΔSCD&ΔLOS (g, h) and ΔFSF&ΔEOS (i, j) for the entire study area.

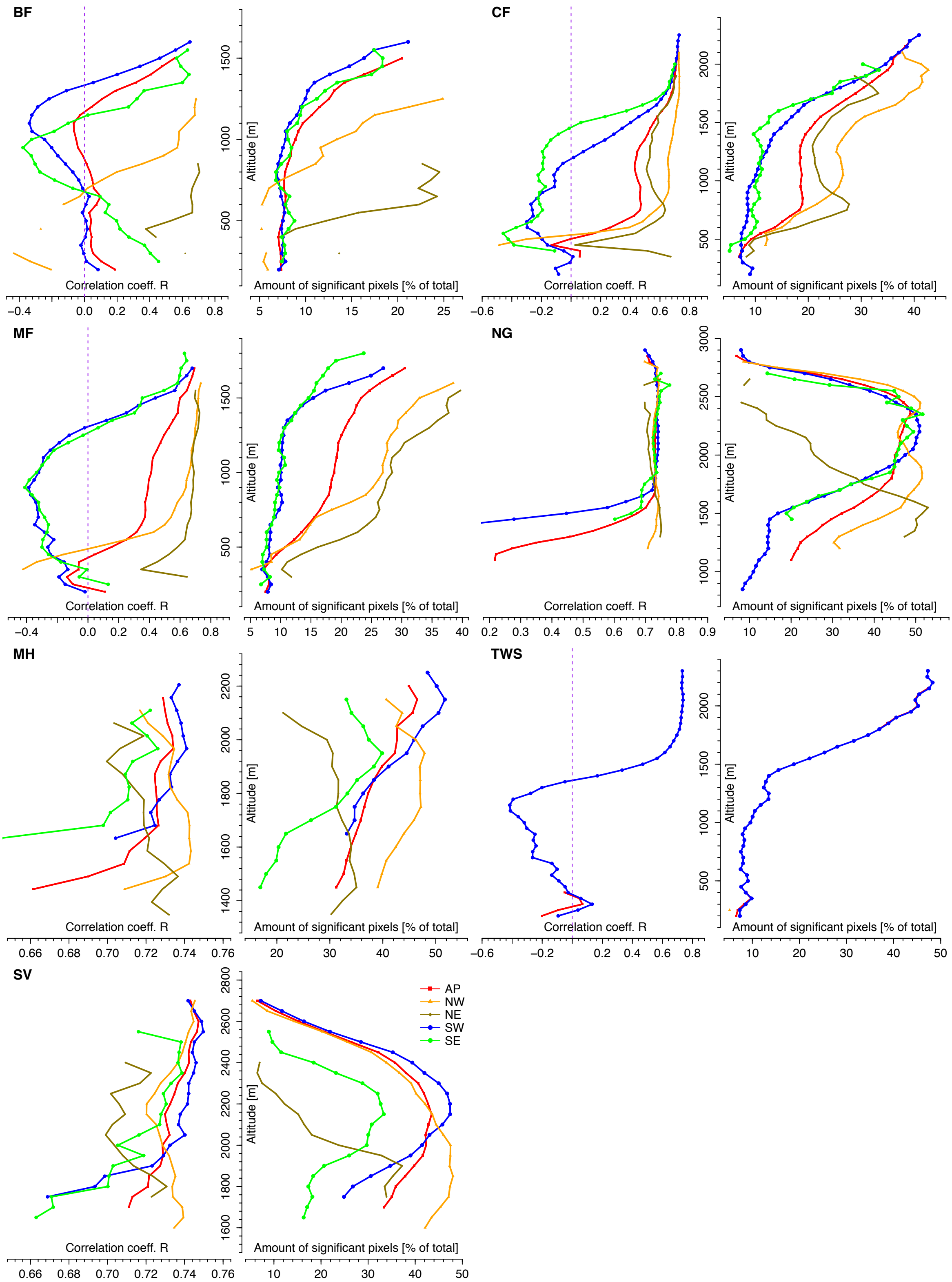

Figure S6: Altitudinal variation in correlation coefficient R (left panel) and corresponding amount of pixels [% of total] (right panel) with a significant correlation between ΔSCD&ΔSOS for seven natural vegetation types (BF, CF, MF, NG, MH, TWS and SV) across the entire study area (AP) and averaged by sub-region (NW, NE, SW, SE). Dashed purple lines represent a correlation coefficient of 0.

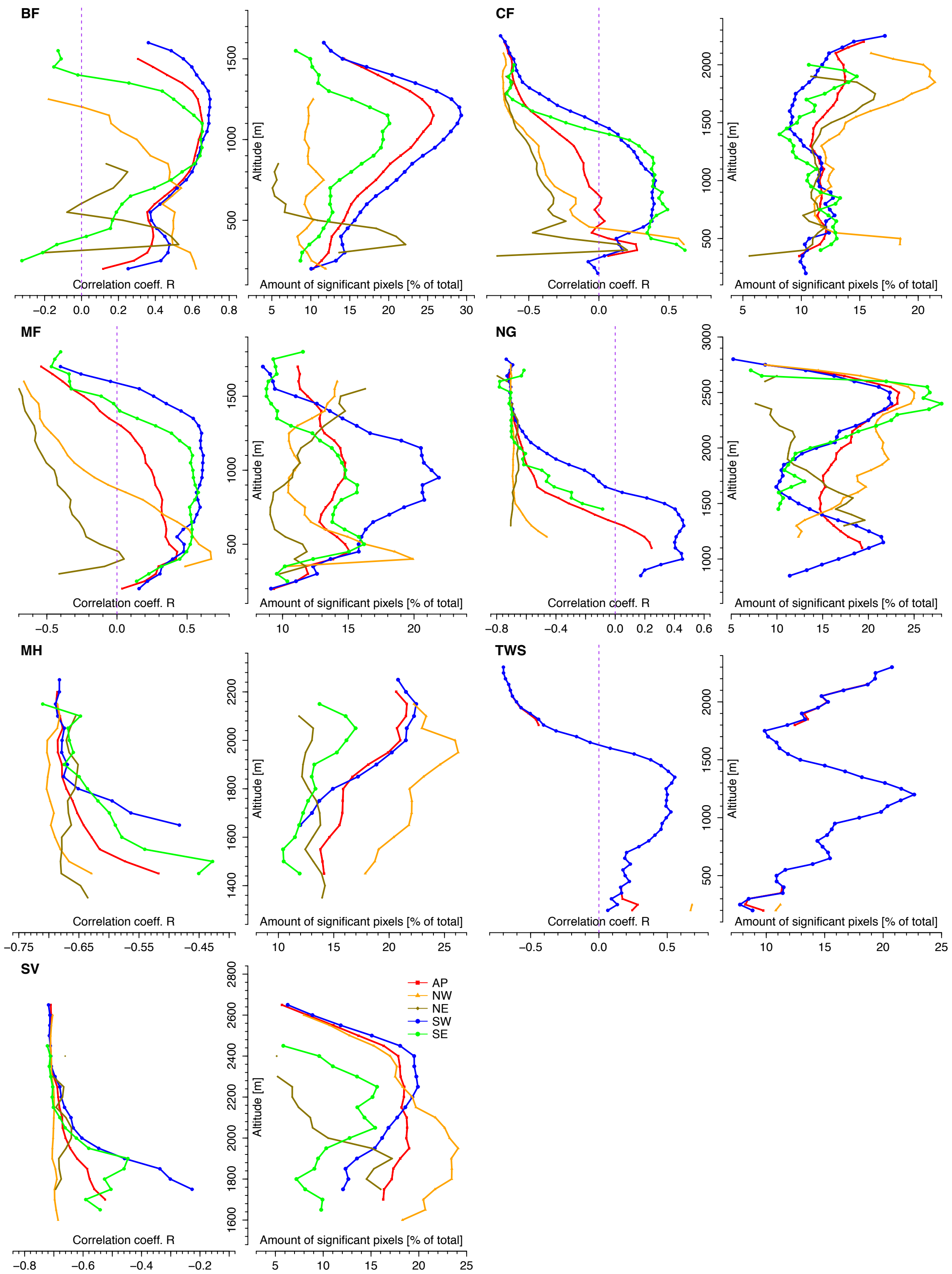

Figure S7: Altitudinal variation in correlation coefficient R (left panel) and corresponding amount of pixels [% of total] (right panel) with a significant correlation between ΔSCD&ΔLOS for seven natural vegetation types (Broad-leaved Forest (BF), Coniferous Forest (CF), Mixed Forest (MF), Natural Grasslands (NG), Moors and Heathland (MH), Transitional Woodland-Shrub (TWS) and Sparsely

Vegetated areas (SV)) across the entire study area (AP) and averaged by subregions (NW, NE, SW, SE). Dashed purple lines represent a correlation coefficient of 0.

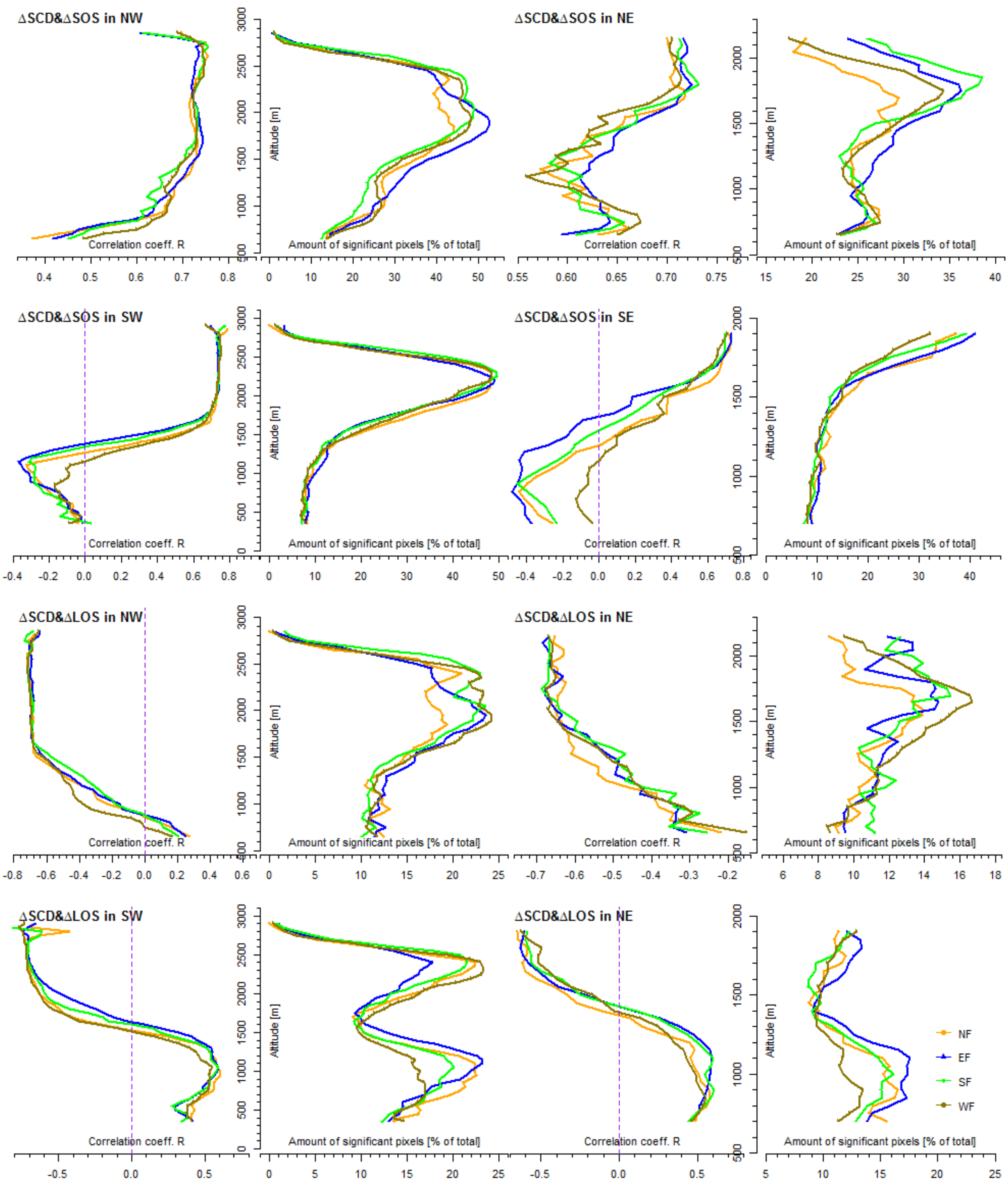

Figure S8: Altitudinal variation in correlation coefficient R (left panel) and corresponding amount of pixels [% of total] (right panel) with a significant correlation between ΔSCD&ΔSOS and between ΔSCD&ΔLOS for north- (NF), west- (WF), south- (SF) and east-facing (EF) terrains of natural vegetation (NV) for the four subregions (NW, NE, SW, SE). Dashed purple lines represent a correlation coefficient of 0.

Tables S1 to S3

	Regression coefficients (±SE) (days/50 m)					Corresponding altitudinal belts (low–high) (m)				
	AP	NW	NE	SW	SE	AP	NW	NE	SW	SE
FSF	-1.28 (±0.01)	-1.17 (±0.02)	-1.05 (±0.01)	-1.41 (±0.02)	-1.18 (±0.01)	1000-3000	1000-3000	1000-3000	1000-3000	1000-3000
LSD	3.21 (±0.12)	2.91 (±0.06)	3.24 (±0.09)	3.18 (±0.12)	3.15 (±0.16)	0-3000	0-3000	0-3000	0-3000	0-3000
SCD	5.65 (±0.14)	5.75 (±0.10)	5.78 (±0.17)	5.77 (±0.19)	5.89 (±0.17)	0-3000	0-3000	0-3000	0-3000	0-3000
SOS	1.65 (±0.04)	2.01 (±0.07)	1.97 (±0.07)	0.49 (±0.05) 1.85 (±0.06)	1.45 (±0.04)	500-3000	800-3000	600-3000	300-1300 1300-3000	500-3000
EOS	-0.91 (±0.02)	-0.85 (±0.04)	-0.89 (±0.03)	-0.86 (±0.02)	-1.02 (±0.02)	1500-2500	800-2500	1000-2800	1500-2,500	1500-2700
LOS	-2.09 (±0.07)	-2.50 (±0.10)	-2.64 (±0.09)	-1.58 (±0.08)	-1.71 (±0.07)	500-3000	500-3000	500-3000	500-3000	500-3000

Table S1: Changes in SCP (FSF, LSD and SCD) and LSP (SOS, EOS and LOS) dependent on altitude (p <0.001) using simple linear regression, and corresponding altitudinal gradients for the entire study area (AP) and the four sub-regions (NW, NE, SW, SE).

	Inter-annual trend (days/year; %)				
	AP	NW	NE	SW	SE
FSF	0.98; 2.94	-2.80;3.43	-2.33;4.01	1.95;3.99	-0.29;4.37
LSD	0.99;1.03	1.01;4.79	-2.98;4.63	1.94;4.87	-0.94;4.50
SCD	0.98;2.00	1.96;1.21	2.94;1.43	2.49;3.58	1.35;1.58
SOS	-0.40;1.99	1.20;0.71	-0.02;0.60	-0.31;2.94	-1.95;3.04
EOS	2.17;3.18	0.05;1.99	1.89;2.41	2.78;4.23	2.34;2.71
LOS	2.53;3.24	--0.07;1.72	1.75;2.33	3.05;4.34	3.85;3.57

Table S2: Significant (p <0.05) inter-annual trend [days/year] and corresponding amount of significant pixels [%] of SCP (FSF, LSD and SCD) and LSP (SOS, EOS and LOS) for the entire study area (AP) and the four subregions (SW, NW, SE, NE).

Vegetation types	Slope aspects	ΔSCD&ΔSOS					ΔSCD&ΔLOS				
		AP (*r*;%)	NW (*r*;%)	NE (*r*;%)	SW (r;%)	SE (*r*;%)	AP (*r*;%)	NW (*r*;%)	NE (*r*;%)	SW (*r*;%)	SE (*r*;%)
NV	NF	0.60;24.9	0.70;32.7	0.64;24.5	0.54;**22.5**	0.24;14.0	-0.15;**15.0**	-0.52;14.9	-0.51;11.0	0.06;**16.4**	0.20;13.0
	EF	0.56;24.4	**0.70**;**35.4**	**0.65**;**26.8**	0.46;20.5	0.18;**14.1**	-0.07;15.0	-0.51;16.0	-0.49;11.4	**0.18**;15.8	**0.22**;**13.7**
	SF	0.58;23.8	0.69;31.8	0.64;26.2	0.49;19.9	0.27;13.8	-0.15;14.7	-0.50;15.7	-0.49;12.0	0.10;15.2	0.19;12.6
	WF	**0.61**;24.3	0.70;33.1	0.64;25.6	**0.55**;20.7	**0.32**;13.0	**-0.25**;14.5	**-0.55**;**16.4**	**-0.51**;**12.1**	-0.02;14.9	0.15;11.8
BF	NF	0.22;**10.8**	**0.57**;**17.3**	**0.70**;**25.1**	0.09;**9.5**	0.04;8.9	**0.53**;**19.6**	0.10;**11.2**	-0.09;9.4	**0.59**;**22.5**	**0.43**;**14.0**
	EF	0.10;10.2	0.54;15.7	0.68;24.5	-0.11;9.0	0.11;8.3	0.52;19.2	0.16;11.5	-0.09;7.8	0.58;22.2	0.33;13.8
	SF	0.07;8.6	0.33;10.0	0.67;19.7	-0.06;8.0	0.15;8.5	0.50;17.9	**0.27**;10.1	**0.30**;**10.3**	0.56;20.8	0.32;13.8
	WF	**0.23**;9.4	0.43;12.2	0.69;20.9	**0.15**;8.7	**0.23**;**8.9**	0.50;16.7	0.17;11.0	0.23;8.4	0.56;18.9	0.31;12.3
CF	NF	0.58;23.0	**0.69**;29.72	0.56;22.0	**0.52**;**20.6**	0.12;**12.6**	-0.33;11.6	-0.52;13.9	**-0.50**;11.2	-0.13;10.4	0.06;10.7
	EF	0.50;21.7	0.68;**31.3**	0.56;22.5	0.37;17.4	-0.13;12.3	-0.21;12.1	-0.45;14.7	-0.45;11.3	0.04;**11.0**	0.15;**11.7**
	SF	0.52;19.8	0.66;24.9	0.56;22.1	0.40;16.4	-0.05;11.0	-0.21;11.4	-0.42;12.7	-0.44;11.8	0.04;10.4	**0.23**;10.0
	WF	**0.58**;**24.5**	0.68;29.0	**0.57**;**23.5**	0.52;18.9	**0.14**;11.8	**-0.36**;**12.3**	**-0.54**;**14.8**	-0.49;**12.5**	**-0.19**;10.7	0.15;10.2
MF	NF	0.46;19.3	**0.67**;26.6	0.68;27.4	0.08;**13.2**	-0.11;19.3	0.17;14.4	-0.17;**12.4**	-0.44;10.8	0.48;18.3	0.42;14.3
	EF	0.42;**19.5**	0.66;**28.0**	0.67;**27.7**	-0.13;11.8	**-0.28**;**19.5**	0.18;**14.5**	**-0.21**;12.3	**-0.44**;**11.3**	**0.53**;**18.9**	**0.48**;**15.0**
	SF	0.39;16.2	0.59;21.2	**0.69**;26.4	-0.05;10.7	-0.14;16.2	**0.26**;13.9	-0.01;11.7	-0.36;11.0	0.51;17.4	0.47;13.2
	WF	**0.50**;18.0	0.65;25.2	0.68;27.0	**0.23**;12.3	0.05;18.00	0.12;12.3	-0.21;11.8	-0.42;10.3	0.41;14.3	0.43;12.0
NG	NF	0.71;40.1	0.73;43.1	0.72;27.2	**0.69**;**40.1**	0.67;33.6	**-0.58**;16.9	-0.68;18.1	-0.66;11.1	-0.48;17.0	-0.39;14.8
	EF	0.69;39.7	0.73;48.3	0.73;36.6	0.65;34.8	0.67;33.1	-0.44;16.5	-0.67;20.1	-0.67;13.5	-0.20;14.6	-0.24;14.9
	SF	0.70;40.7	0.73;47.2	**0.73**;**37.9**	0.66;35.1	0.68;**39.5**	-0.52;17.6	-0.68;20.7	**-0.68**;**13.7**	-0.29;15.6	-0.37;16.1
	WF	**0.71**;**41.7**	**0.73**;**48.3**	0.72;31.0	0.69;38.0	**0.70**;36.9	-0.60;**19.2**	**-0.69**;**22.0**	-0.67;13.1	**-0.48**;**18.0**	**-0.51**;**17.7**
MH	NF	0.69;34.1	0.73;41.3	0.71;27.2	0.66;34.5	**0.70**;**31.5**	**-0.60**;16.1	-0.69;20.3	-0.65;11.8	-0.52;17.0	**-0.58**;12.1
	EF	0.65;31.3	0.72;41.7	**0.72**;32.8	0.52;25.2	0.60;26.6	-0.46;14.4	-0.61;19.0	-0.65;12.0	-0.21;13.2	-0.51;**13.5**
	SF	0.67;31.4	0.72;41.3	0.71;**33.4**	0.59;25.9	0.62;25.6	-0.56;14.9	-0.66;20.7	**-0.66**;13.5	-0.40;13.4	-0.54;11.0
	WF	**0.71**;**36.7**	**0.74**;**45.9**	0.72;31.7	**0.69**;**36.6**	0.68;26.3	-0.64;**18.4**	**-0.69**;**25.0**	-0.65;**14.0**	**-0.59**;**18.4**	-0.57;12.2
TWS	NF	0.59;28.00	0.70;33.9	0.63;34.5	0.59;28.2	0.21;15.1	-0.09;14.8	-0.50;13.9	-0.44;15.0	-0.08;15.1	0.21;12.2
	EF	0.41;19.0	**0.72**;32.5	0.66;30.4	0.39;18.7	-0.03;12.0	0.24;15.0	-0.44;14.2	-0.39;10.0	0.27;15.1	**0.42**;**15.0**
	SF	0.50;22.3	0.69;27.6	**0.68**;25.6	0.50;22.5	0.02;11.7	0.01;14.3	-0.44;12.5	-0.60;10.7	0.02;14.5	0.36;14.2
	WF	**0.61**;**29.6**	0.70;**35.6**	0.60;**35.6**	**0.61**;**29.8**	**0.39**;**16.8**	**-0.31**;**16.0**	**-0.53**;**15.0**	**-0.63**;**18.6**	**-0.29**;**16.2**	-0.10;14.1
SV	NF	0.72;28.9	0.73;30.7	0.72;15.1	SW (r;%)	0.61;16.5	-0.63;14.1	-0.70;13.7	-0.62;7.8	SW (*r*;%)	-0.52;8.9

EF	0.70;30.7	0.73;33.6	**0.72**;**25.8**	-0.06;8.0	0.58;20.8	-0.54;14.4	-0.68;16.3	-0.62;10.6	0.56;20.8	-0.30;11.9
SF	0.71;**35.1**	**0.73**;**39.7**	0.71;22.8	**0.15**;8.7	0.67;**22.6**	-0.62;**16.9**	-0.69;**19.3**	**-0.67**;**11.1**	0.56;18.9	-0.45;**12.6**
WF	**0.72**;31.6	0.73;35.9	0.71;20.9	0.09;**9.5**	**0.70**;19.6	**-0.66**;15.8	**-0.70**;17.6	-0.65;11.0	**0.59**;**22.5**	**-0.59**;9.0

Table S3: Mean significant Spearman's correlation coefficient R between ΔSCD&ΔSOS and ΔSCD&ΔLOS of north- (NF), west- (WF), south- (SF) and east-facing (EF) terrains for each vegetation type (NV, BF, CF, MF, NG, MH, TWS and SV) and corresponding significant pixels [%] for the entire study area (AP) and the four subregions (NW, NE, SW, SE). Highest values among the four terrain aspects are given in BOLD.

Text S1 to S2

Text S1.

Snow Cover Phenology (SCP)

Data on snow cover duration (SCD), first snow fall (FSF) and last snow day (LSD) are derived from snow maps obtained with Terra MODIS images, with a novel algorithm that takes into account the specific characteristics of mountain areas [*Notarnicola et al.*, 2013a; b]. The two main characteristics of this novel algorithm are the improved ground resolution of 250 m and a tailored topographic correction [*Dietz et al.*, 2012; *Notarnicola et al.*, 2013a; b]. In our study, SCD, FSF and LSD have been derived on a yearly basis for the period from 2002 to 2014. These provide information about snow cover characteristics over the last decade and are used to examine the spatiotemporal variation of snow cover condition in this period. The analysis of a single snow season can be useful for identifying the years with exceptionally early or late FSF and LSD and/or SCD. The daily availability of snow maps allows the calculation of SCD without gaps. It also allows the calculation methodology to be kept as simple as possible: the snow information of the daily combined snow cover maps is accumulated by "addition". However, gaps appear when a pixel is classified as "cloud" or "no data", which are treated equally. The SCD of "gap days" in between the information "snow" or "no snow" is calculated according to the principle of a linear interpolation technique: if a gap is preceded by a "snow" day and followed by a "snow" day the pixel is assumed to have the highest probability of being snow covered as well, and therefore the SCD for the gap day is 1 day. Accordingly, if the gap is preceded by a "no snow" day and followed by a "no snow" day its SCD equals 0. If, however, either of the two fringe days is "snow" and the other "no snow", the probability of snow coverage – without any further information – is 50 %, therefore the SCD of the pixel equals ½. The same principle is applied if several consecutive days show cloud or no data classes.

The calculation algorithm processes the vector of every pixel of the map over the study period. Eventually, each pixel has a certain number of "snow" days to which the individual SCD of all gap days is added. This procedure results in a SCD value for each pixel and comprises the Snow Cover Duration Map. As the name suggests, the FSF is defined as the first date in the hydrological year that a pixel is snow covered. This index is useful to identify shifts in the starting of snow season. For each pixel of the snow map, the implemented algorithm extracts the first date that there is snow starting from 1 October to 30 September of the following year. With the proposed approach, the FSF calculation also takes into account the sporadic snowfall in the early fall, and thus, not always, refers to the starting date of the continuous winter snow covered period.

The LSD is the last date in the water year (WY) that a pixel is snow covered; this parameter can provide useful information about the melting process. For calculating LSD, the algorithm extracts from the time series of snow maps of every hydrological year the last day in which the pixels are covered by snow. Even in this case, as well as for FSF, the algorithm detects the last snow day. This means that LSD not necessarily represents the last date of the continuous winter snow covered period and it takes into account possible multiple late season transient snowfall events. In order to eliminate pixels with wrong values due to misclassification, the final maps of FSF and LSD have been filtered, by removing pixels where: the FSF date was in the range between 91 (1 April) and 181 (30 June) and the SCD (Snow Cover Duration) was <10; or FSF and LSD dates were the same.

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Chapter 3

Relative influence of timing and accumulation of snow on alpine land surface phenology

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Author contributions

Jing Xie conceived the study and designed the analyses under the supervision of Mathias Kneubühler and Michael E. Schaepman. Jing Xie collected and performed the data analyses of land surface phenology, snow cover phenology, and snow accumulation metrics. Jing Xie and Mathias Kneubühler carried out interpretation of results jointly, and Jing Xie prepared the initial manuscript. Jing Xie, Irene Garonna, and Rogier de Jong computated and interpretated the land surface phenology metrics. Jing Xie computed the snow accumulation metrics. Claudia Notarnicola and Ludovica De Gregorio provided the snow cover phenology metrics. Jing Xie, Mathias Kneubühler, Irene Garonna, Rogier de Jong, and Michael E. Schaepman edited the final version of the manuscript.

AGU PUBLICATIONS

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RESEARCH ARTICLE
10.1002/2017JG004099

Key Points:
- Snow accumulation shows strong correspondence with snow cover duration across elevations
- The influence of timing and accumulation of snow on start and length of the growing season is more pronounced above 1,500 m than below
- Snow cover duration plays a more significant role than snow accumulation on Alpine start and length of the growing season

Supporting Information:
- Supporting Information S1
- Data Set S1

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Relative Influence of Timing and Accumulation of Snow on Alpine Land Surface Phenology

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Abstract Timing and accumulation of snow are among the most important phenomena influencing land surface phenology in mountainous ecosystems. However, our knowledge on their influence on alpine land surface phenology is still limited, and much remains unclear as to which snow metrics are most relevant for studying this interaction. In this study, we analyzed five snow and phenology metrics, namely, timing (snow cover duration (SCD) and last snow day), accumulation of snow (mean snow water equivalent, SWE_m), and mountain land surface phenology (start of season and length of season) in the Swiss Alps during the period 2003–2014. We examined elevational and regional variations in the relationships between snow and alpine land surface phenology metrics using multiple linear regression and relative weight analyses and subsequently identified the snow metrics that showed strongest associations with variations in alpine land surface phenology of natural vegetation types. We found that the relationships between snow and phenology metrics were pronounced in high-elevational regions and alpine natural grassland and sparsely vegetated areas. Start of season was influenced primarily by SCD, secondarily by SWE_m, while length of season was equally affected by SCD and SWE_m across different elevational bands. We conclude that SCD plays the most significant role compared to other snow metrics. Future variations of snow cover and accumulation are likely to influence alpine ecosystems, for instance, their species composition due to changes in the potential growing season. Also, their spatial distribution may change as a response to the new environmental conditions if these prove persistent.

1. Introduction

Global climate is changing more rapidly in alpine and arctic regions than in other areas, and the average temperature in alpine areas is expected to continue to rise faster than the average global increase (Intergovernmental Panel on Climate Change (IPCC), 2007, 2014). Changes in mountainous vegetation phenology are considered an important and observable trace of mountainous ecosystem response to these climatic changes (Jonas et al., 2008; Menzel et al., 2006), as well as a key determinant of coupled water and energy exchange (White et al., 2009), land surface carbon fluxes (Barrio et al., 2013; Richardson et al., 2010), and species distributions (Chuine & Beaubien, 2001). As a climate driver, snow is one of the most important controlling factors in mountainous ecosystems (Cornelius et al., 2013; Wipf et al., 2009). It shields harsh winds and provides frost protection in winter (Chen, An, et al., 2015; Desai et al., 2016; Groffman et al., 2006; Wahren, et al., 2005; Wipf et al., 2006) and nutrient mobilization and water supply in spring (Keller & Körner, 2003). Variations in timing and accumulation of snow have been reported to significantly influence vegetation phenology, as well as the energy balance (Euskirchen et al., 2007), water cycling (Barnett et al., 2005; Rawlins et al., 2006), and soil carbon cycling (Dorrepaal et al., 2003; Monson et al., 2006). For these reasons, it is critical to understand the response of alpine land surface phenology to the variation of the timing and accumulation of snow, which can change ecological interactions and thereby reshape alpine ecosystems.

Many studies have documented that the timing and accumulation of snow influence the start and length of mountainous land surface phenology (Chen, Liang, et al., 2015; Dunne, 2003; Jonas et al., 2008; Paudel & Andersen, 2013; Trujillo et al., 2012; Yu et al., 2013). For instance, a larger snowpack and longer snow cover duration can result in later snowmelt and timing of phenological events (Cooper et al., 2011; Inouye, 2008). In contrast, shorter snow cover duration and earlier snowmelt often advance plant development (Chen et al., 2011; Dunne, 2003; Hu et al., 2010; Wipf et al., 2009; Wipf & Rixen, 2010). Moreover, both the timing and accumulation of snow (Beniston et al., 2003; Hüsler et al., 2014; Trujillo et al., 2012) and phenological events (Benadi et al., 2014; Cornelius et al., 2013; Defila & Clot, 2005; Lambert et al., 2010; Schuster et al.,

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2014) have been reported to change with elevation. For a long time, the timing and accumulation of snow have been referenced as important drivers of mountainous ecosystems across topographic gradients (Wipf & Rixen, 2010). Several studies have documented that the impacts of snow metrics on vegetation growth and land surface phenology varied with elevation and geographical region (Huelber et al., 2006; Keller et al., 2005; Paudel & Andersen, 2013; Trujillo et al., 2012; Xie et al., 2017). More specifically, above 2,000 m asl in the European Alps, the snow cover duration was reported to be positively correlated with the start of the growing season but negatively correlated with the length of the growing season. Besides, the last snow day was found to be moderately correlated with the start and length of the growing season (Xie et al., 2017). In high-elevation drier regions in Nepal Trans Himalaya, the last snow day was also observed to be highly correlated with the start of the growing season (Paudel & Andersen, 2013) and in northern China, the start of the growing season was reported to be sensitive to snow depth change for most of the alpine and subalpine vegetation (Yu et al., 2013). In the Sierra Nevada region, maximum snow accumulation and the date of snow disappearance were reported to explain variability in vegetation greenness between 2,000 and 2,600 m asl because snow melt eases water limitation (Trujillo et al., 2012). Nevertheless, there is a lack of detailed studies comparing the impact of multiple snow metrics on land surface phenology of snow-dominated mountainous regions. Furthermore, in particular the relative importance and weight of snow timing and snow accumulation to the alpine phenology is not fully understood. This study is based on a large amount of available data spanning the entire Swiss Alps to investigate the characteristics, magnitude, and elevation dependency of these relationships.

Snow metrics are known to covary under certain conditions. For instance, the date of snow disappearance may be correlated with the maximum snowpack accumulation (Trujillo et al., 2012). Similarly, in combination with spring temperatures, the winter snow depth codetermines the time of snow melting (Richardson et al., 2013). Moreover, snow cover duration is closely linked to both the start day and melt day of snow cover in high-elevational regions with continuous snow cover (Hüsler et al., 2014). However, across elevation, the characteristic and magnitude of the correlation between snow timing and snow accumulation still need detailed understanding. Furthermore, while (i) the snow cover duration is highly correlated with the start and the length of a phenological cycle and (ii) the last snow day is moderately correlated with the start of the growing season in high-elevational regions, the elevation-dependent amount of snow accumulation and its influence on mountainous land surface phenology require further investigation. In snow sensitive regions with weak or no interdependence between timing and accumulation of snow, the relative importance of these parameters remains to be assessed to find most relevant metrics for studying snow-vegetation dynamics.

As a consequence, investigations of relationship between snow and phenology metrics may facilitate the understanding of the mechanisms of vegetation response to snow cover and accumulation in mountainous ecosystems, as well as the magnitude of the relative importance between these snow metrics to land surface phenology. In this study, we focused on snow timing (SCD and last snow day (LSD)), snow accumulation (SWE_m), and alpine land surface phenology (start of season, SOS; length of season, LOS) for the period 2003–2014 in the Swiss Alps. We aimed to (i) test the variation of snow accumulation and its correspondence with snow timing across elevation, (ii) investigate the characteristic and magnitude of the influence of snow accumulation and snow timing on land surface phenology, and (iii) identify the snow metric that has the strongest effect on land surface phenology for different elevations and regions.

2. Material and Methods

2.1. Study Area

Located in the central European Alps, the Swiss Alps (6.8°E–10.5°E, 45.8°N–47.4°N) encompass an area of 25,194 km^2 (Figure 1). They were selected for our analysis given their typical mountainous character with complicated topography (Jonas et al., 2008; McVicar et al., 2010; Scherrer et al., 2004), as well as long-term changes of snow attributed to climate changes (Beniston et al., 2003; Marty et al., 2017; OcCC-Consortium, 2007). We separated the study region into the northern Swiss Alps (NSA; 10,867 km^2, 43.1% of total area), the eastern Swiss Alps (ESA; 5,825 km^2, 23.1%), the southern Swiss Alps (SSA; 3,667 km^2, 14.6%), and the western Swiss Alps (WSA; 4,834 km^2, 19.2%) according to the subdivision of biogeographical regions (Gonseth et al., 2001). NSA, WSA, and ESA are subject to temperate westerly and oceanic features of

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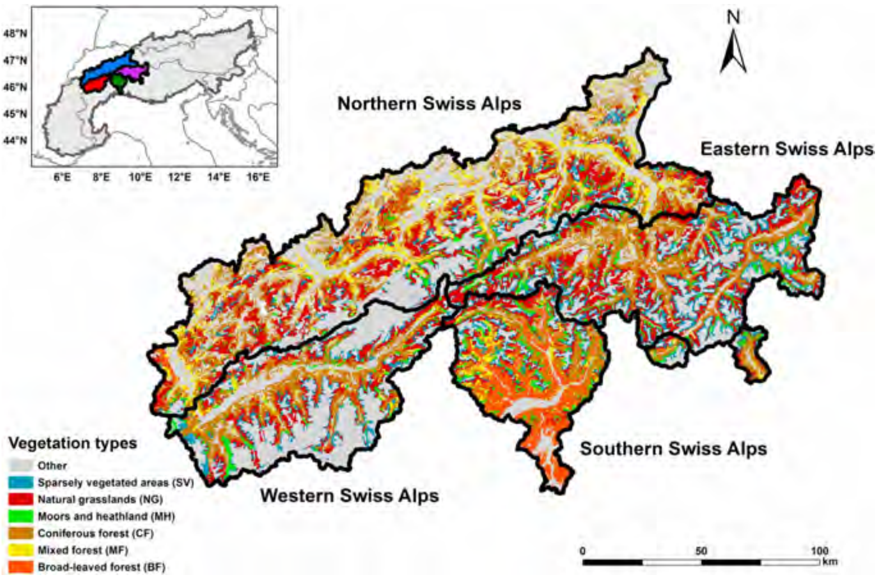

Figure 1. Location and natural vegetation types of the Swiss Alps (separated as northern Swiss Alps, eastern Swiss Alps, southern Swiss Alps, and western Swiss Alps).

climate variability, while SSA experiences Mediterranean subtropical and oceanic features of climate variability (Auer et al., 2007). At particular times, the NSA often show different climatic conditions compared to the SSA (Laternser & Schneebeli, 2003). The climate of the four subregions has differed in past decades and is expected to differ in the projected future (Rammig et al., 2010). The subregions are assumed to reflect different ecological and climatological regimes. We focused on six natural vegetation (NV) types (Figure 1), excluding the areas that experienced land cover change between 2000 and 2012 (i.e., 2.5% of NV in 2000), based on the CORINE Land Cover 2000 and 2012 seamless vector data (http://land.copernicus.eu/, accessed May 2017). NV in our statistical analysis covers 60.0% of the study area and includes broad-leaved forest (BF, 6.8% of NV), mixed forest (MF, 8.8% of NV), coniferous forest (CF, 35.7% of NV), moors and heathland (MH, 7.1% of NV), natural grasslands (NG, 32.0% of NV), and sparsely vegetated areas (SV, 10.1% of NV). NV is found at elevations up to 3,000 m asl, bordering with the alpine-nival ecotone (Gottfried et al., 2011).

2.2. Snow Metrics

In this study, we defined the SCD as the total number of snow-covered days in each water year (WY, running from 1 October to 30 September of the following year) (Hüsler et al., 2014; Xie et al., 2017), the LSD as the last snow-covered date in each WY, and the snow accumulation, that is, SWE_m, as the mean value of snow water equivalent (SWE) of the corresponding SCD in each WY. LSD is expressed in a day of the (calendar) year and SCD is expressed in days of each WY (days). The unit of SWE is millimeter (mm). These snow metrics can provide information about the spatiotemporal variation of timing and accumulation of snow characteristics in the Swiss Alps for the period 2002–2014.

To derive these snow metrics, we employed snow cover maps (SCM) at 250 m/daily resolution (Notarnicola et al., 2013a, 2013b) and a SWE grid at 1 km/daily resolution (Jonas et al., 2009; Magnusson et al., 2014). SCM were obtained from Terra Moderate Resolution Imaging Spectroradiometer images with a tailored topographic correction and improved ground resolution of 250 m in order to take into account the specific characteristics of mountainous areas (Notarnicola et al., 2013a, 2013b). The daily SWE data, being generated on the basis of 298 observational snow monitoring sites in Switzerland using a distributed snow hydrological model (Griessinger et al., 2016; Magnusson et al., 2014), were assessed using validation points following the methods of Foppa et al. (2007) and further elaborated by Magnusson et al. (2014). SWE grids were resampled to 250 m resolution using the Nearest Neighbor method in order to match the SCM.

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The calculation of SCD and LSD, using the method described in Xie et al. (2017), was based on the daily availability of SCM. The LSD can provide useful information about the melting process, given that multiple late season transient snow patterns and snowfall occur during snowmelt seasons (Crawford et al., 2013; Hüsler et al., 2014) across elevations. Moreover, a pixel of the SWE grid is involved in the calculation of SWE_m only if the corresponding SCM pixel is identified as snow cover (Figure S1 in the supporting information) using the method described in Xie et al. (2017). The detailed calculation of SWE_m is presented in Text S1.

2.3. Phenology Metrics

We used remote sensing data sets to assess land surface phenology metrics, largely because field-based surveys are mostly restricted to species level information in mountainous regions (Chen, An, et al., 2015; Pellerin et al., 2012) and have limited spatial coverage (Fisher et al., 2006; Studer et al., 2007). Satellite remote sensing supports monitoring and characterizing land surface phenology of vegetated areas, as well as responses to changing climate at landscape level and across ecological scales (Paudel & Andersen, 2013; Trujillo et al., 2012; Yu et al., 2013).

Normalized Difference Vegetation Index (NDVI) is one of the most widely used indices for monitoring land surface phenological events at various scales (Cleland et al., 2007; Fisher et al., 2006; Garonna et al., 2014, 2016). NASA Moderate Resolution Imaging Spectroradiometer/Terra NDVI products (MOD13Q1-collection 5) were used to derive yearly phenology metrics for SOS and LOS on a pixel-by-pixel basis. The available 276 MOD13Q1 images were of 250 m/16 day resolution, spanning from 2003 to 2014, with corresponding quality and day-of-observation information data.

To derive SOS from the annual NDVI time series, we selected the day when NDVI reached half its annual range. This relative threshold method—called $\text{Midpoint}_{\text{pixel}}$—is based on the comprehensive intercomparison of SOS metrics by White et al. (2009). The end of season is then defined as the day on which NDVI reaches the midpoint again in the calendar year, and the LOS is simply the number of days between SOS and end of season. For the calculation of each annual SOS and LOS using MOD13Q1 images, the method described by Xie et al. (2017) was applied in NV areas. SOS is always expressed in day of (calendar) year and LOS in days.

2.4. Statistical Analysis

Topographic information of the study area at a 1 arc sec scale (~30 m) obtained from the European Environment Agency (http://www.eea.europa.eu/, accessed May 2017) was used to generate a 250 m scale digital elevation model (DEM). The maps of snow and phenology metrics were transformed to zone 32 of the Universal Transverse Mercator projection and resampled to a 250 m grid for statistical analysis. Then, a Pearson correlation was employed to test the correlation between snow metrics (i.e., SCD&LSD, SCD&SWE_m, and LSD&SWE_m) on an interannual timescale based at pixel level. Linear least squares regression was used to analyze the interannual trend (significance defined as $p < 0.05$) over the study period for each pixel and the elevation-dependent responses (significance defined as $p < 0.001$) of 12 year averaged values for each snow and phenology metric. Partial Spearman's correlation, which can remove the dependency effects from other parameters, was used to estimate the correlation (based on a two-tailed significance test and $p < 0.05$) between SWE_m and phenology metrics for each pixel. Multiple linear regression was employed to investigate the characteristic and magnitude of the relationships (significant model was selected with $p < 0.05$) between snow and phenology metrics. This method was applied to identify the key snow metrics (excluding the pixels with significant Pearson correlation between snow metrics) with direct influence on phenology metrics (significance defined as $p < 0.05$ for each predictor in each model) based on pixel level. The slopes of the multiple linear regressions between snow and phenology metrics were calculated to determine variation in the strength of the relationships between snow and phenology metrics.

Accordingly, the generalized model is expressed as follows:

$$y = f(\mathrm{SCD}, \mathrm{LSD}, \mathrm{SWE_m}), \text{ where } y \text{ is SOS or LOS} \tag{1}$$

The R^2 of the multiple linear regressions (1) quantitatively explain the relationship between snow and phenology metrics. Johnson (2000) defined relative weight as the contributing proportion of each predictor to R^2, considering both its contribution combined with other variables and its unique contribution. We used relative weight (% of R^2) analysis to assess the relative importance of snow metrics based on R^2, as well as to identify the snow metric with the strongest effect on alpine phenology.

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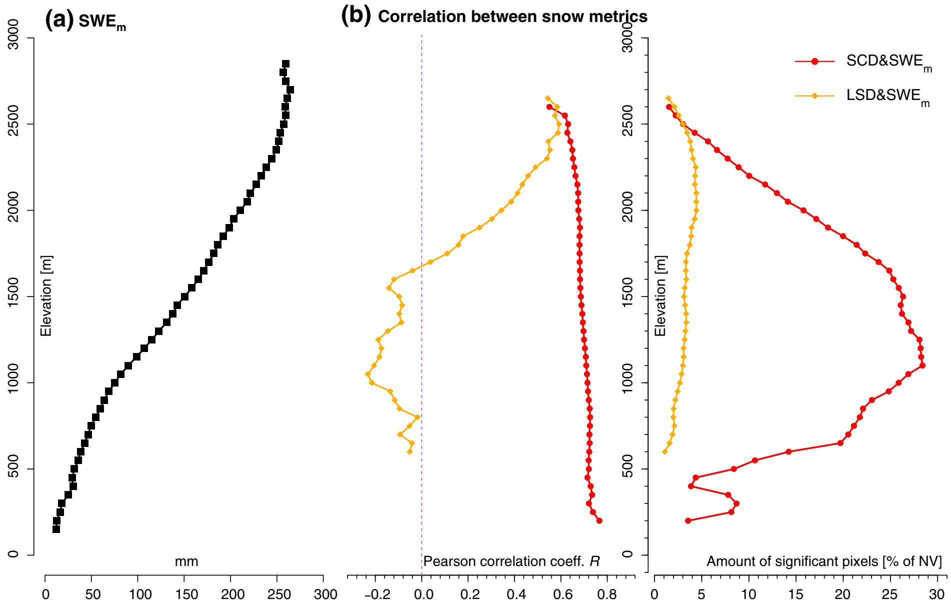

Figure 2. Elevational variation in mean mean snow water equivalent (SWE_m) for the period 2003–2014 (a) and mean Pearson correlation coefficients (a) between snow metrics (i.e., snow cover duration (SCD) and SWE_m and last snow day (LSD) and SWE_m) and the corresponding amount of significant pixels [% of total] (b) across the entire Swiss Alps. The dashed line represents a mean correlation coefficient of 0.

The 250 m grids of statistical results were intersected with the 250 m subregions and NV maps. The elevation-dependent analyses consisted of selecting distinct zones within a 100 m band with a 50 m elevational resolution (between 200 and 3,000 m asl, corresponding to the range of elevational distribution of NV types), based on the DEM across the study area. The statistics between snow and phenology metrics were analyzed along elevation gradients and between the four subregions. The corresponding values for each band contain the mean statistically significant results, such as the mean correlation coefficient and mean regression slopes. Bands with (i) mean SCD larger than 360 days, (ii) mean SCD lower than 10 days, and (iii) the proportion of pixels in statistical significance less than 1% masked out in the elevational analysis. Image data processing was performed using ArcGIS (v10.4.1, ESRI, USA), ENVI/IDL (v5.1, the EXELIS Inc., McLean, VA, USA), and statistical analysis was performed using the R (v3.2.3) program environment.

3. Results

3.1. Variation of SWE_m and Correlations Between Snow Metrics With Elevations

In the areas of NV types, SWE_m varies with elevations (Figure 2a) and increases by 5.46 (±0.10) mm/50 m between 200 and 3,000 m asl. Above 1,500 m asl, where grasslands dominate (Figure S2a), SWE_m amounts to more than 150 mm, while SWE_m is less than 150 mm at lower elevations. The mean SWE_m in WSA and ESA are larger than in NSA and SSA, with the mean SWE_m in NSA being larger than in SSA.

SWE_m showed a strong significant positive correlation with SCD (with mean $R = 0.69$), and the mean correlation coefficients slightly decreased with elevation (Figure 2b). The corresponding amount of pixels with significant correlation accounted for 26.5% of NV and reached a maximum between 1,000 and 1,500 m asl. However, SWE_m presented a less significant correlation with LSD across elevation (Figure 2). In addition, the significant correlations between SWE_m and LSD above 2,000 m asl (with mean $R = 0.53$) were stronger than those in other elevations but were only present in a few pixels (<5% of NV). The spatial patterns of Pearson correlation coefficients between snow metrics (i.e., SCD&LSD, SCD&SWE_m, and LSD&SWE_m) are presented in Figure S3.

Over the 12 investigated years, less than 5% of total pixels showed a significant temporal trend ($p < 0.05$) in both snow (i.e., SCD, LSD and SWE_m) and phenology (i.e., SOS and LOS) metrics across the entire research area

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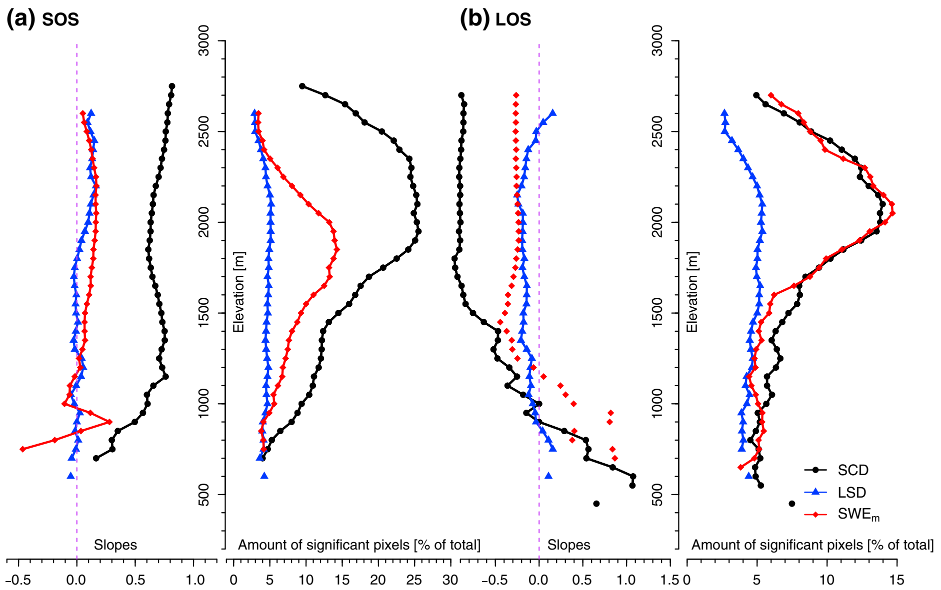

Figure 3. Elevational variation in mean multiple linear regression slopes (a) between snow and phenology metrics (i.e., snow cover duration (SCD) and start of season (SOS), last snow day (LSD) and SOS, mean snow water equivalent (SWE_m) and SOS (d/mm) (a); SCD and length of season (LOS), LSD and LOS, SWE_m and LOS (d/mm) (b)) and the corresponding amount of significant pixels [% of total] (b) of each snow metric for the Swiss Alps. A total of 65.7% of all natural vegetation pixels were employed in this analysis. Dashed lines represent a mean regression fit of 0.

by estimation of linear least squares regression. In addition, both snow and phenology metrics changed with elevation (Figure S2). Linear least squares regression (significant with $p < 0.001$) results showed that both snow and phenology metrics responded to the change of elevation across the entire study area (Text S2). The spatial patterns of elevational gradients, SOS, LOS, SCD, LSD, and SWE_m are presented in Figure S4.

3.2. Multiple Linear Regressions Between Snow and Phenology Metrics Depending on Elevations and Subregions

As an overview of the correlation between SWE_m and phenology parameters, partial Spearman's correlation values have been computed between SWE_m and SOS and between SWE_m and LOS, as well as the corresponding amount of significant pixels depending on elevation. The mean R between SWE_m and SOS was larger than 0.60 between 1,500 and 2,000 m asl, and the corresponding significant pixels amounted to 15–20%. A negative correlation between SWE_m and LOS (mean $R < -0.60$) was found above 1,500 m asl, and the corresponding significant pixels amounted to 15–20%, as well (see Figures S5 and S6).

In the following multiple linear regression analysis between snow metrics (i.e., SCD and LSD, SCD and SWE_m, and LSD and SWE_m) a total of 34.3% NV pixels (see Figure S3) with significant Pearson correlation ($p < 0.05$) was excluded to avoid duplicate information. The mean slopes of the multiple linear regression between snow and phenology metrics with elevation are shown in Figure 3. SCD showed a positive relationship for SOS, and with the largest amount of corresponding significant pixels, compared to LSD and SWE_m, with elevation (Figure 3a). The slopes of SOS with SCD showed no apparent change (between 0.6 and 0.8) above 1,500 m asl in regions which were dominated by grassland (i.e., SV, NG, and MH), with corresponding pixels reaching a maximum (>25%) between 1,900 and 2,400 m asl. In comparison, the LSD showed a much weaker significant relationship for SOS than SCD for SOS and had a much smaller amount of significant pixels (<7%) across elevation. The relationship of SOS with SWE_m was positive above 1,500 m asl and reached a maximum (mean slopes between 0.18 and 0.20 d/mm) between 1,800 and 2,400 m asl. In contrast, a few pixels with significance had negative slopes below 1,500 m asl in regions which were dominated by forest (i.e., CF, MF, and BF).

Above 1,500 m asl, the relationships of LOS with SCD (mean slopes >−0.70) and with SWE_m (mean slopes around −0.20 d/mm) showed no apparent variation with elevation, and presented an equal maximum of

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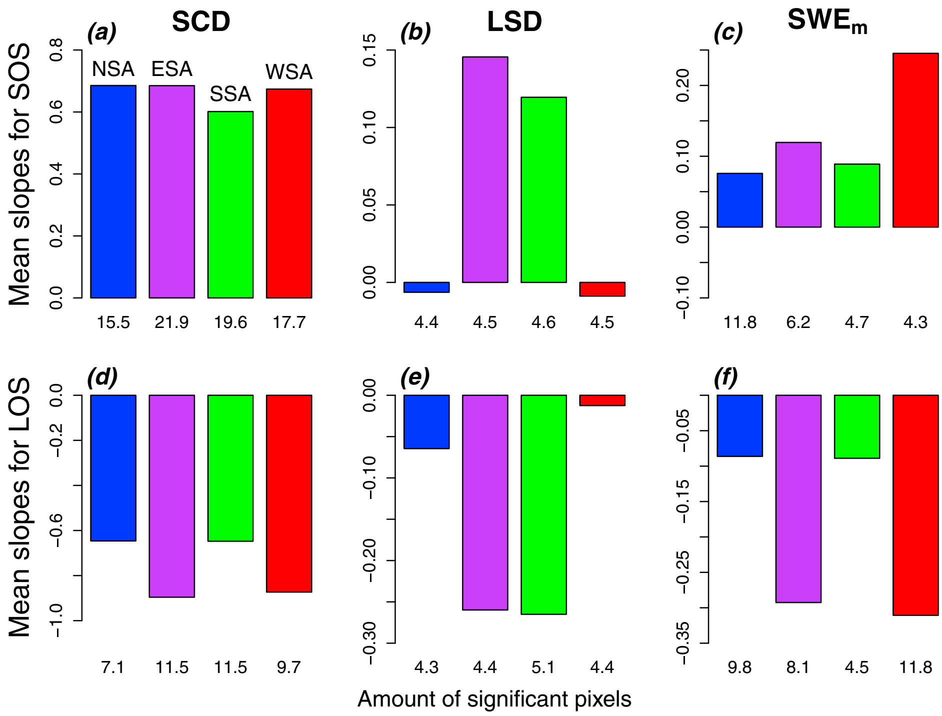

Figure 4. Mean multiple linear regression slopes between snow and land surface phenology metrics (i.e., snow cover duration (SCD) and start of season (SOS) (a), last snow day (LSD) and SOS (b), mean snow water equivalent (SWE_m) and SOS (d/mm) (c), SCD and length of season (LOS) (d), LSD and LOS (e), SWE_m and LOS (d/mm) (f)) and the corresponding amount of pixels with a significant regression [% of total] for each snow metric for the four subregions (northern Swiss Alps (NSA), eastern Swiss Alps (ESA), southern Swiss Alps (SSA), and western Swiss Alps (WSA)). A total of 65.7% of all natural vegetation pixels were employed in this analysis.

corresponding significant pixels between 2,000 and 2,200 m asl (Figure 3b). The relationships of LOS with SCD, with LSD and with SWE_m varied from positive to negative between 900 and 1,200 m asl with elevation. In contrast to the results of SOS, the positive relationships of LOS with SCD, LSD, and SWE_m were mainly below 1,500 m asl with fewer corresponding significant pixels (<7%). SOS and LOS in SV, NG, and MH showed stronger and broader impacts from snow metrics than those in CF, MF, and BF. (Figures S7–S9).

The relationship of SOS with SCD (mean slopes > 0.60) showed slight differences between the four subregions (Figure 4a). Mean slightly positive slopes of the relationship of SOS with LSD were only found in the ESA and the SSA and for a smaller portion of corresponding significant pixels (Figure 4b). The mean negative relationship of SOS with SWE_m in SSA is in contrast with the positive relationships in the other subregions (Figure 4c). The relationships of LOS with SCD in ESA and the WSA (mean slopes < -0.90) were stronger than those in the NSA and SSA (mean slope < -0.60) (Figure 4d). Mean slightly negative slopes of the relationship of LOS with LSD were only found in ESA and SSA and with a smaller portion of corresponding significant pixels (Figure 4e). The relationships of LOS with SWE_m in ESA and WSA (mean slope < -0.25 d/mm) showed much stronger negative slopes than those in NSA and SSA (mean slopes < -0.05 d/mm) (Figure 4f). The spatial patterns of multiple linear regression relationships between snow and phenology metrics (i.e., SCD and SOS, LSD and SOS, SWE_m and SOS, SCD and LOS, LSD and LOS, and SWE_m and LOS) are presented in Figure S10.

3.3. Relative Weights of Snow on Phenology Metrics Depending on Elevations and Subregions

Figure 5 shows the relative weight (% of R^2) of snow metrics on phenology metrics with elevation. The mean R^2 ($p < 0.05$) of the multiple linear regressions between snow and phenology metrics ranged between 0.70 and 0.75 across elevation (Figure S11). The relative weight of SCD on SOS increased from 40% to 70% and was

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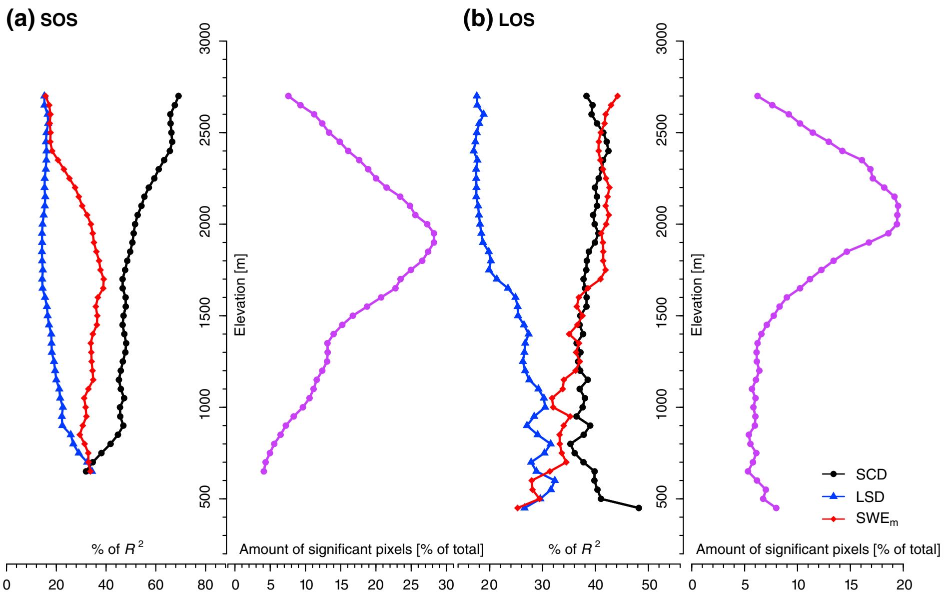

Figure 5. Elevational variation in mean relative weight [% of R^2] (a) of snow metrics (i.e., snow cover duration (SCD), last snow day (LSD), and mean snow water equivalent (SWE$_m$)) on start of season (SOS) (a) and length of season (LOS) (b), and corresponding amount of significant pixels [% of total] (b) for the Swiss Alps. A total of 65.7% of all NV pixels was employed in this analysis.

the highest across elevation (Figure 5a). The corresponding percentage of significant pixels of the multiple linear regression models increased with elevation until reaching a maximum at 2,000 m asl with 23%, and decreased again afterward. Above 1,500 m asl, SCD showed the largest relative weight (>50%), increasing with elevation. SWE$_m$ had less than 30% relative weight across elevation. Below 1,500 m asl, SCD was still the dominating metric but with less relative weight than above 1,500 m asl. Meanwhile, SWE$_m$ had about 35% relative weight.

SCD and SWE$_m$ had similar relative weights on LOS across elevation (Figure 5b). The corresponding amount of significant pixels for R^2 was higher above 1,500 m asl and reached a maximum at 2,200 m asl. The relative weight values were also higher above 1,500 m asl than below. LSD showed the least relative weight on both SOS and LOS across elevations. The relative importance (% of R^2) of SCD, LSD, and SWE$_m$ to SOS and to LOS, obtained over the entire study area for six vegetation types (BF, CF, MF, NG, MH, and SV), are presented in Figures S12–S14.

The mean R^2 of the multiple linear regressions between snow and phenology metrics showed no difference between the six NV types (Figures S12d and S12h), as well as the four subregions (Figures S15 and S16). More precisely, the amount of significant pixels in R^2 of snow metrics to SOS is almost equal between the four subregions (18.8% in NSA, 18.0% in ESA, 17.5% in SSA, and 17.9% in WSA), whereas for LOS, the amount is slightly lower in NSA (10.5%) than in the other subregions (12.9% in ESA, 11.2% in SSA, and 14.5% in WSA) (Figure S16).

Figure 6 shows that the relative weights (% of R^2) of SCD on SOS and LOS are slightly higher in ESA and SSA than in NSA and WSA. In contrast, the relative weights of SWE$_m$ on SOS and LOS are higher in NSA and WSA than in ESA and SSA (Figures 6c and 6f). The relative weights of LSD on SOS and LOS, however, only showed slight differences with a mean value around 20% (Figures 6b and 6e). The spatial patterns of the relative weights of SCD, LSD, and SWE$_m$ on SOS and on LOS for the entire study area are presented in Figure S17.

4. Discussion

4.1. Variation in SWE$_m$ and Correlations Between Snow Metrics With Elevation

Our results in section 3.1 and Figure 2 present a significant positive correlation between SCD and SWE$_m$ across elevations in the Swiss Alps. This finding is in agreement with previous studies that showed snow

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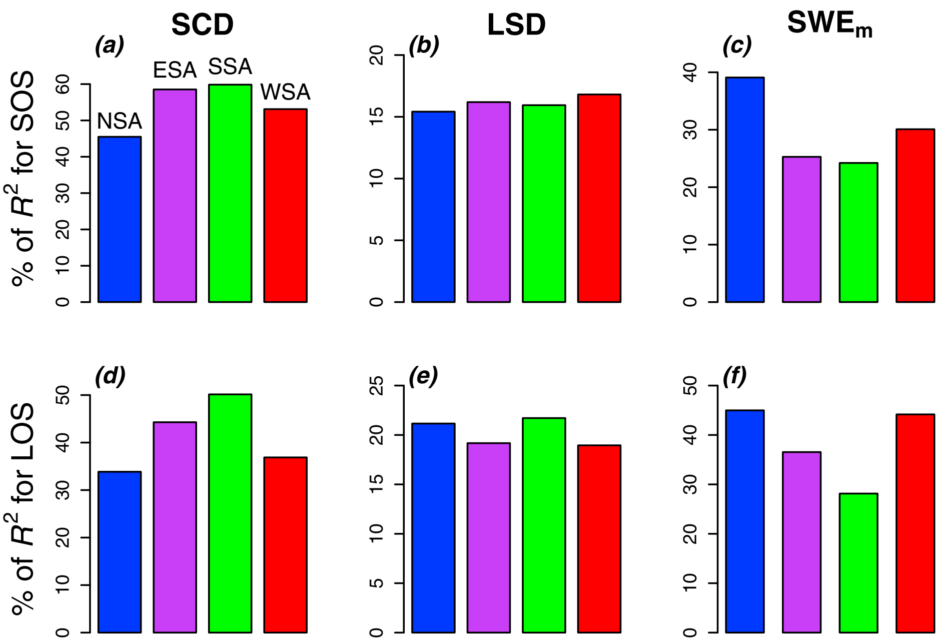

Figure 6. Mean relative weight [% of R^2] of snow metrics (i.e., snow cover duration (SCD), last snow day (LSD), and mean snow water equivalent (SWE_m) on start of season (SOS) (a–c) and on length of season (LOS) (d–f)) for the four subregions (northern Swiss Alps (NSA), eastern Swiss Alps (ESA), southern Swiss Alps (SSA), and western Swiss Alps (WSA)). A total of 65.7% of all NV pixels was employed in this analysis.

cover being correlated with snow accumulation metrics such as snow depth and SWE (Metsämäki et al., 2012; Yu et al., 2013). However, the lack of a significant correlation between SCD and LSD, as well as between LSD and SWE_m (Figure 2), is in contrast to a study performed in the Sierra Nevada Mountains, USA (Trujillo et al., 2012), where a strong correlation of LSD with maximum SWE is reported, albeit under different climatic conditions than in our study area. This may be due to the fact that SCD is closely linked to LSD only in alpine regions with continuous snow cover (Bormann et al., 2012; Dedieu et al., 2014; Hüsler et al., 2014). LSD is different from the snow melting day because of the existence of multiple late season transient snow patterns and snowfall during snowmelt seasons in the study area (Hüsler et al., 2014). Therefore, our findings may further indicate that SCD and SWE_m have no significant correlation with the multiple late season transient snow patterns and snowfall during snowmelt seasons in the study area.

The elevational variation of SOS and LOS (Text S2 and Figures S2b and S2c) confirm the dependency of both SOS and LOS on elevation in mountainous areas (Cornelius et al., 2013; Gottfried et al., 2012; Hwang et al., 2011; Richardson et al., 2006). These results are in line with previous reports presenting the variation in the snow timing and accumulation with elevation in mountainous regions (Bormann et al., 2012; Hüsler et al., 2014).

In this study, we found no significant trend in both snow (i.e., SCD, LSD, and SWE_m) and phenology (i.e., SOS and LOS) metrics during 2003–2014 (Text S2). This was also the case for snow metrics in previous studies over the period 1990–2011 (Hüsler et al., 2014; Marty, 2008). However, our finding is in disagreement with Defila and Clot (2005) who reported significant trends of phenology metrics over the study region in recent decades, although they considered much longer time extents (50 years). This inconsistency may be due to differences in study periods, since the strength and direction of a trend can strongly depend on time periods considered (Marty et al., 2017).

4.2. Influence of Snow on Phenology Metrics Depending on Elevations and Subregions

At elevations above 1,500 m asl, dominated by SV and NG, we found that snow metrics (i.e., SCD, LSD, and SWE_m) had stronger relationships with SOS and LOS than below 1,500 m asl, where forests are prevalent (see Figures 3 and S7–S9). These results correspond well to the fact that both timing and accumulation of

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snow have a great effect on determining phenology in high-elevation regions (Huelber et al., 2006; Hülber et al., 2011; Wipf et al., 2009). Furthermore, our results are in agreement with the conclusion that the vegetative season can be reduced by longer lasting snow cover (Björk & Molau, 2007; Cooper et al., 2011), and that a deep snowpack invariably leads to delaying the plant growing season (Borner et al., 2008; Löffler, 2005) (Figure 3).

Our findings indicate that the SWE_m impacts vegetation growth in an alpine ecosystem (Figures 4c and 4f). This is in line with experimental studies of Dunne (2003), which reported on shallower snowpacks leading to an earlier SOS for most of the subalpine species in Gunnison County, Colorado (USA). Our findings are also in agreement with Trujillo et al. (2012), who report that maximum SWE explained 50% of the significant variability in maximum NDVI between 1,900 and 2,600 m asl in the Sierra Nevada region during the period 1982–2006. Furthermore, the negative relationship between LOS and SWE_m (Figures 3b and S7d–S7f) may support the fact that increased snow thickness often results in a short-term ecosystem process (Hejcman et al., 2006; Morgner et al., 2010). More specifically, the relationships between SWE_m and phenology (i.e., SOS and LOS) metrics above 1,500 m asl may be due to the fact that a deep snowpack always delays and reduces plant development, thus shortening the growing season (Borner et al., 2008; Inouye, 2008). In addition, snow metrics may influence LOS through their effect on SOS (White et al., 2009) and greenness (Trujillo et al., 2012). The latter can be attributed to the effect that winter snow has an effect on soil water reserves, such as keeping soils moist through the growing season (Hiller et al., 2005; Richardson et al., 2013; Trujillo et al., 2012). However, our results indicate that both SOS and LOS showed no significant responses to LSD across elevation (Figure 3) and subregions (Figures 4b and 4e). This is neither in line with Trujillo et al. (2012), where the LSD explained significant change in vegetation greenness in the Sierra Nevada region, nor with Paudel and Andersen (2013), where the LSD was highly correlated with the start of the growing season in high-elevational drier regions of Nepal Trans Himalaya. These differences may be due to the fact that the climate and other environmental factors in these two regions are different from the Swiss Alps. Specifically, our findings at high elevations corroborate the different relationships of vegetation with snow accumulation and snow cover found between alpine vegetation zones, topography, and climate conditions in the Tibetan Plateau (Wang, Wang, et al., 2017; Wang, Xiao, et al., 2017).

At elevations below 1,500 m asl, which are dominated by forests (coniferous, mixed and broad-leaved forest, i.e., CF, MF, and BF) and where the accuracy of our snow cover data is lower than for grassland and pasture areas (Notarnicola et al., 2013a, 2013b), the responses of SOS and LOS to snow metrics are less pronounced than above 1,500 m asl (Figure 3). This finding comes close to those of previous studies where the effect of snow depth on the start of the growing season of grasslands and shrubs was found to be stronger than that of forests (Yu et al., 2013), and where the influence of winter snow depth variation on spring and summer temperate vegetation growth was primarily dependent on vegetation type (Peng et al., 2010). This may be because atmospheric temperatures are more tightly coupled to trees in forests than to other vegetation types (Körner & Paulsen, 2004). The main influence of snow on taller vegetation (such as forest) growth is through its frost protection (Thompson et al., 2015). Furthermore, the smaller amount of pixels with a significant relationship between snow and phenology metrics in low elevation forest may be due to the fact that the vegetation growing period depends on other factors such as temperature and sunshine duration (Dunne, 2003; Rixen et al., 2010).

The magnitude and character of the responses of SOS and LOS to snow metrics differed between subregions (Figure 4). The responses of SOS and LOS to snow metrics were more pronounced in the WSA and the ESA (regions with higher mean elevations) than in the NSA and the SSA (that have lower mean elevations) (Figures 4 and S10). These differences may be due to the fact that mountainous plants are affected by snow which also varies with elevation (Cornelius et al., 2013). However, the relationships between snow and phenology metrics also showed spatial variation with elevation when vegetation type and subregion were the same (Figures 3 and S8–S10). In a word, we found that in the Swiss Alps, the influence of snow metrics on SOS and LOS is different between different vegetation types and subregions, and the differences are more pronounced between elevations than between vegetation types and subregions.

Snow metrics mainly presented positive relationships with SOS across elevations (Figure 3), whereas the relationship between snow metrics and LOS changed from negative to positive for elevations below 1,200 m asl (Figure 3). This elevation threshold may be associated with ecological adaptations of the forest

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relating to water/nutrient requirements and air temperature (Bergeron et al., 2007; Dunn et al., 2007). This finding comes close to the influence of snow accumulation on the start of the growing season, which changed from delay to advance with increasing snow depth in Yu et al. (2013). Therefore, the role of timing and accumulation of snow in mountainous ecosystems might also change with elevation. Specifically, longer SCD and more SWE_m advance the SOS and prolong the LOS at low elevation (<1,000 m asl) (Figures 3 and S8 and S9). This may be due to the fact that the climate at low elevations is warmer than that at high elevations, and snowfall can melt to water quickly. Therefore, longer SCD and more snow accumulation may provide increasing soil moisture and nutrient mobilization, which could be beneficial to the forest growth (Bergeron et al., 2007; Dunn et al., 2007; Walker et al., 1999).

4.3. Relative Influence of Snow on Phenology Metrics Depending on Elevations and Subregions

Our results present different effects of SCD and SWE_m on the interannual variation of SOS and LOS (Figures 5 and S12). These effects appeared to vary with elevation (Figure 5) and between subregions (Figure 6). SCD and SWE_m had more influence on SOS and LOS than LSD across elevations (Figure 5). Indeed, it is important to note that considering possible multiple late season transient snowfall events, LSD did not represent the last date of the continuous winter snow-covered period in our study. LSD may be meaningful in regions with a certain number of days of consecutive snow meltout (Hüsler et al., 2014). Our results showed insignificant influence of LSD on alpine land surface phenology. Furthermore, both SCD and SWE_m explained more interannual variation of SOS than of LOS (Figures 5 and S17a, S17c, S17d, and S17f). These differences might be caused by the fact that duration and depth of snow cover can strongly influence the soil temperature and moisture content in the vegetation growing season, particularly in the early stages (Cooper et al., 2011; Hiller et al., 2005; Löffler, 2005).

In this respect, we found first SOS to be influenced primarily by SCD and second by SWE_m across elevations (Figure 5a). In general, both the snowmelt timing and snow depth have important effects on plant phenology and growth, but the snowmelt timing has stronger implications than snow depth (Wipf et al., 2009). Shorter duration of snow cover is mainly caused by earlier melt of snow cover in spring (Laternser & Schneebeli, 2003). Moreover, the timing and growth of phenological events is highly correlated to the date of snowmelt (Julitta et al., 2014; Rammig et al., 2010; Steltzer et al., 2009). A delayed snowmelt can compress the length of growing seasons and thus may decrease vegetation productivity (Morgner et al., 2010; Wipf & Rixen, 2010). Thus, these arguments support our finding that SCD has a stronger influence and a higher relative weight effect on alpine phenology compared to SWE_m. In addition, the snow melt date and snow depth are often strictly linked (Hejcman et al., 2006). Together with springtime temperatures, the depth of the winter snowpack determines the timing of snowmelt (Richardson et al., 2013). Therefore, the timing and accumulation of snow may have synergistic effects with spring temperature in the determination of the alpine phenology.

Second, we found LOS be equally influenced by SCD and SWE_m across elevations (Figure 5b). In alpine ecosystems, snow may influence LOS through its effect on vegetation greenness (Trujillo et al., 2012). A deeper snowpack raises winter soil temperatures and may increase soil moisture and nutrient availability and lead to higher rates of litter decomposition (Chen et al., 2005; Wahren et al., 2005). In contrast, thin and early melting snow may result in plants being exposed to cold air temperatures that cause frost damage or inhibit rates of development (Wipf et al., 2006). For instance, Hiller et al. (2005) reported that low temperature, saturation of soil with water during snowmelt, and occasional drought may hamper plant activity during the growing season in the alpine tundra. In contrast, deep and late melted snow provides frost protection (Desai et al., 2016; Hu et al., 2010) for the plants until air temperatures are suitable for growth (Richardson et al., 2013). In addition, abundant snow will also result in increased N mineralization, N_2O flux and net nitrification (Williams et al., 1998). These aspects may demonstrate the importance of both SCD and SWE_m for LOS.

4.4. Potential Climate Change Influence on Future Alpine Phenology

According to the latest Climate Change Advisory Body (OcCC) Consortium report (OcCC-Consortium, 2007) on the Swiss Alps, a temperature increase of 2°C in winter and spring, and a precipitation increase by 10% in winter can be expected by 2050. Changes in temperature-precipitation patterns may result in snowpack increases (Beniston, 2012; Saccone et al., 2012) in midwinter above 2,000 m asl (Marty & Meister, 2012; OcCC-Consortium, 2007), where grasslands (i.e., SV and NG) are predominant. In addition, several studies

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(Beniston et al., 2003; Keller et al., 2005; Rammig et al., 2010) expect significantly earlier snow meltout dates at these elevations, by as much as a few weeks, until the end of the 21st century. These temperature-precipitation changes could also result in increasing SWE_m but decreasing continuous SCD above 2,000 m asl in the future. Furthermore, variation of timing and accumulation of snow will influence the phenology and growth of plants in alpine regions (Abeli et al., 2011; Julitta et al., 2014; Keller et al., 2005), which will in turn affect the distribution and composition of vegetation (Jonas et al., 2008; Löffler, 2005; Wipf & Rixen, 2010).

Our study showed significant influence of SCD and SWE_m, unlike LSD, on both SOS and LOS (section 3.2). This supports the previous findings that the future variation of snow cover and accumulation, which codetermine the sensitivity of alpine ecosystems to warming (Menzel et al., 2006; Pellerin et al., 2012), may alter alpine vegetation distribution and composition. In addition, the relative importance of each snow metric to land surface phenology may change in the future. At elevations dominated by forest (i.e., CF, MF, and BF), this study found less significant relationships between snow and phenology metrics (Figures 3 and S7–S9). In addition, our study found a smaller SWE_m and a shorter SCD in forest compared to grassland (Figure S2). A warmer climate, however, may result in longer vegetation activity and shorter SCD in temperate deciduous forests (Richardson et al., 2013). In forest ecosystems, soil carbon sequestration rates may be affected by a warmer climate due to changes in snow cover depth (Monson et al., 2006). Soil temperatures are generally lower in snow-free regions than in snow-covered regions (Groffman et al., 2006), and they increase with snow depth (Richardson et al., 2013). Nevertheless, future change and response of forest ecosystems will more likely be driven by other factors than snow, for instance, temperature, solar radiation, and rain.

4.5. Limitation and Outlook

Several studies point out that snow presence in vicinity of green vegetation may result in errors when detecting greenness (Jönsson et al., 2010; Quaife & Lewis, 2010). Consequently, the dynamics of snow cover may impact satellite monitoring of land surface phenology in vegetated regions (Jönsson et al., 2010; White et al., 2009). Moreover, satellite-derived SCD and LSD can be error prone, especially in conditions when snow cover and clouds are spectrally difficult to distinguish (Xie et al., 2017). Uncertainties in SWE estimates arise with snow under critical illumination conditions and snow in forested regions (Thirel et al., 2012).

A number of questions remain and require further research, in particular related to driving factors such as temperature, precipitation, and solar radiation. In addition, a combination of long-term in situ observations and remote sensing of snow and vegetation phenology will be necessary to better investigate the relationships between snow metrics and land surface phenology in future research in the Swiss Alps.

5. Conclusion

This study assessed the impact of snow metrics on the vegetation activity of mountainous ecosystems. We used a novel 250 m satellite-based snow cover and mountainous land surface phenology data set and 1 km modeling-based snowpack accumulation data set of the Swiss Alps (2003–2014). The results show that the variations in SCD, LSD, and SWE_m explained 71.0% of the interannual changes in SOS of 21.5% NV pixels, and 70.0% in LOS of 14.5% NV pixels above 1,500 m asl where snow metrics were not mutually correlated.

Our analysis concluded that (i) SCD was correlated with SWE_m, although both SCD and SWE_m showed no significant correlation with LSD; (ii) mountainous phenology was more sensitive to timing and accumulation of snow above 1,500 m asl than below; (iii) the relationship of mountainous phenology with snow was more pronounced in high-elevational regions such as the WSA and ESA, as well as in alpine vegetation types such as natural grassland and sparsely vegetated areas as compared to other areas; and (iv) SOS was influenced primarily by SCD, secondarily by SWE_m, while LOS showed equal effects from SCD and SWE_m across elevations. In contrast, LSD showed no significant effect on both SOS and LOS across elevation in the Swiss Alps.

The results presented here indicate that alpine ecosystems are significantly sensitive to timing and accumulation of snow variation associated with elevation. Moreover, changes in high-elevation vegetation activity and composition should be expected in response to changes in timing and accumulation of snow. However, along with extreme events and land use practices, other factors such as temperature, precipitation, and soil water and nutrient availability might lead to linear or nonlinear changes in phenology in the regions where snow plays a limited role. Unfortunately, it is difficult to make future predictions based on short-term

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analyses. Nevertheless, the role of the above factors in the future, combined with possible climate change scenarios in mountainous regions, was beyond the research scope of this study and remains to be investigated.

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3.8 Supporting Information

Contents of this section

Figures S1 to S17

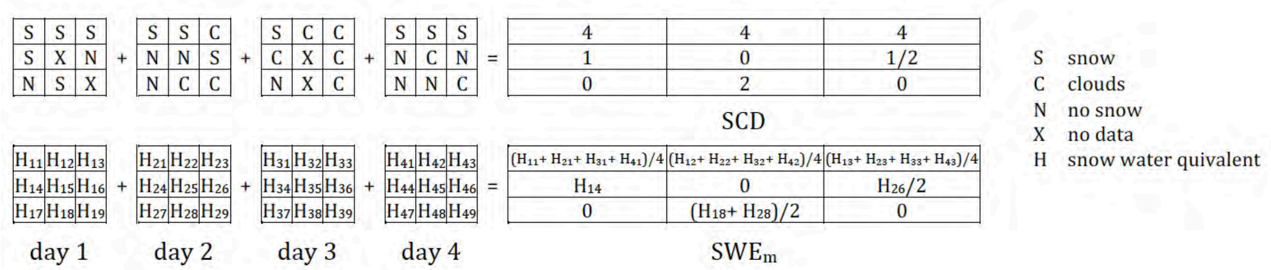


Figure S1: Illustration of the SCD/SWE$_m$ algorithm; example of SCD/SWE$_m$ calculation of four days.

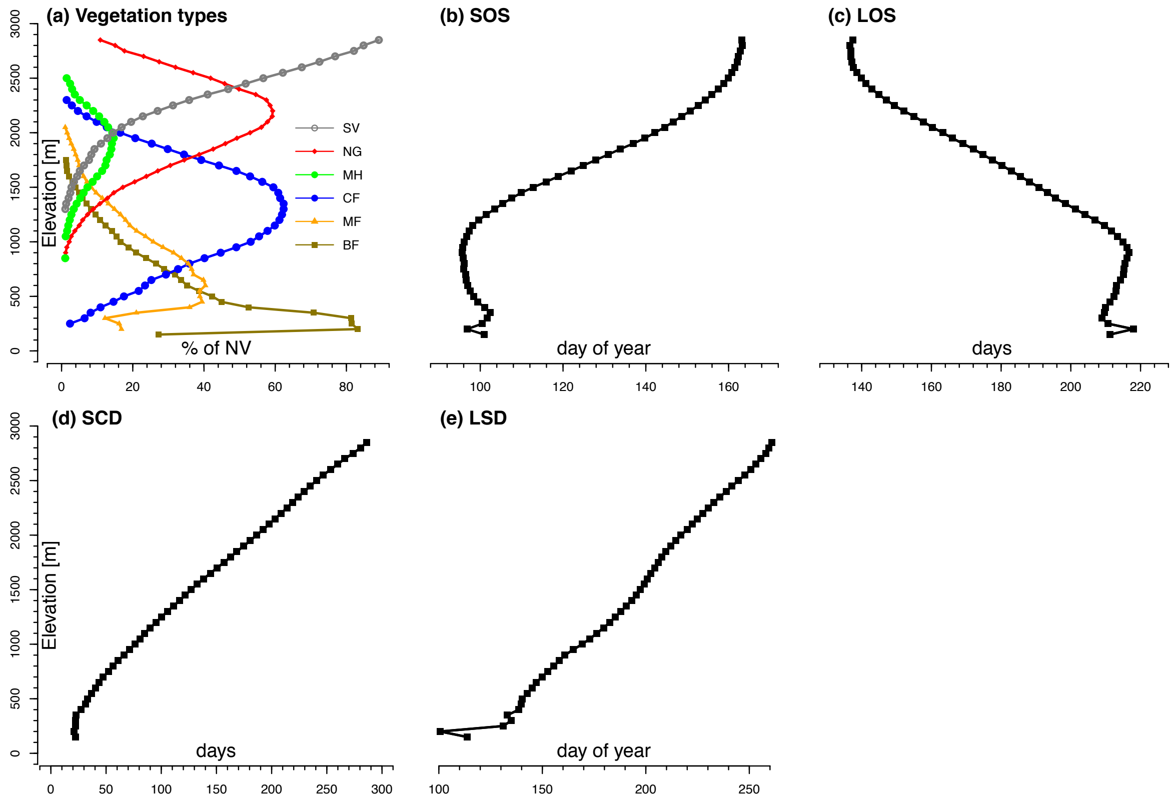
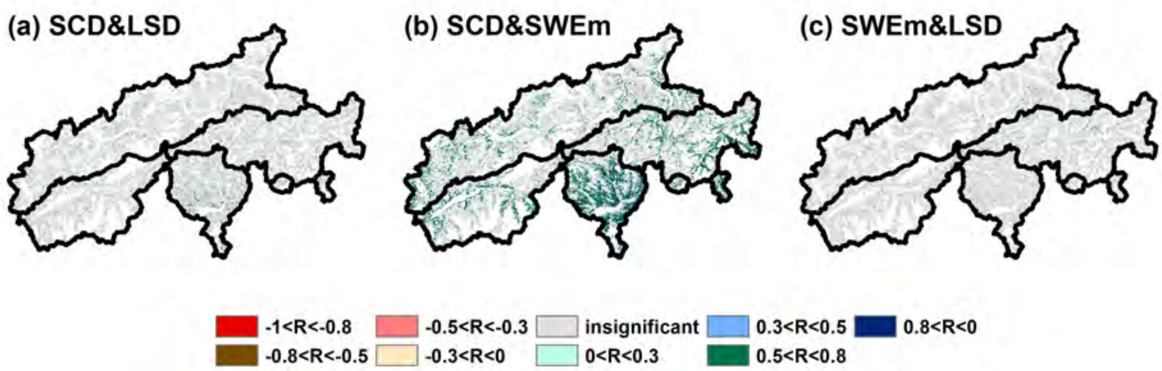


Figure S2: Elevational variation in the proportion of vegetation types [% of NV] (i.e., Sparsely Vegetated areas (SV), Natural Grasslands (NG), Moors and Heathland (MH), Coniferous Forest (CF), Mixed Forest (MF), Broad-leaved Forest (BF)) (a); elevational variation of mean SOS (b), mean LOS (c), mean SCD (d), mean LSD (e), and mean SWEm (f) for the period 2003-2014 for the entire study area.



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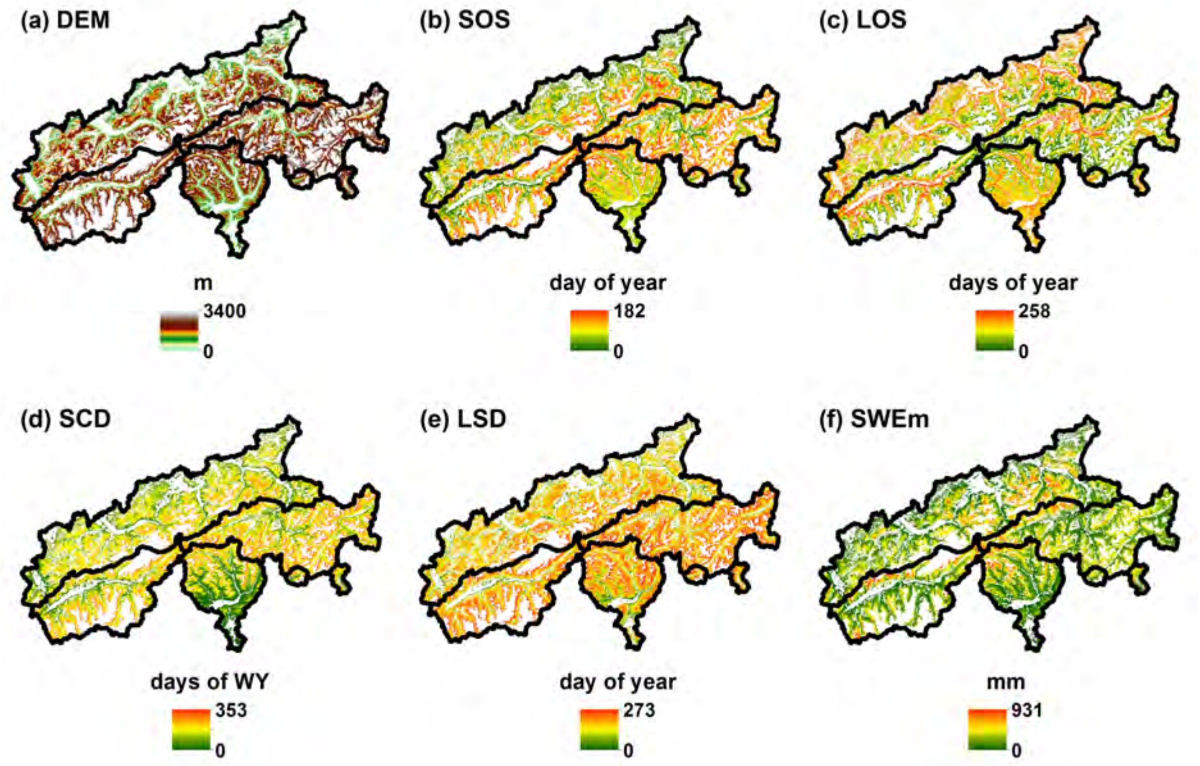

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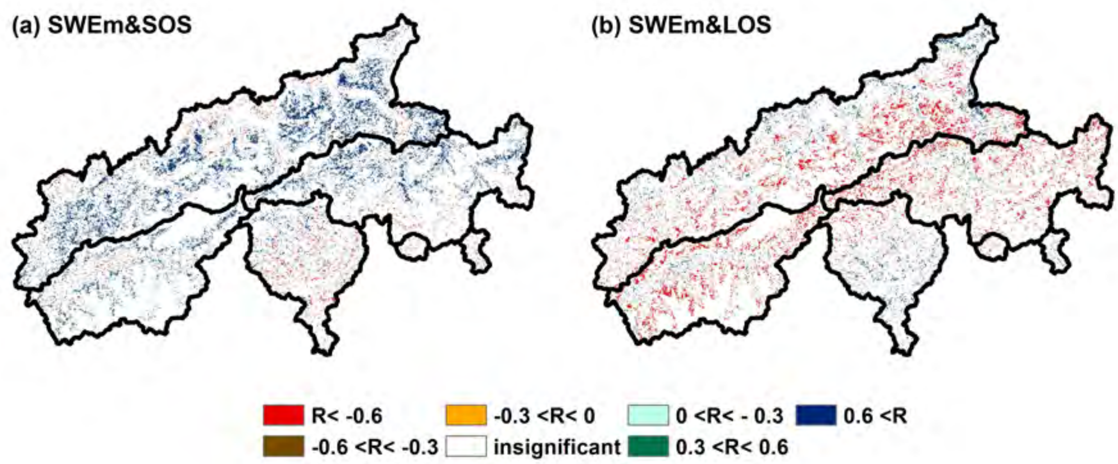

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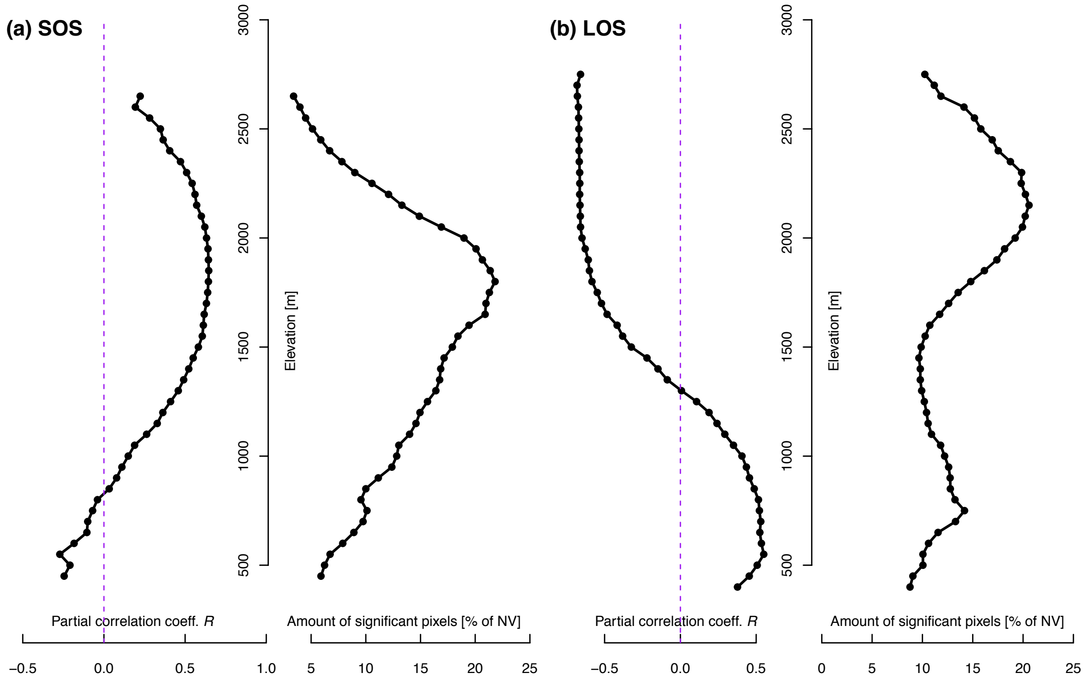

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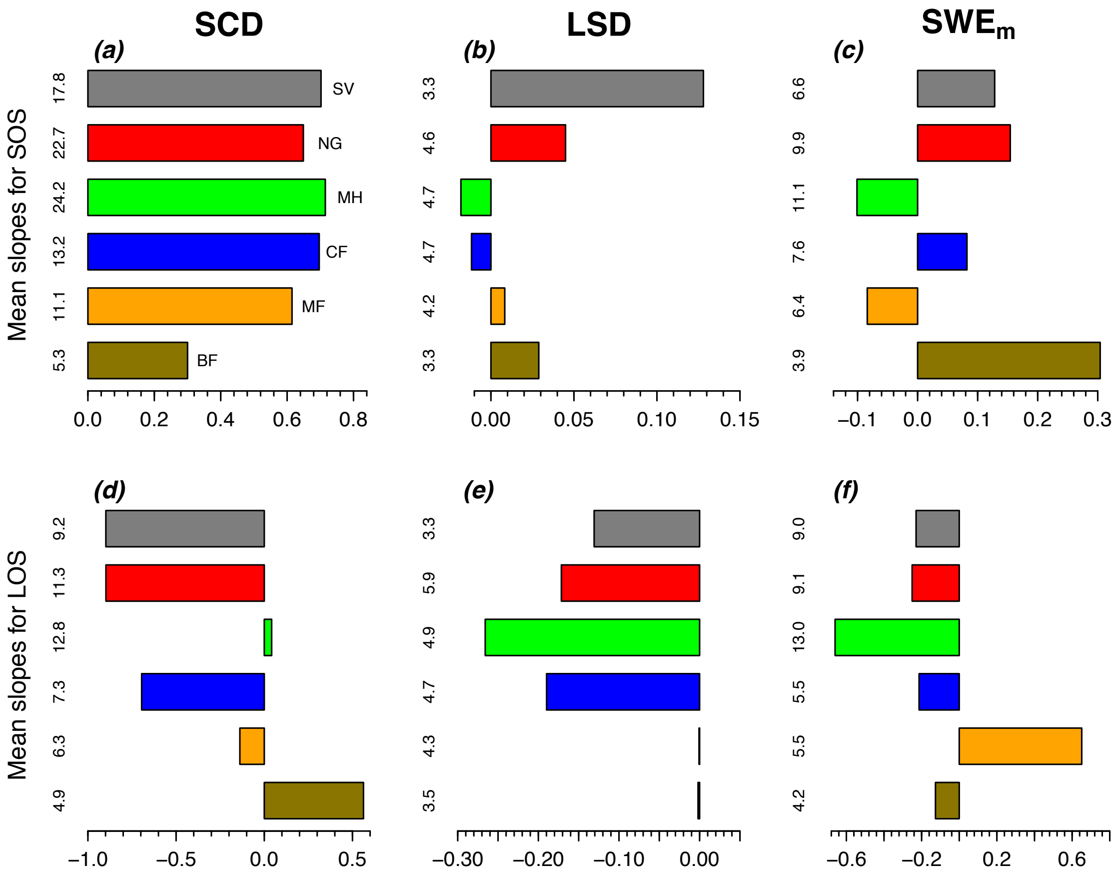

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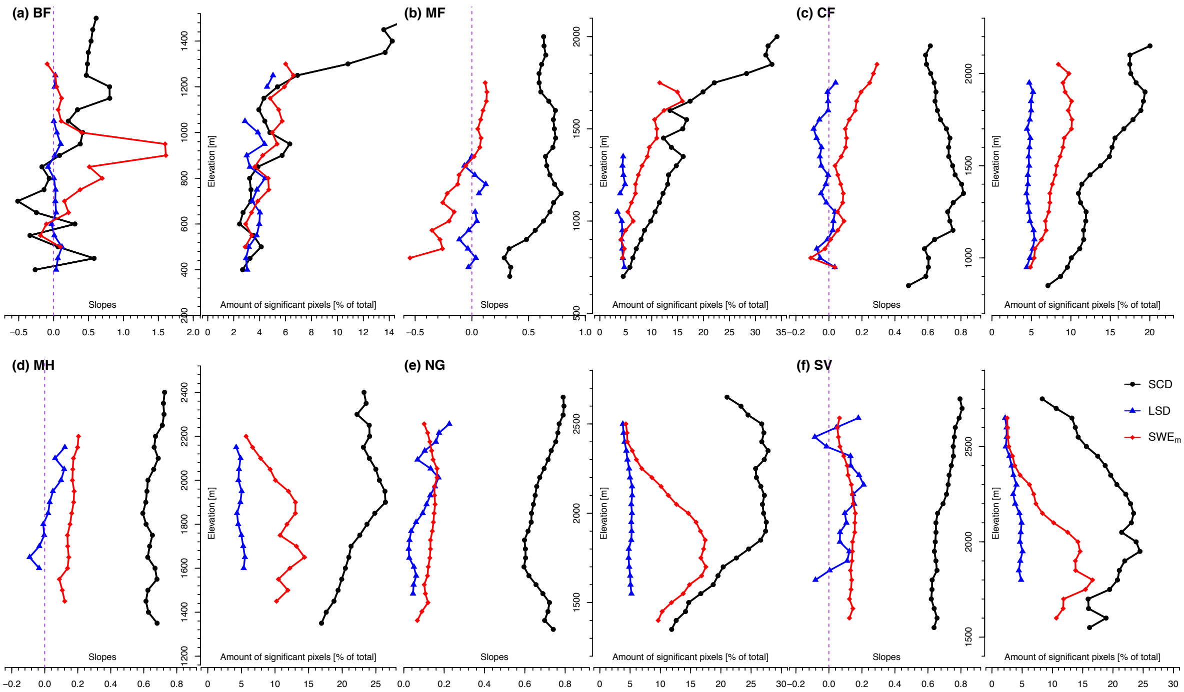

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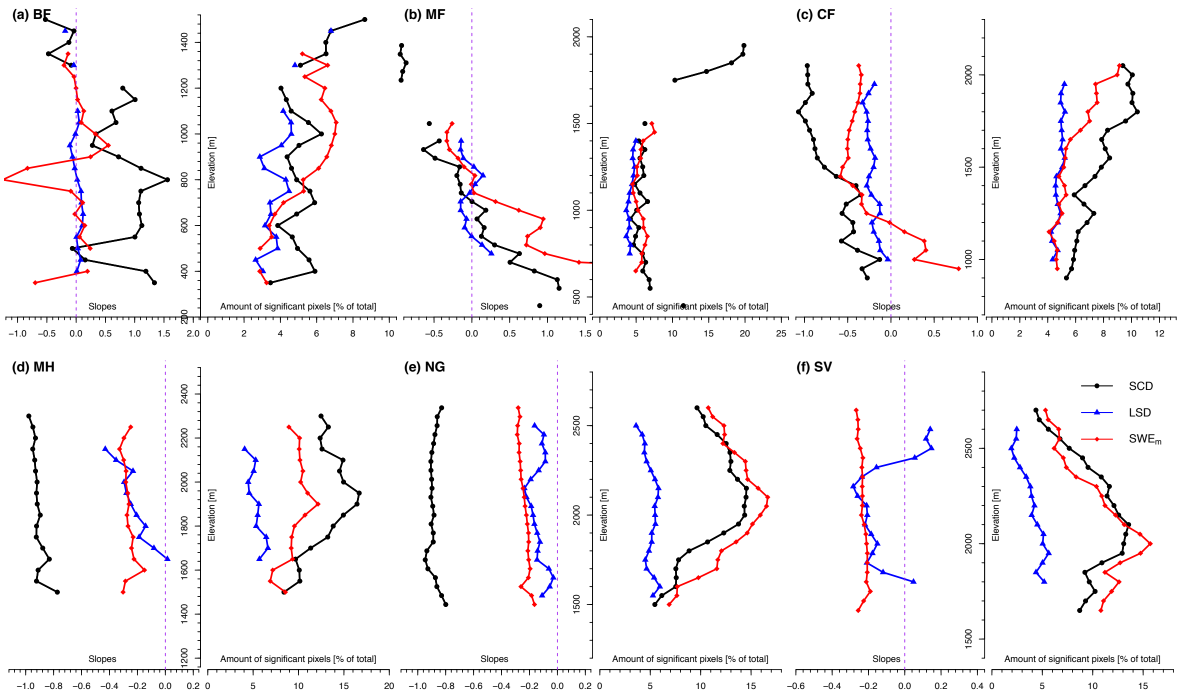

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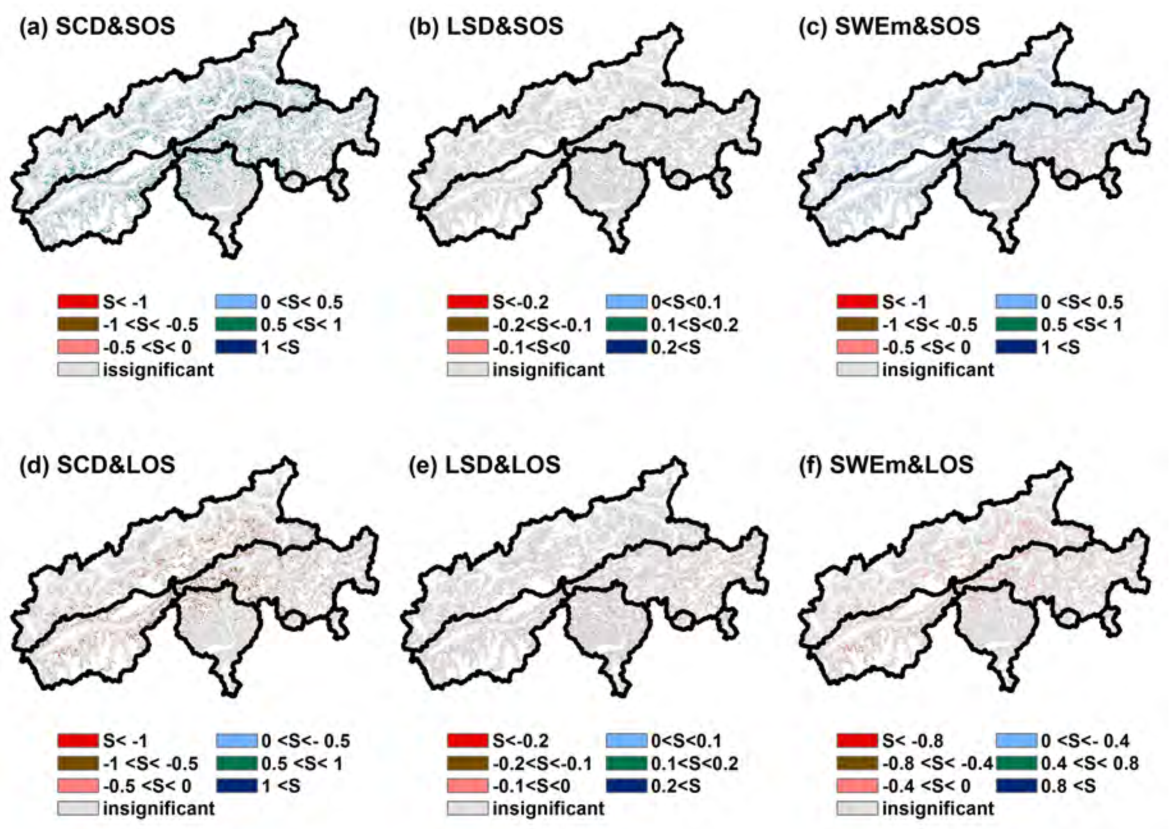

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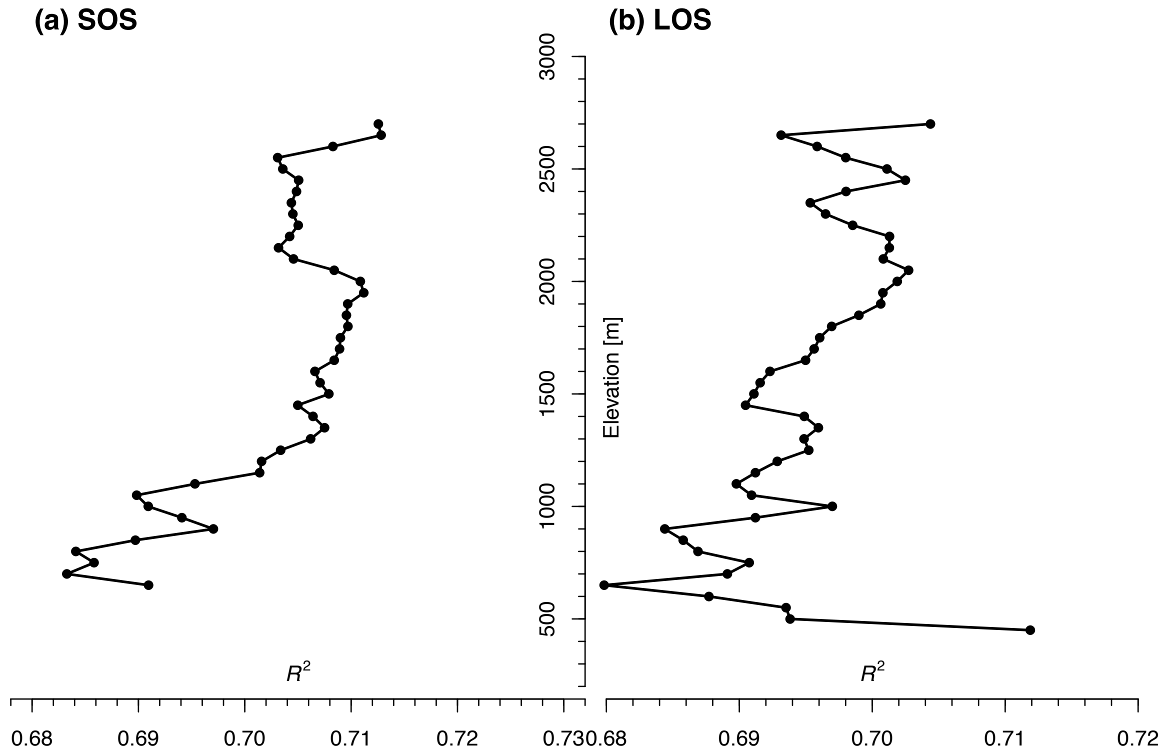

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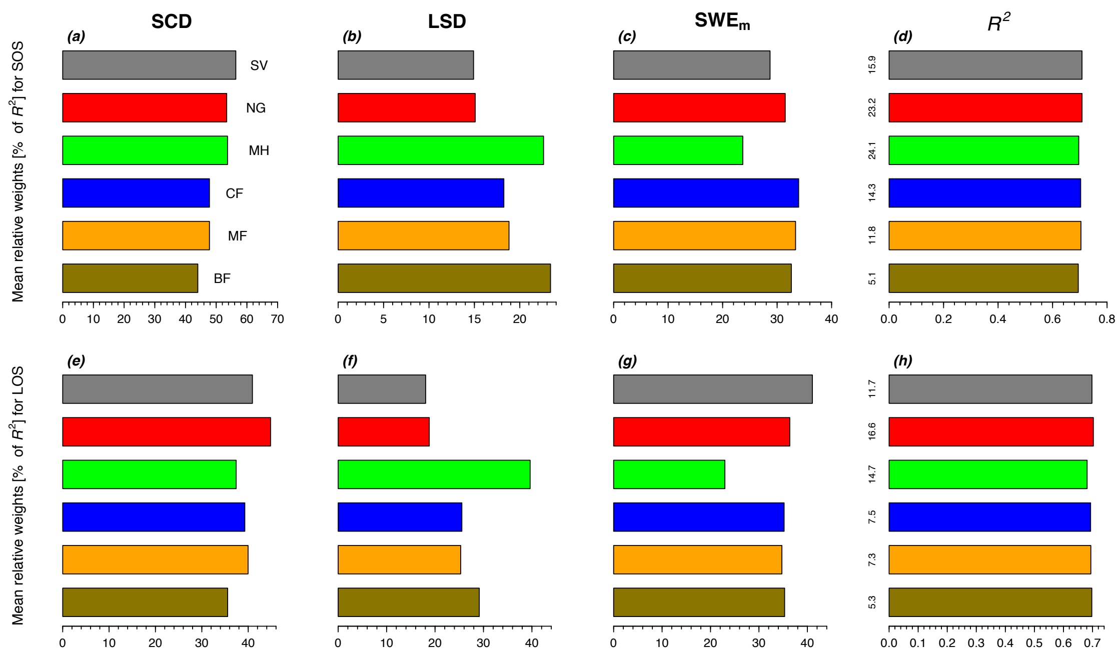

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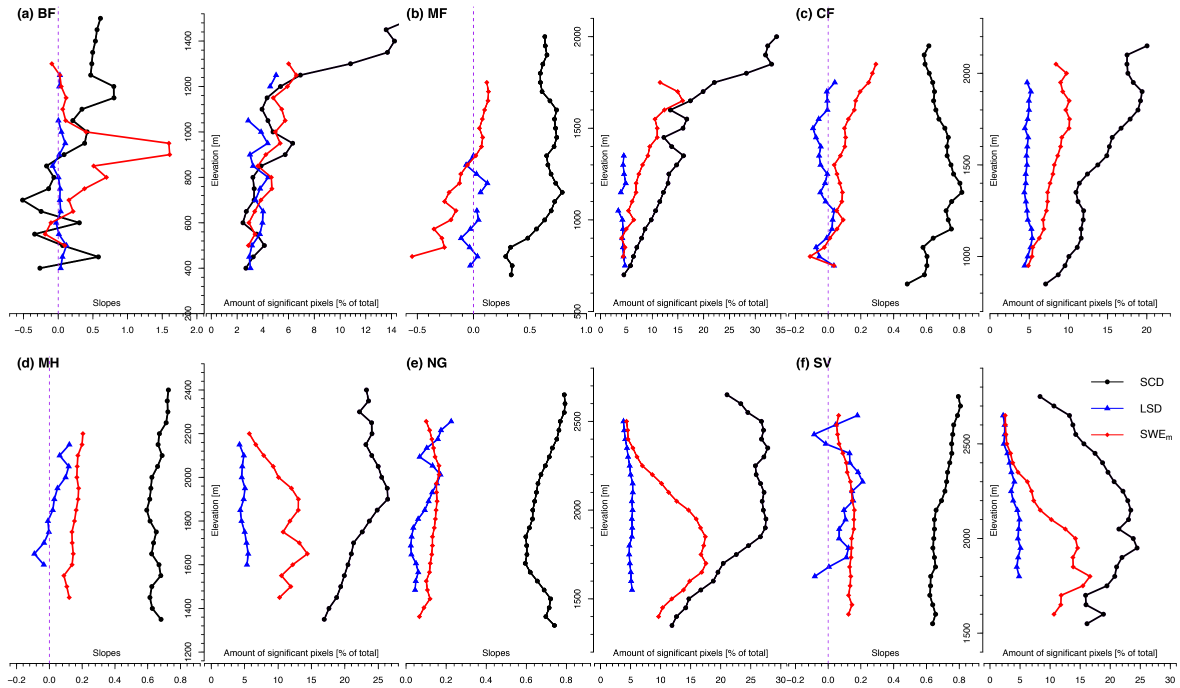
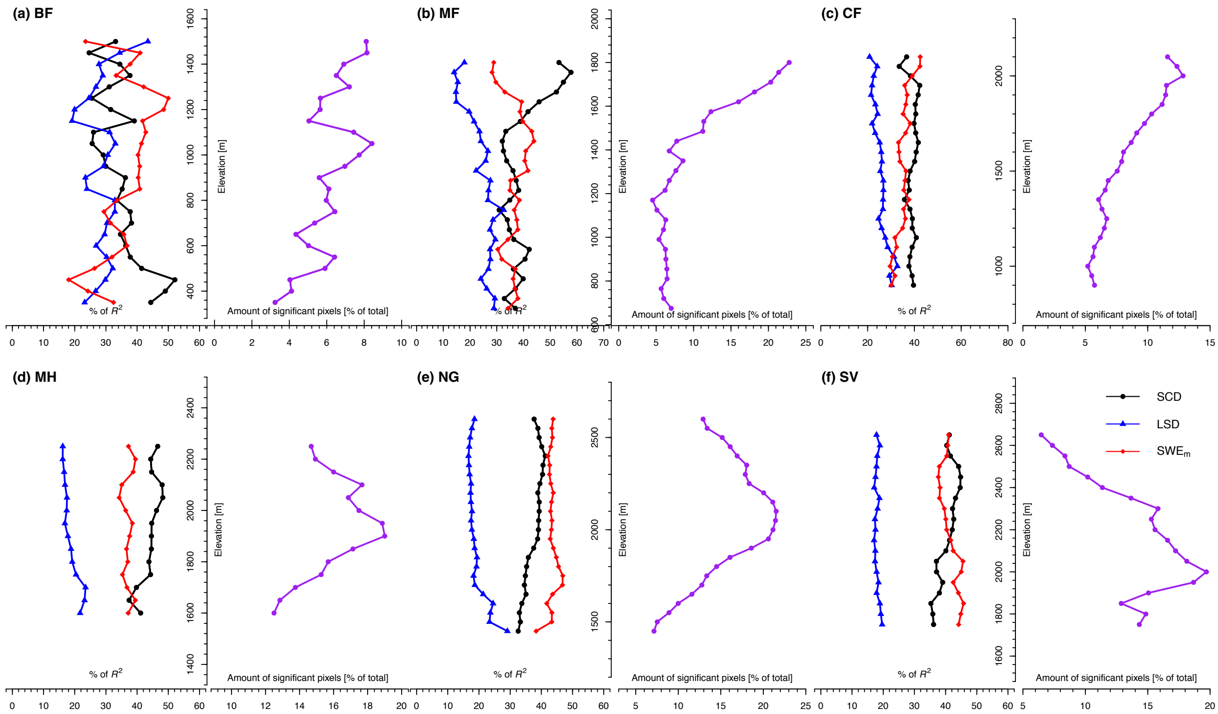


Figure S13: Elevational variation in mean relative weight [% of R^2] influence (left panel) of snow metrics (i.e., SCD, LSD and SWE_m) on SOS, and the corresponding amount of significant pixels [% of total] (right panel) of the six vegetation types: BF (a), MF (b), CF (c), MH (d), NG (e), and SV (f) for the Swiss Alps.



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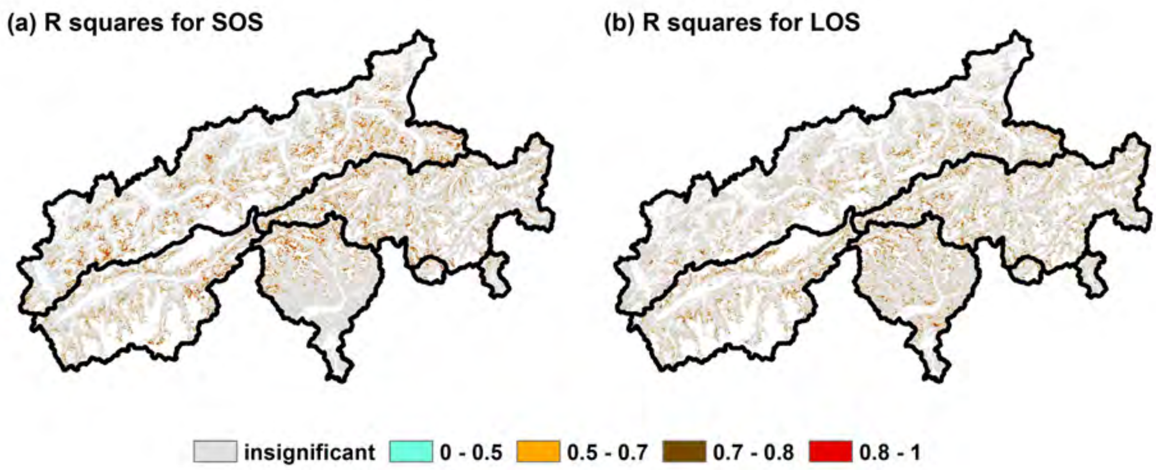

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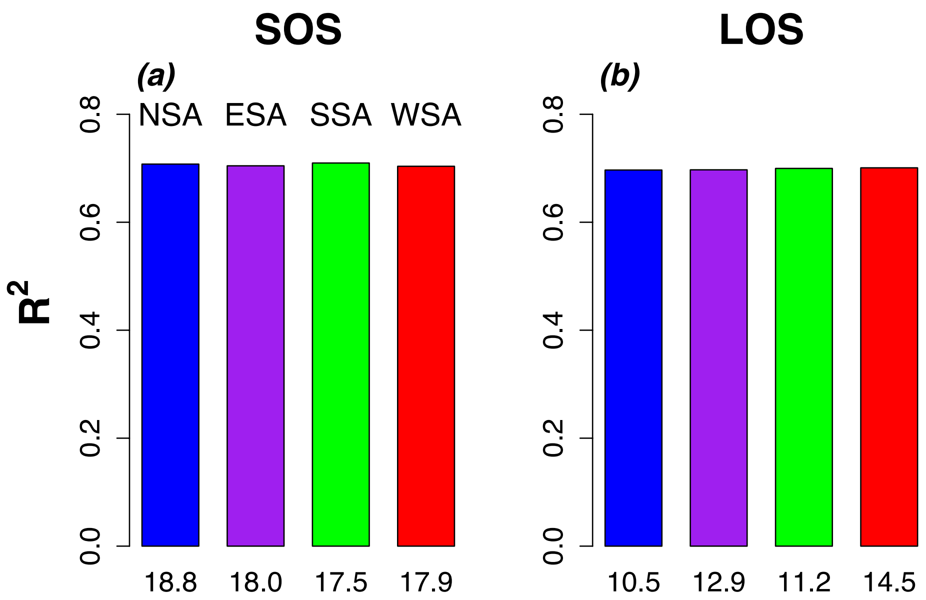

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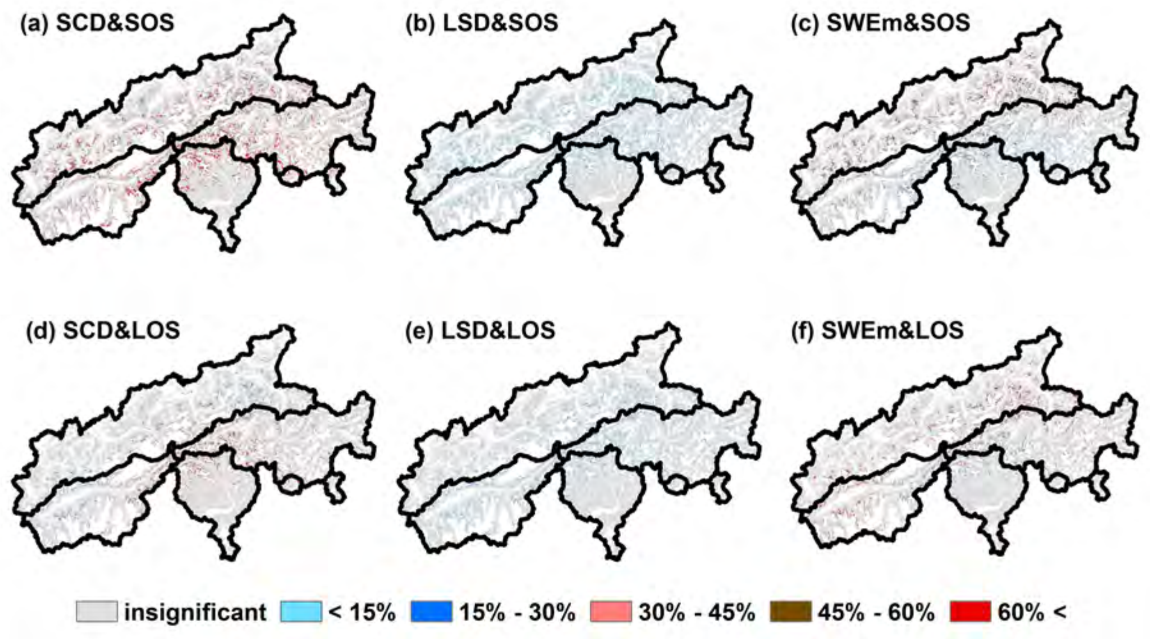

Figure S17: Spatial pattern of relative weight [% of R^2] of significant multiple linear regression models between snow and phenology parameters (i.e., SCD&SOS (a), LSD&SOS (b), SWE_m&SOS [days/mm] (c), SCD&LOS (d), LSD&LOS (e), SWE_m&LOS [days/mm] (f)) for each snow predictor across the entire NV areas in the Swiss Alps.

Text S1 to S2

Text S1.

Snow metrics

The daily availability of snow cover maps (SCM) allows the calculation of snow cover duration (SCD) and corresponding snow water equivalent (SWE) without gaps. The calculation methodology was kept as simple as possible: the snow information of the daily combined SCM is accumulated by “addition”. However, gaps appear when a pixel is classified as “cloud” or “no data”. In the following process these two classes are treated equally. The SCD of “gap days” in between the information “snow” or “no snow” is calculated according to the principle of a linear interpolation technique: if a gap is preceded by a “snow” day and followed by a “snow” day the pixel is assumed to have the highest probability of being snow covered as well and therefore the SCD for the gap day is 1 day. Accordingly, if the gap is preceded by a “no snow” day and followed by a “no snow” day its SCD and corresponding SWE equal 0. If, however, either of the two fringe days is “snow” and the other “no snow”, the probability of snow coverage – without any further information – is 50 %, therefore the SCD and corresponding SWE of the pixel equals ½. The same principle is applied if several consecutive days show cloud or no data classes. The calculation algorithm processes the vector of every pixel of the maps over the required time frame. Eventually, each pixel has a certain number of “snow” days to which the individual SCD of all gap days is added. This procedure results in a SCD and mean snow water equivalent (SWE_m) value for each pixel and comprises the SCD and SWE_m map.

Text S2.

Correlations between snow metrics with elevations

The elevational distribution of natural vegetation (NV) types (which grow between 200-3000 m asl) in the Swiss Alps is given in *Figure S2a*. At high elevations (> 2000 m asl), Natural grasslands (NG) and sparsely vegetated areas (SV) are the major vegetation types. NG and coniferous forest (CF) are dominant vegetation types, together with minority vegetation types such as CF, mixed forest (MF) and moors and heathland (MH), distributing at mid elevations (1000-2000 m asl). The low elevational regions (<1000 m asl) are covered by forest (broad-leaved forest (BF), CF and MF).

Linear least squares regression was used to analyse the elevation-dependent responses (significance defined as $p<0.001$) of 12-year averaged values for each snow and phenology metric. On average, start of season (SOS) delays 2.14 (±0.06) days/50m (*Figure S2b*) and length of season (LOS) shrinks 2.37 (±0.12) days/50m (*Figure S2c*) between 1000-3000 m asl across the entire research region over the period 2003-2014. Whereas, both SOS and LOS show no variation with elevation below 1000 m asl. snow cover duration (SCD) enlarges 5.17 (±0.06) days/50m (*Figure S2d*), last snow day (LSD) delays 2.62 (±0.04) days/50m

Chapter 4

Land surface phenology and greenness in alpine grasslands driven by seasonal snow and meteorological factors

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Author contributions

Jing Xie conceived the study and designed the analyses under the supervision of Mathias Kneubühler and Michael E. Schaepman. Jing Xie collected and performed the data analyses of land surface phenology and greenness, seasonal snow, and meteorological metrics. Jing Xie, Mathias Kneubühler, and Tobias Jonas carried out interpretation of results jointly, and Jing Xie prepared the initial manuscript. Tobias Jonas provided the SWE data, and contributed with computation and interpretations of the SCMD and SWE_{acc}. Jing Xie, Rogier de Jong, and Irene Garonna computated and interpretated the land surface phenology and greenness metrics. Claudia Notarnicola and Sarah Asam provided the LAI and NDVI data. Jing Xie, Mathias Kneubühler, Tobias Jonas, Christian Rixen, Rogier de Jong, and Michael E. Schaepman edited the final version of the manuscript.

Land surface phenology and greenness in Alpine grasslands driven by seasonal snow and meteorological factors

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A B S T R A C T

Snow accumulation and melt have multiple impacts on the land surface phenology and greenness in alpine grasslands, but our understanding of these impacts and interactions with meteorological factors is still limited. Related uncertainties are associated with variations in seasonal snow and meteorological drivers between the start and end of season and among elevation zones. We used satellite time series and other data sources to analyze start, peak, end, and length of season, and greenness metrics such as the maximum and mean normalized difference vegetation index and mean leaf area index during the growing season. As explanatory variables we used snow accumulation, snow cover melt date and other meteorological factors such as air temperature, relative sunshine duration, and precipitation. We tested for inter-annual co-variation of land surface phenology and greenness metrics with seasonal snow and meteorological metrics across elevations and for four specific subregions of the natural grassland in the Swiss Alps over the period 2003–2014. We found strong positive correlations of snow cover melt date and snow accumulation with the start of

season especially at higher elevation. Autumn temperature was found to be important at the end of season below 2000 meters above sea level (m asl), while autumn precipitation was relevant above 2000 m asl, indicating climatic growth limiting factors to be elevation dependent. The effects of snow and meteorological factors on greenness metrics were complex and differed among regions; however, greenness tended to be influenced by temperatures at high elevation and by snow melt date at low elevation. Given the high sensitivity of alpine grassland ecosystems, our results suggest that they will be particularly sensitive to future change of seasonal snow.

Keywords: Land surface phenology, Land surface greenness, Snow cover melt, Snow water equivalent, Air temperature, Sunshine duration, Precipitation, Grassland, Swiss Alps

1. Introduction

The global climate is reported to continue warming in the next decades (IPCC 2018), and related changes will threat ecological systems and biodiversity in mountainous regions (Brigham et al. 2018; IPCC 2014, 2018). Alpine ecosystems were shown to be particularly sensitive to dynamics in climatic controls such as temperature and photoperiod (Castellia et al. 2018; Dorjia et al. 2018; Gobiet et al. 2014) and to climate-related drivers such as snow and rain (Jonas et al. 2008; Prevéy et al. 2014; Xie et al. 2018; Zeeman et al. 2017). As observable and important traces of alpine ecosystem response to changing climate, the variations of land surface phenology and greenness have been documented as critical determinants of land surface carbon fluxes (Barrio et al. 2013; Beniston 2005; Galvagno et al. 2013; Gobiet et al. 2014). These variations furthermore influence coupled water and energy exchange (White et al. 2009), habitat distributions (Chuine and Beaubien 2001; Wipf et al. 2006), as well as the genetic makeup of species (Diez et al. 2012; Fox 2003; Primack et al. 2009).

Many studies reported that the seasonal accumulation and cover of snow influence alpine land surface phenology and productivity through their time-integrated effects (Cornelius et al. 2013; Dunne 2003; Inouye and McGuire 1991; Jonas et al. 2008; Trujillo et al. 2012; Wipf et al. 2009; Xie et al. 2017; Yu et al. 2013). Changes in the accumulation and melt of snow have been reported to significantly affect the variation of land surface phenology and greenness by influencing the cycling of water (Barnett et al. 2005; Rawlins et al. 2006) and soil carbon (Dorrepaal 2003), as well as the energy balance (Euskirchen et al. 2007). However, most existing studies were based on limited field observations or experimental data to investigate the influence of snow accumulation and melt, and meteorological factors on vegetation phenology and productivity in alpine regions. Remote sensing can provide comprehensive ground coverage and regularly repeated observations at large scale (Fisher et al. 2006; Pettorelli et al. 2005) to monitor alpine ecosystem responses to environmental changes due to climate variability, land use changes or ecological dynamics.

A deeper snowpack and later snowmelt can result in a delay of phenological events (Cooper et al. 2011; Inouye 2008), while earlier snowmelt often results in advancing spring plant development (Chen et al. 2011; Wipf and Rixen 2010; Wipf et al. 2009). Apart from snow cover, temperature and photoperiod have been documented as the main climatological factors regulating spring phenology (Garonna et al. 2016; Körner and Basler 2010; Linkosalo et al. 2009; Menzel et al. 2006), and recent climatic warming has already resulted in an advancement of spring phenology (Delbart et al. 2008; Menzel et al. 2006; Schwartz et al. 2006). In alpine ecosystems, both snowmelt and temperature after timing of snowmelt are critical in regulating the spring onset of vegetation growth (Richardson et al. 2013). While some studies found clear evidence of temperature sensitivity of plant phenology in alpine regions (Jonas et al. 2008; Körner and Basler 2010), others emphasize links between snow cover and the start of season in high-elevation natural grasslands (Xie et al. 2018; Xie et al. 2017). The relative importance of these parameters may depend on topography, microhabitat and ecosystem type. Hence, effects of snow accumulation and melt, combined with spring meteorological factors and their relative influence on spring phenology are not yet sufficiently well understood due to limited availability of observation data and the terrain complexity in alpine regions.

Recent studies reported that delayed senescing in autumn can result in an extension of the growing period (Garonna et al. 2014; Zhu et al. 2012) and therefore plays an indispensable role in regulating carbon cycling in temperate ecosystems (Piao et al. 2008). Autumn phenology was found to show positive significant relationships with autumn air temperature, sunshine duration, and precipitation (Gill et al. 2015; Jeong et al. 2011; Liu et al. 2016; Ren et al. 2017; Sun et al. 2014). While some studies showed that warmer summers postpone autumn senescence (Gunderson et al. 2012; Marchin et al. 2015), others report a weak or insignificant relationship between air temperature and autumn senescence (Menzel et al. 2006; Pudas et al. 2008). Hence, we need to better understand, which meteorological factors influence autumn phenology in different environmental settings e.g., along elevational gradients.

Variation in seasonal snow may interact with air temperature and therefore affect start, peak, and length of the growing season, as well as the peak vegetation productivity (Legay et al. 2013; Yu et al. 2013). However, the directions of the effect, i.e., if large amounts of snow increase or decrease vegetation activity, may depend on the environmental setting and on processes affected. Overall, there is much support for the notion that the presence of sufficient snow in winter positively affects vegetation activity after melting. For instance, a thin snow cover or early snowmelt can increase soil freezing (Groffman et al. 2006) and root mortality (Peng et al. 2010; Wahren et al. 2005), which in turn leads to a reduction of vegetation growth (Grippa et al. 2005). In forested regions of the Sierra Nevada region, maximum snow accumulation was reported to show significant positive relationships with the inter-annual variability of the maximum productivity of forests between 2000-2600 m asl (Trujillo et al. 2012). In the grasslands of China, winter snow depth showed a significant positive correlation with May–June greenness (Peng et al. 2010). However, in the high Arctic, Cooper et al. (2011) reported that a late snow melt delayed the development of plants and resulted in lower success of reproduction. Hence, the effects of snow on greenness may depend on meteorological factors, vegetation type, topography and region (e.g., (Huelber et al. 2006; Keller et al. 2005; Paudel and Andersen 2013; Trujillo et al. 2012; Xie et al. 2017). Remote sensing of vegetation provides information on the activity and dynamics of mountainous ecosystems over time and across large areal extents (Pettorelli et al. 2005). To date, the relative role of winter, spring, and summer meteorological factors and the possible lag effects of accumulation and melt of snow involved in the variability of vegetation greenness remain to be investigated.

We studied land surface phenology and greenness in semi-natural grasslands of the Swiss Alps between 1000 - 3000 m asl. Plant ecology in the study area is dominated by snow particularly during winter and spring season, and long-term changes of seasonal snow cover and accumulation have been documented and attributed to changes of climate (Beniston et al. 2003; OcCC-Consortium 2007). We focused our analyses on land surface phenology (i.e., start of season (SOS), end of season (EOS), and peak of season (POS)) and greenness metrics (i.e., $NDVI_{max}$, $NDVI_{mean}$, and LAI_{mean}), and how these metrics are affected by seasonal snow (i.e., snow accumulation (expressed as accumulated snow water equivalent (SWE_{acc})) and snow cover melt day (SCMD)) as well as meteorological factors (i.e., temperature, precipitation, and relative sunshine duration (see abbreviations of metrics in Table 1)) spanning the study period 2003–2014. We aimed to i) assess the relationship of seasonal snow and other meteorological metrics with SOS, ii) identify the most significant meteorological factors affecting EOS, and iii) investigate the impact of seasonal snow and other meteorological metrics on land surface greenness across elevations and subregions. We hypothesize that i) the importance of snow melt timing on spring phenology (SOS) increases with elevation, ii) autumn phenology is more driven by temperature than precipitation or sunshine duration, and iii) effects of snow and temperature on greening metrics during the growing season vary among regions and elevations.

Table 1 Abbreviations of metrics used in this article.

Metrics	Abbreviation
Normalized Difference Vegetation Index	NDVI
Land Surface Phenology	LSP
Start Of Season	SOS
End Of Season	EOS
Peak Of Season	POS
Mean NDVI between SOS and EOS	$NDVI_{mean}$
Maximum NDVI between SOS and EOS	$NDVI_{max}$
Leaf Area Index	LAI
Mean LAI between SOS and EOS	LAI_{mean}
Snow Water Equivalent	SWE
Snow Cover Melt Day	SCMD
Mean SWE in the accumulation period (from January to April)	SWE_{acc}
Average value of mean Temperature in 7-days, 14-days, 21days and 28-days after SCMD	T_{mean_melt7}, T_{mean_melt14}, T_{mean_melt21}, T_{mean_melt28}
Average value of max Temperature in 7-days, 14-days, 21days and 28-days after SCMD	T_{max_melt7}, T_{max_melt14}, T_{max_melt21}, T_{max_melt28}
Average value of min Temperature in 7-days, 14-days, 21days and 28-days after SCMD	T_{min_melt7}, T_{min_melt14}, T_{min_melt21}, T_{min_melt28}
Average value of Precipitation in 7-days, 14-days, 21days and 28-days after SCMD	$P_{\_melt7}$, $P_{\_melt14}$, $P_{\_melt21}$, $P_{\_melt28}$
Average value of Relative Sunshine Duration in 7-days, 14-days, 21days and 28-days after SCMD	$RSD_{\_melt7}$, $RSD_{\_melt14}$, $RSD_{\_melt21}$, $RSD_{\_melt28}$

Average value of mean Spring Temperature	ST_{mean}
Average value of max Spring Temperature	ST_{max}
Average value of min Spring Temperature	ST_{min}
Average value of Spring Precipitation	SP
Average value of Spring Relative Sunshine Duration	SRSD
Average value of mean Summer Temperature	MT_{mean}
Average value of max Summer Temperature	MT_{max}
Average value of min Summer Temperature	MT_{min}
Average value of Summer Precipitation	MP
Average value of Summer Relative Sunshine Duration	MRSD
Average value of mean Autumn Temperature	AT_{mean}
Average value of max Autumn Temperature	AT_{max}
Average value of min Autumn Temperature	AT_{min}
Average value of Autumn Precipitation	AP
Average value of Autumn Relative Sunshine Duration	ARSD
Average value of mean Winter Temperature	WT_{mean}
Average value of max Winter Temperature	WT_{max}
Average value of min Winter Temperature	WT_{min}
Average value of Winter Precipitation	WP
Average value of Winter Relative Sunshine Duration	WRSD

2. Methods

2.1. Study area

The Swiss Alps (6.8°E–10.5°E, 45.8°N–47.4°N), located in the central European Alps, encompass an area of 25,194 km^2 (Fig. 1). These regions have typical complex mountainous character (Marty et al. 2017; McVicar et al. 2010; Scherrer et al. 2004). The North Atlantic Oscillation (NAO) phase anomalies mainly influence the temperature and moisture regimes of the region in late autumn and early winter (Beniston and Jungo 2002). In this study, we separated the study area into the northern Swiss Alps (NSA; 43.1% of total area), southern Swiss Alps (SSA; 14.6%), western Swiss Alps (WSA; 19.2%), and eastern Swiss Alps (ESA; 23.1%), given their geographical difference (Gonseth et al. 2001) and expected difference in the projected future climate (Rammig et al. 2010). NSA, WSA and ESA experience temperate westerly and oceanic features, while SSA is subject to Mediterranean subtropical and oceanic features (Auer et al. 2007). At particular times, the SSA often show significant meteorological contradistinction with the NSA (Laternser and Schneebeli 2003). The grasslands in our study have to be considered as semi-natural grassland (Studer-Ehrensberger 2000), i.e., low-yielding permanent grasslands, dominated by indigenous, naturally occurring grasses, herbaceous plant species and shrubs or small trees. The land-use intensity usually decreases with increasing elevation. We selected semi-natural grassland regions (covering 19.2% of the study area) based on the CORINE Land Cover 2000 seamless vector data (http://land.copernicus.eu/, accessed December 2017). Semi-natural grassland range from 1000 to 3000 m asl (Fig. 1 and *Figure S 1.1*). Permafrost is absent below elevations of 2600 m asl (Boeckli et al. 2012), and the alpine–nival ecotone is around 3000 m asl (Gottfried et al. 2011).

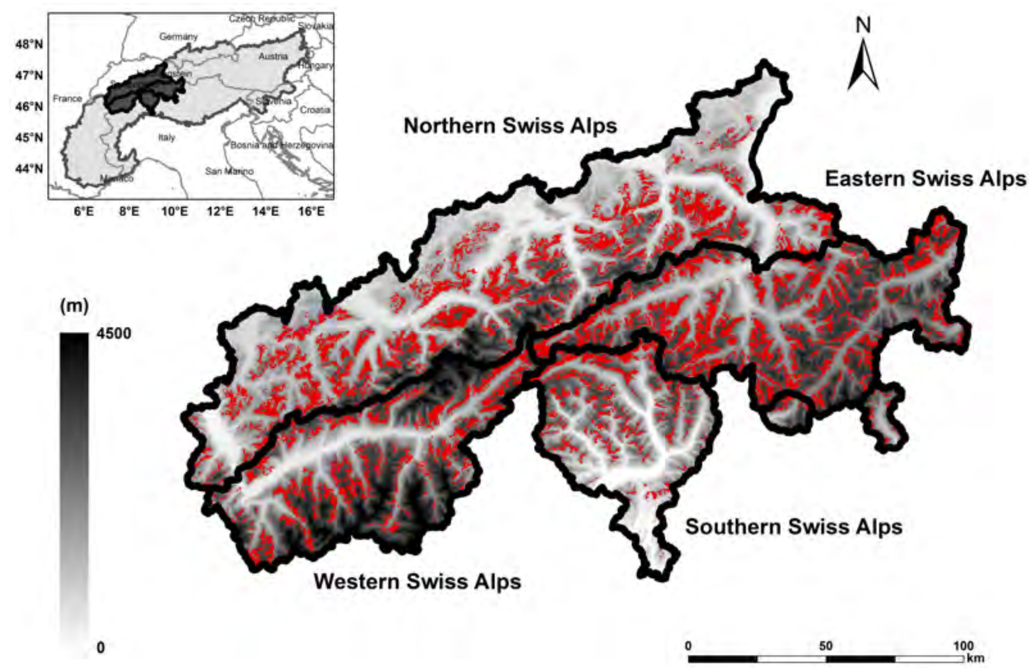

Fig. 1. Location and topography of the Swiss Alps (separated as NSA, ESA, SSA and WSA). The patterns with dark red color are areas of the semi-natural grassland.

2.2. Land Surface Phenology (LSP) and greenness metrics of semi-natural grassland

Normalized difference vegetation index (NDVI) is referenced as one of the most widely used vegetation exponents for monitoring phenological events and greenness of vegetation at regional and global scales (Cleland et al. 2007; Fabio et al. 2008; Fisher et al. 2006; Garonna et al. 2014; Garonna et al. 2016). NASA Moderate Resolution Imaging Spectroradiometer (MODIS) Terra NDVI products (MOD13Q1-collection 5) were used to derive yearly LSP metrics for the start, peak, end, and length of season (SOS, POS, EOS, and LOS, respectively) on a pixel-by-pixel basis. The available 276 MOD13Q1 images of 250-m/16-day resolution for the period of 2003-2014, with corresponding quality and day-of-observation information data, were processed with masking out the pixels with lower NDVI (<0.3) (Xie et al. 2017), as well as by using quality assurance (QA) information in order to generate higher-quality, cloud-free NDVI images.

The relative threshold method we used to derive SOS from the annual MOD13Q1 NDVI time series - named Midpoint$_{pixel}$ method- is based on the comprehensive inter-comparison of SOS metrics by White et al. (2009). This method was also applied in studies at coarser spatial resolution at both European and global scale (Garonna et al. 2014; Garonna et al. 2016). The EOS is then defined as the day on which NDVI reaches half of its range again in the calendar year, and the LOS is simply the number of days between SOS and EOS. This method to describe phenology was previously applied to land surface phenology modeling across vegetated regions in the Swiss Alps (e.g. Xie et al. (2018) and Oehri et al. (2017)). Besides, the POS and the maximum value of NDVI ($NDVI_{max}$) were derived between SOS and EOS according to the definition from Zhang et al. (2003). SOS, POS, and EOS are expressed in a day of the (calendar) year (DOY). A total of 96.3% of the semi-natural grassland areas contained pixel-based LSP metrics of documented quality (Xie et al. 2017).

Both NDVI and leaf area index (LAI) correlate well with the productivity and greenness of vegetation (Asam et al. 2013; Jenerette et al. 2009; Myneni et al. 1997; Pettorelli et al. 2005). To compute the greenness metrics, we employed the NDVI and LAI products provided by the Institute for Earth Observation, EURAC (Asam et al. 2018; Pasolli et al. 2015). These data comprise an NDVI and LAI time series at a 250-m/4-days resolution in the Alps covering the years 2003-2014. The NDVI and LAI values were extracted for grassland according to the CORINE 2006 land cover classification. While both parameters describe plant phenology, the information content of the data sets is different. NDVI represents a relative measure of photosynthetic activity, which is, however, also influenced by vegetation type, growing stage, soil background and angular effects. LAI, on the other hand, is a biophysical parameter, which reports on a measureable and therewith comparable plant trait. LAI is closely correlated with total biomass of grassland species (Halabuk et al. 2013). The LAI maps were produced with an innovative algorithm developed by EURAC based on radiative transfer modeling (Pasolli et al. 2015). Through this approach, it incorporates hence additional information on the canopy structure and on viewing and illumination effects. This algorithm exploits the 250 m MODIS surface reflectance data and therefore provides LAI at higher resolution compared to the MODIS standard product (1-km). The NDVI and LAI data sets were resampled to daily resolution. Pixels that changed classification between the CORINE Land Cover 2000 and 2006 seamless vector data were removed. Then, the mean NDVI ($NDVI_{mean}$) and mean LAI (LAI_{mean}) between SOS and EOS were calculated as the greenness metrics. The retrieved amount of $NDVI_{mean}$ pixels equals 93.7% of the semi-natural grassland areas. In the case of LAI_{mean}, 68.5% of the semi-natural grassland areas contain information, while the remaining pixels with missing values were masked out (Pasolli et al. 2015).

2.3. Snow accumulation (SWE_{acc}) and snow cover melt date (SCMD)

To derive the accumulation and melt of seasonal snow, we employed snow water equivalent (SWE) grids at 1-km/daily resolution in each hydrological year (HY, running from September 1st to October 31st of the following year). Daily SWE grids were generated on the basis of 298 observational snow monitoring sites in Switzerland using a distributed snow hydrological model (Griessinger et al. 2016; Magnusson et al. 2014).

In this study, we computed the snow accumulation (SWE_{acc}) as an average value of SWE from January 1st to April 30th per pixel, and snow cover melt date (SCMD) as the first date after February 15th with a snow-covered fraction below 33% in a SWE grid. The unit of SWE_{acc} is millimeter (mm), and SCMD is expressed in a day of the (calendar) year (DOY).

2.4. Meteorological metrics and digital elevation model

Daily gridded datasets with 1.25 degree minutes (0.02083 degree) in longitude and latitude, corresponding to ~2.3-km (~1.6-km) spatial resolution in the West-East direction (South-North direction), of mean, maximum, and minimum air temperature, mean precipitation, and mean relative sunshine duration over the period 2003-2014 were collected from the Swiss Federal Office of Meteorology and Climatology, *MeteoSwiss* (http://www.meteoswiss.admin.ch/, accessed December 2017). The maps of meteorological data and seasonal snow metrics were transformed into the zone 32 of the Universal Transverse Mercator projection and resampled into a 250-m grid using a Nearest Neighbour method to match the LSP and greenness metrics for the subsequent statistical analysis. Spring (March, April, and May), summer (June, July, and August), autumn (September, October, and November), and winter (December, January, and February) meteorological metrics were calculated by computing averaged values per season (see Table 1). In addition, considering that the beginning of plant growth and the timing of snowmelt are reported to be tightly linked across elevational bands (Vitasse et al. 2017), we computed the mean values of spring air temperature, precipitation, and relative sunshine duration using a one-week (seven-days) moving window in the first four weeks after SCMD to exclude indirect effects of correlation between SCMD and spring meteorological metrics, since snow cover provides protection in winter (Chen et al. 2015; Groffman et al. 2006; Wahren et al. 2005; Wipf et al. 2006) and shields off photosynthetic activity (Rogiers et al. 2008) before snowmelt.

Digital topographic information of the study region at a 1 arc-sec scale (~30-m) obtained from the European Environment Agency (http://www.eea.europa.eu/, accessed December 2017) was used to generate a 250-m scale digital elevation model (DEM). The elevation gradients were computed, selecting distinct zones within a 100-m band with a 50-m elevational resolution (between 1000 and 3000 m asl, corresponding to the range of elevational distribution of semi-natural grassland covers), based on the DEM.

2.5. Statistical analysis

Spearman's correlation coefficients (*r*) were employed to test the inter-annual relationships of seasonal snow (SCMD and SWE_{acc}), winter (WT_{mean}, WT_{max}, WT_{min}, WP, and WRSD), and other meteorological metrics (T_{mean_melt7}, T_{max_melt7}, T_{min_melt7}, $P_{\_melt7}$ and $RSD_{\_melt7}$; T_{mean_melt14}, T_{max_melt14}, T_{min_melt14}, $P_{\_melt14}$ and $RSD_{\_melt14}$; T_{mean_melt21}, T_{max_melt21}, T_{min_melt21}, $P_{\_melt21}$ and $RSD_{\_melt21}$; T_{mean_melt28}, T_{max_melt28}, T_{min_melt28}, $P_{\_melt28}$ and $RSD_{\_melt28}$) after SCMD with SOS, and the inter-annual relationships of autumn meteorological metrics (AT_{mean}, AT_{max}, AT_{min}, AP, and ARSD) with EOS on pixel level. The inter-annual relationships of seasonal snow (SCMD and SWE_{acc}), winter (WT_{mean}, WT_{max}, WT_{min}, WP, and WRSD), spring (ST_{mean}, WT_{max}, ST_{min}, SP, and SRSD), and summer (MT_{mean}, MT_{max}, MT_{min}, MP, and MRSD) meteorological metrics with POS and greenness metrics ($NDVI_{max}$, LAI_{mean}, and $NDVI_{mean}$) were also tested by Spearman's correlation on pixel level.

The 250-m grids of the statistical results were intersected with the 250-m DEM, subregions, and semi-natural grassland maps. The statistics results were then analyzed across elevations and regions. Each elevational band is characterized by the average values of the statistically significant correlation results. Elevations below 1000 m asl with a few pixels of semi-natural grassland were masked out in this analysis. Bands with the proportion of pixels in statistical significance less than 5% were masked out in the elevational analysis. Image data processing was performed with ArcGIS (v10.4.1, ESRI, USA), ENVI/IDL (v5.1, the EXELIS Inc., McLean, VA, USA), and statistical analysis was performed using the R (http://www.r-project.org/, version 3.4.1) programming environment.

3. Results

3.1. Start of season (SOS)

Mean Spearman's correlation coefficients of seasonal snow metrics with SOS, which were computed over the period 2003-2014, varied with elevation for the entire Swiss Alps (Fig. 2). Most conspicuously, the correlations between SCMD and SOS were the strongest (with mean *r* around 0.7) across the entire elevation gradient. The corresponding amount of significant pixels (% of total) was largest at higher elevations. The mean correlations of SWE_{acc} with SOS (with mean $r > 0.6$) were secondary across elevations and reached maximum values at elevations between 1500-2000 m asl. The correlations of SCMD with SOS (mean r >0.70) were high across all subregions, and the subregions differed little in that respect (Fig. 2). Also, the correlations of SCMD and SWE_{acc} with SOS were similar across subregions, but slightly more pronounced in NSA (Fig. 2 and *Figure S1.2*). In particular, the average SOS occurs closely after SCMD across the study areas (*Figure S1.3*).

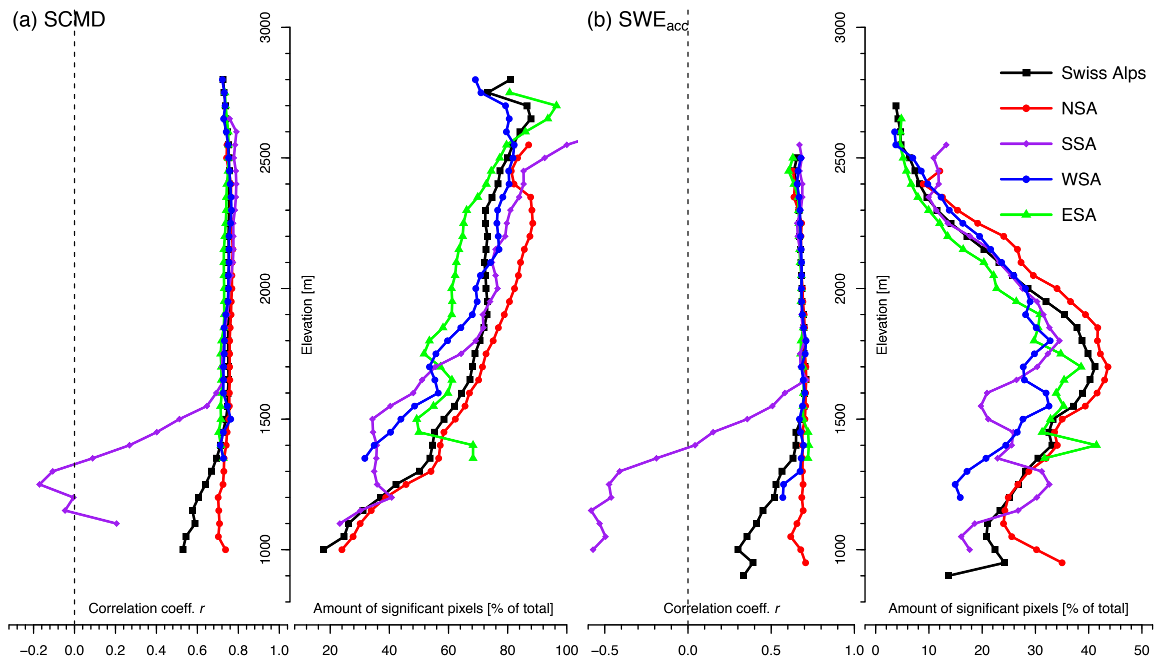

Fig. 2. Variation of mean Spearman's correlation coefficients (left panel) between snow metrics and SOS (SCMD & SOS (a), and SWE_{acc} & SOS (b)) and the corresponding amount of significant pixels [% of total] (right panel) of each elevational band across the entire grassland area for the four subregions (NSA, SSA,

WSA, ESA). The dashed grey line represents a mean correlation coefficient of 0.

In contrast, the spring meteorological metrics (i.e., T_{mean_melt7}, T_{max_melt7}, T_{min_melt7}, $P_{\_melt7}$ and $RSD_{\_melt7}$; T_{mean_melt14}, T_{max_melt14}, T_{min_melt14}, $P_{\_melt14}$ and $RSD_{\_melt14}$; T_{mean_melt21}, T_{max_melt21}, T_{min_melt21}, $P_{\_melt21}$ and $RSD_{\_melt21}$; T_{mean_melt28}, T_{max_melt28}, T_{min_melt28}, $P_{\_melt28}$ and $RSD_{\_melt28}$) after SCMD showed less significant correlations with SOS (with the corresponding amount of significant pixels less than 15%) in all subregions (Fig. 3). Specifically, the mean values of 7-days, 14-days, 21-days and 28-days spring mean, maximum, and minimum air temperature and mean precipitation after SCMD showed positive correlations with SOS across the study area (*Figure S1.5, S1.6, S1.7,* and *S1.8*). Correlations between SOS and spring sunshine duration were negative (with mean *r*<-0.62) with 11% of total pixels for the entire study area. In addition, winter meteorological factors showed less significant correlation with SOS (*Figure S1.9*).

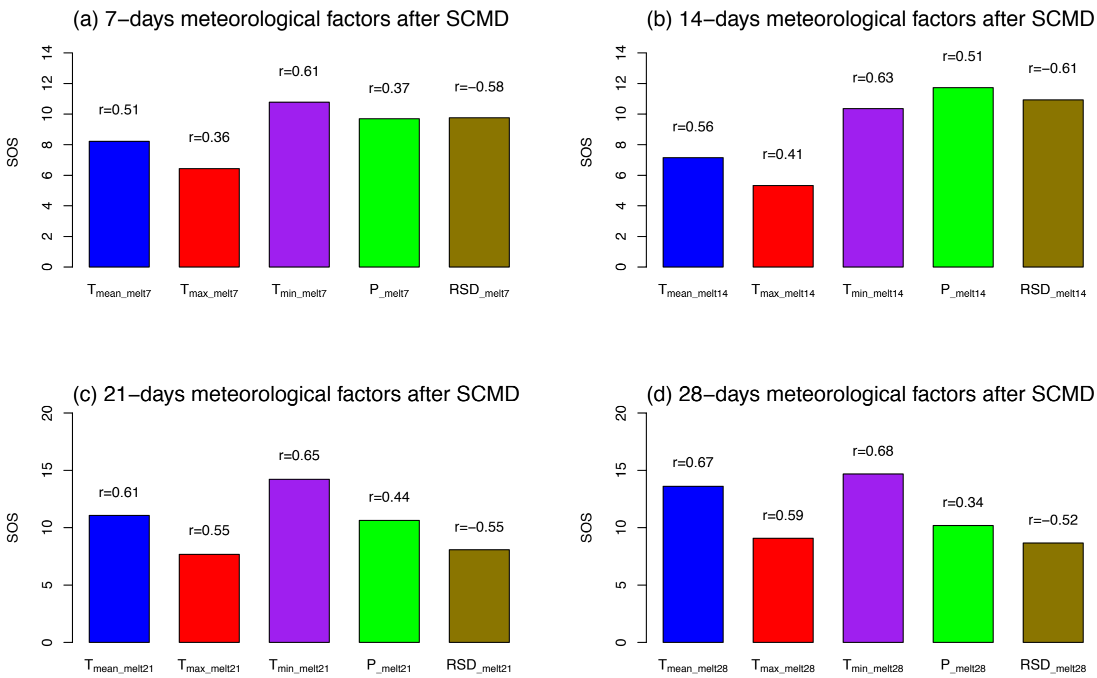

Fig. 3. Mean Spearman's correlation coefficients between SOS and spring meteorological metrics after SCMD (i.e., T_{mean_melt7} & SOS, T_{max_melt7} & SOS, T_{min_melt7} & SOS, $P_{\_melt7}$ & SOS and $RSD_{\_melt7}$ & SOS; T_{mean_melt14} & SOS, T_{max_melt14} & SOS, T_{min_melt14} & SOS, $P_{\_melt14}$ & SOS and $RSD_{\_melt14}$ & SOS; T_{mean_melt21} & SOS, T_{max_melt21}

& SOS, T_{min_melt21} & SOS, $P_{\_melt21}$ & SOS and $RSD_{\_melt21}$ & SOS; T_{mean_melt28} & SOS, T_{max_melt28} & SOS, T_{min_melt28} & SOS, $P_{\_melt28}$ & SOS and $RSD_{\_melt28}$ & SOS) and the corresponding amount of significant pixels [% of total] across the entire grassland area.

3.2. End of season (EOS)

The significant correlation coefficients and the corresponding amount of pixels between autumn meteorological metrics and EOS varied considerably along elevation (Fig. 4). Below 2000 m asl, air temperatures (in particular AT_{mean}, but also AT_{max}, and AT_{min}) showed positive correlations with EOS (mean r>0.66). In contrast, above 2000 m asl, the mean negative correlations of AP with EOS were stronger than the positive correlations of other autumn meteorological metrics.

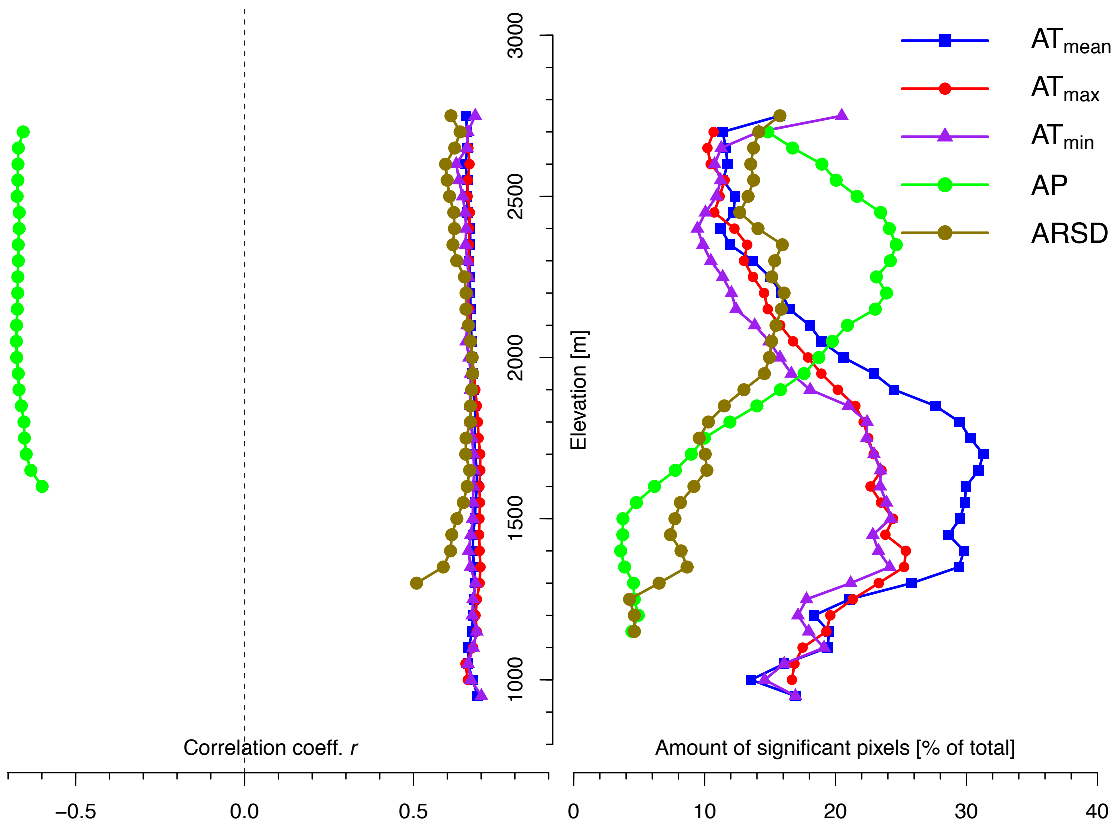

Fig. 4. Variation of mean Spearman's correlation coefficients (left panel) between autumn driving metrics and EOS (i.e., AT_{mean} & EOS, AT_{max} & EOS, AT_{min} & EOS, AP & EOS, and ARSD & EOS) and the corresponding

amount of significant pixels [% of total] (right panel) of each elevational band across the entire grassland area. The dashed purple line represents a mean correlation coefficient of 0.

Air temperature had the highest positive correlations with EOS in NSA. In the other regions of Switzerland, autumn precipitation (AP) had the highest correlations with EOS (Fig. 5). The amount of pixels with significant positive correlations between ARSD and EOS was higher in ESA than that in other subregions.

Besides, we observed significant negative correlations between SCMD and LOS (with mean *r*=-0.59 over 20.3% of total pixels) and between SWE_{acc} and LOS (with mean *r*=-0.31 over 8.9% of total pixels) for the entire study area.

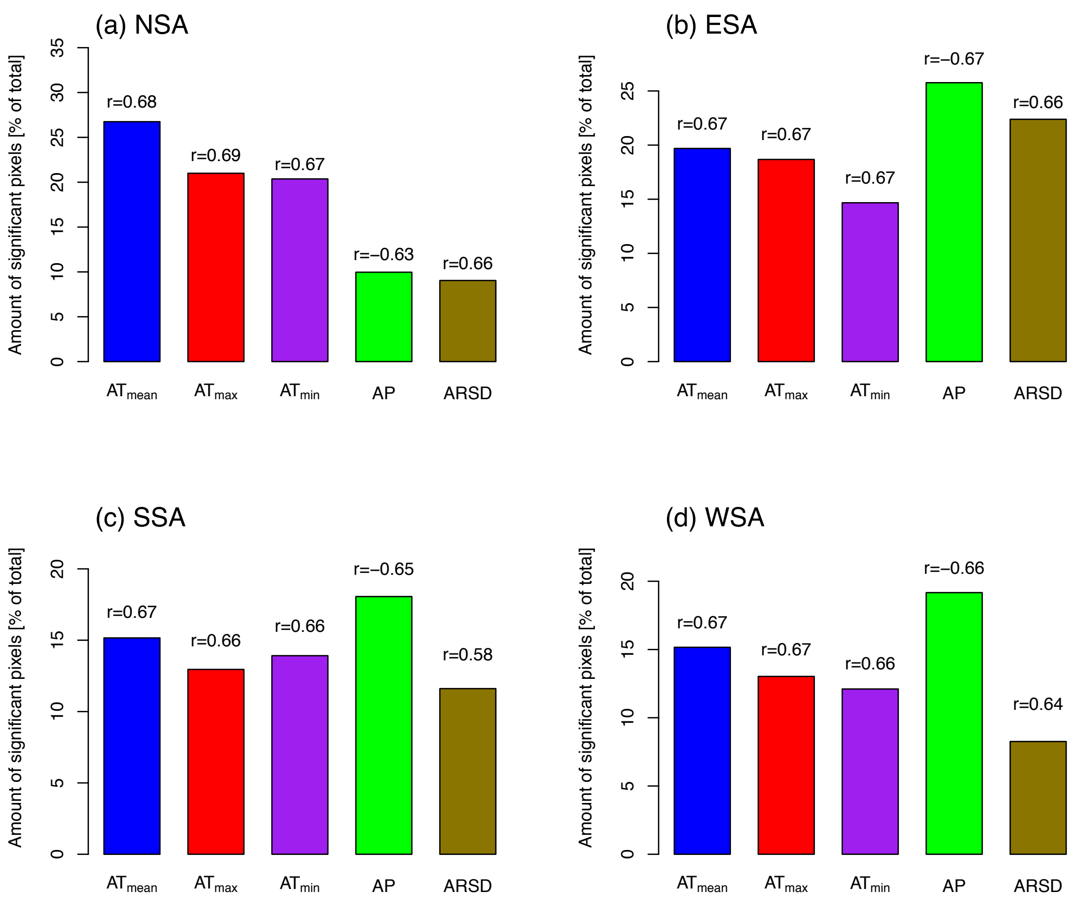

Fig. 5. Mean Spearman's correlation coefficients between autumn driving metrics and EOS (i.e., AT_{mean} & EOS, AT_{max} & EOS, AT_{min} & EOS, AP & EOS and ARSD & EOS) and the corresponding amount of significant pixels [% of total] for the four subregions (NSA (a), ESA (b), SSA (c), and WSA (d)).

3.3. Grassland greenness

The greenness metrics LAI_{mean} and $NDVI_{mean}$ differed considerably in their correlation coefficients with meteorological data (Fig. 6). LAI_{mean} showed positive correlations (with mean r around 0.68) with SCMD across the elevation gradient (Fig. 6a). Above 2000 m asl, mean summer air temperatures (MT_{mean}) showed higher correlations with LAI than SCMD.

A significant correlation of $NDVI_{mean}$ with meteorological data was found in less pixels than in the case of LAI_{mean} across elevations (Fig. 6b). Similar to LAI_{mean}, significant correlation between $NDVI_{mean}$ and MT_{mean} showed a high amount of pixels at elevations above 2000 m asl, however, significant correlation between $NDVI_{mean}$ and SWE_{acc} had similar amounts of pixels. Below 2000 m asl, only SCMD and MP showed significant pixels with $NDVI_{mean}$ (however less than 10% of total).

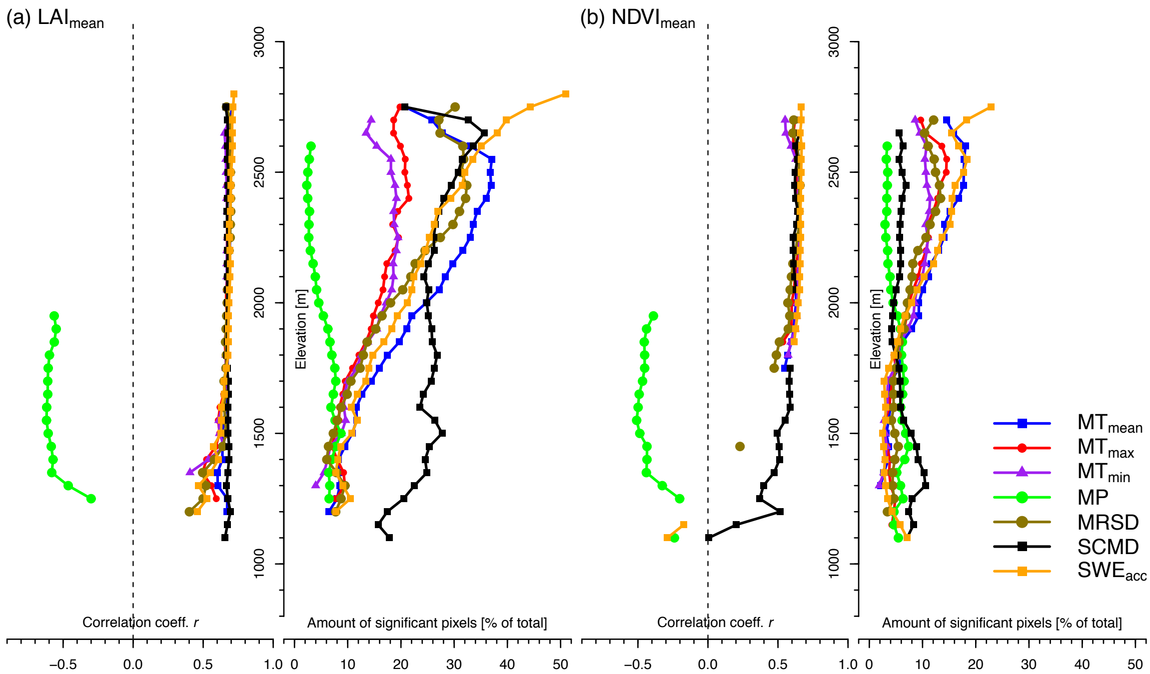

Fig. 6. Variation of mean Spearman's correlation coefficients (left panel) between seasonal snow and summer

meteorological metrics and greenness (i.e., (a) MT_{mean} & LAI_{mean}, MT_{max} & LAI_{mean}, MT_{min} & LAI_{mean}, MP & LAI_{mean}, MRSD & LAI_{mean}, SCMD & LAI_{mean} and SWE_{acc} & LAI_{mean}; (b) MT_{mean} & $NDVI_{mean}$, MT_{max} & $NDVI_{mean}$, MT_{min} & $NDVI_{mean}$, MP & $NDVI_{mean}$, MRSD & $NDVI_{mean}$, SCMD & $NDVI_{mean}$ and SWE_{acc} & $NDVI_{mean}$) and the corresponding amount of significant pixels [% of total] (right panel) of each elevational band across the entire grassland area.

Many of the positive correlations of seasonal snow and summer meteorological metrics with LAI_{mean} were in a similar range (0.70>mean r>0.60) across subregions (Fig. 7). However, the amount of significant pixels for these correlations differed considerably among the four subregions. Specifically, SCMD showed the largest amount of significant pixels in NSA (Fig. 7a). The ESA region stood out with a large amount of significant pixels for MT_{mean} and MRSD (Fig. 7b). The correlations between SCMD and LAI_{mean} had most pixels in SSA (Fig. 7c). In WSA, LAI_{mean} was mainly correlated with SWE_{acc} with more than 35% of total pixels (Fig. 7d).

The mean correlations of seasonal snow and summer meteorological metrics with $NDVI_{mean}$, as well as the amount of significant pixels, were overall lower than those with LAI_{mean} in each subregion (Fig. 8). NSA had the smallest amount of pixels with significant correlations of seasonal snow and summer meteorological metrics with $NDVI_{mean}$ (Fig. 8a). In SSA, SCMD showed the largest amount of significant pixels (Fig. 7c). In WSA, SWE_{acc} had more pixels than other metrics with significant correlation with $NDVI_{mean}$, but they represented only 11% of the total pixels (Fig. 8d). We did not observe significant correlation of seasonal snow and meteorological metrics with $NDVI_{max}$ and POS (*Figure S3.6 and S3.7*), except for the mean correlation between SCMD and POS (with mean R=0.57 of 11.5% pixels). Besides, we found that 59.4% of grassland pixels present significant correlation between LAI_{mean} and $NDVI_{mean}$ (with mean r=0.78).

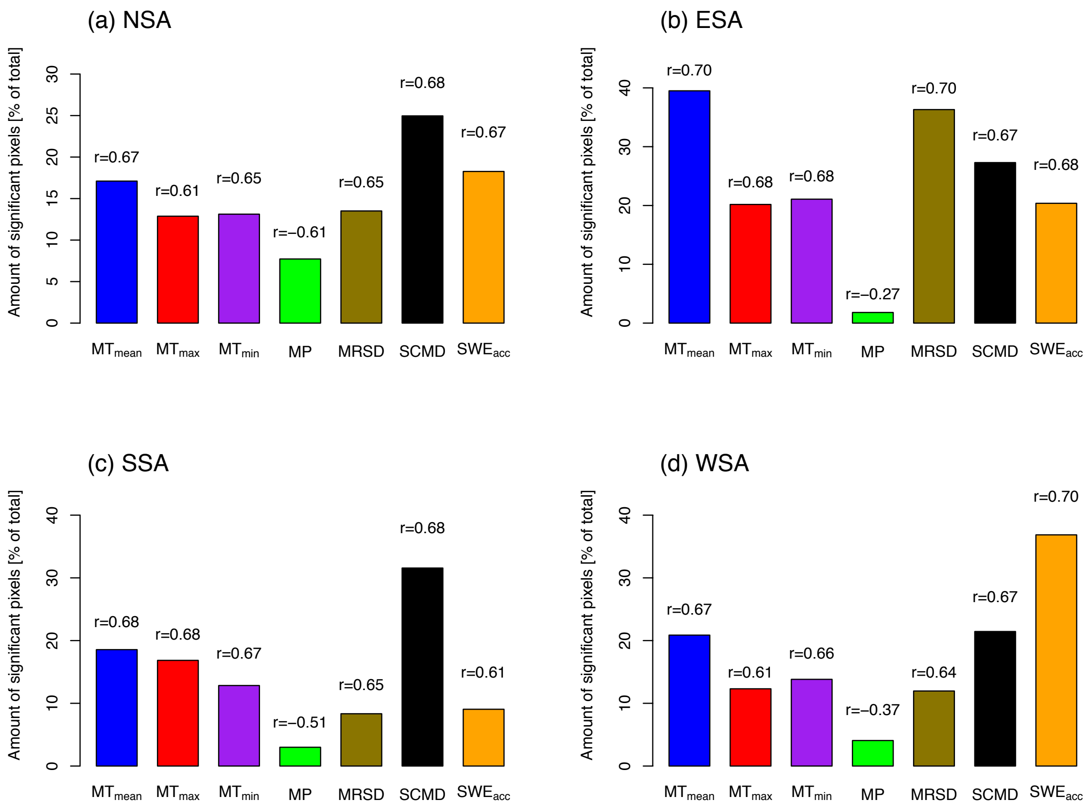

Fig. 7. Mean Spearman's correlation coefficients between seasonal snow and summer meteorological metrics and LAI_{mean} (i.e., MT_{mean} & LAI_{mean}, MT_{max} & LAI_{mean}, MT_{min} & LAI_{mean}, MP & LAI_{mean}, MRSD & LAI_{mean}, SCMD & LAI_{mean} and SWE_{acc} & LAI_{mean}) and the corresponding amount of significant pixels [% of total] for the four subregions (NSA (a), ESA (b), SSA (c), and WSA (d)).

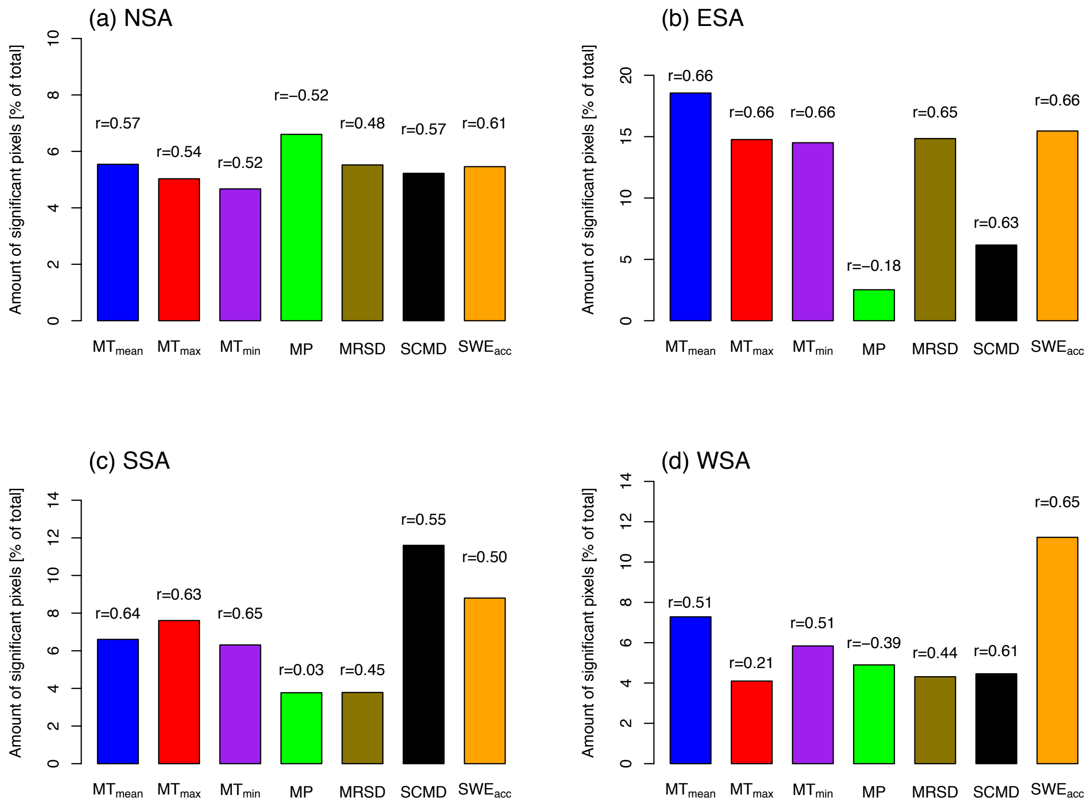

Fig. 8. Mean Spearman's correlation coefficients between seasonal snow and summer meteorological metrics and $NDVI_{mean}$ (i.e., MT_{mean} & $NDVI_{mean}$, MT_{max} & $NDVI_{mean}$, MT_{min} & $NDVI_{mean}$, MP & $NDVI_{mean}$, MRSD & $NDVI_{mean}$, SCMD & $NDVI_{mean}$ and SWE_{acc} & $NDVI_{mean}$) and the corresponding amount of significant pixels [% of total] for the four subregions (NSA (a), ESA (b), SSA (c), and WSA (d)).

4. Discussion

In this study, we investigated the influence of seasonal snow and meteorological factors on the NDVI-based land surface phenology metrics such as start of season, end of season, mean and maximum NDVI of the growing season, and the mean LAI of the growing season across semi-natural grasslands of the Swiss Alps. For the start of season, we found positive correlation of snow cover melt date and snow accumulation with the investigated phenology metrics, especially at higher elevations. For the end of season, autumn temperature was the strongest explanatory variable among the investigated factors below 2000 m asl, and autumn precipitation above 2000 m asl. The effects of snow and meteorological factors on grassland greenness were complex and differed among regions, however, greenness tended to be influenced by temperatures at high elevation and by snow melt date at low elevation among the driving factors investigated in this study.

4.1. Start of season (SOS)

Our findings indicate that snowmelt has the most critical effect on the start of the growing season in alpine grasslands across all subregions of the Swiss Alps. These results are in agreement with previous studies where snow cover melt day showed a strong positive correlation with spring phenology in grassland (Borner et al. 2008; Buus-Hinkler et al. 2006; Cooper et al. 2011; Filippa et al. 2015; Julitta et al. 2014; Suzuki 2014; Vitasse et al. 2017; Wipf et al. 2009; Zeeman et al. 2017). While temperature, sunshine duration and precipitation after snowmelt may all affect plant phenology (Li et al. 2016; Linkosalo et al. 2009; Liu et al. 2016; Menzel et al. 2006; Piao et al. 2006), our analyses only suggested a limited influence of these factors on the SOS (see also (Vitasse et al. 2017; Wang et al. 2013b; Yu et al. 2013). The large influence of snowmelt timing on SOS is plausible as the disappearance of snow ultimately affects the ground surface characteristics recognized by the satellite sensors. However, the greening signal we analyzed results from a combination of snow disappearance and actual greening after snowmelt. Hence, our results have to be interpreted with caution as the greening after snowmelt may be outweighed by the change from a snow-covered to a not snow-covered state. The magnitude and characteristics of the correlation of SOS with SCMD and SWE_{acc} differed between subregions (Fig. 2). The response of SOS to snow metrics was more pronounced in the NSA than in the other subregions (Fig. 2). Interestingly, we found that in the Swiss Alps, the influence of snow metrics on SOS was more pronounced between elevations than between subregions, which is in line with findings by Xie et al. (2018).

At higher elevation, our results showed a notable increase in the relative amount of significant pixels for the relationship of SOS and SCMD (Fig. 2). Moreover, and in line with numerous previous studies (Choler 2015; Galen and Stanton 1995; Stöckli and Vidale 2004), we found SOS to occur closely after SMCD (*Figure S1.3*). The tight coupling of SOS and SCMC at high altitudes is clear when considering the very narrow seasonal window with favourable conditions for plant growth, that is characteristic of these environments, and with which alpine plants have to cope (Billings 1973). Indeed, in such harsh environments, the rapid green-up of plants after snow-melt may be understood as an adaptation to the limited period of possible growth (Galen and Stanton 1995; Körner and Basler 2010). Also, it is to be considered that, aside from temperature, photoperiod constrains plant growth seasonally in the study area (Jolly et al. 2005). Thus, at lower elevations, snow might melt when the day length is still too short for plant development (Björk and Molau 2007), thus increasing the time-lag between snow-melt time and SOS.

4.2. End of season (EOS)

We hypothesized that autumn phenology would be driven more by temperature than by other factors, but this was only the case for elevations below 2000 m asl. Above 2000 m asl, autumn precipitation explained more variation in the end-of-season signal. This is plausible as our EOS signal, like the SOS, is driven by both actual greening (or browning) and snow presence and absence. At high elevation, an autumn precipitation event will more likely be in the form of snow than at low elevation. At lower elevation it is likely that autumn temperatures influence the greenness on the ground. This discrepancy of different processes influencing greenness may also explain inconclusive findings in previous studies. Many studies found positive relationships of EOS in mountain grasslands with temperature (Jeong et al. 2011; Menzel et al. 2006; Sun et al. 2014) and relative sunshine duration (Migliavacca et al. 2011). But, nevertheless, a number of studies found a negative correlation of EOS with autumn precipitation (Choler 2015; Prevéy et al. 2014).

The magnitude and character of the responses of EOS to autumn meteorological metrics differed among subregions (Fig. 5 and Figure S2.3). While air temperature showed the highest positive correlations with EOS in NSA, autumn precipitation resulted in the highest correlations with EOS in the other regions of the Swiss Alps. This could partly be explained by the elevational distribution of pixels within each subregion (*Figure. S1.1*). The northern Swiss Alps are situated lower than the other regions, hence, it is more likely that EOS is better explained by temperature there. Furthermore, climate differences among subregions may drive the differences in correlations (Beniston et al. 2003; OcCC-Consortium 2007). The northern Swiss Alps are a region with relatively high precipitation (often >1500 mm). Hence, water may be less limiting for plant growth, and temperatures may have a more direct influence in terms of inter-annual greening and browning than variation in precipitation. In this study, the amount of pixels with significant correlations between EOS and potential driving factors was much lower than for SOS, and the characterization of meteorological factors at the EOS seemed more complex and weaker across elevations and subregions compared to SOS. This might be partly due to higher difficulties in tracking EOS compared to SOS (Gallinat et al. 2015), and furthermore by autumn phenology being affected by other environmental factors (such as frost and wind) than spring phenology (Gill et al. 2015; Parmesan and Hanley 2015).

4.3. Grassland greenness

Our results suggested that both temperature (MT_{mean}) and snow parameters (SCMD, SWE_{acc}) influence the greenness (LAI_{mean}, $NDVI_{mean}$) of alpine grasslands. While it is obvious that the high temperature combined with water availability can determine greenness of alpine grasslands (Grippa et al. 2005; Jonas et al. 2008; Kudernatsch et al. 2008), the role of snow cover and snowmelt timing was less evident. On the one hand, later snowmelt shortens the growing season (e.g. Wipf and Rixen (2010), which could reduce greenness.

On the other hand, late snowmelt (and more snow) can improve water and nutrient provision (Clement et al. 2012; Fernandez-Pascual et al. 2017; Julitta et al. 2014; Keller and Körner 2003; Suzuki 2014; Trujillo et al. 2012; Wang et al. 2013a) and protect vegetation from freezing events (e.g. (Björk and Molau 2007; Julitta et al. 2014; Rixen et al. 2012; Wipf et al. 2006). Our results probably reflect both processes, especially as SCMD was the most important metric, which explained LAI_{mean} and $NDVI_{mean}$ values at low elevation, whereas mean summer temperature explained greenness best at high elevation. At high elevation, warm summer temperatures will probably enhance greenness. At low elevation, on the other hand, plants are less limited by the length of the growing season and early snowmelt does not necessarily enhance plant growth and greenness. Rather contrary, late snowmelt at low elevation probably improves water and nutrient availability throughout the summer and protects from late freezing events. As a result, greenness could be higher in years with late snowmelt and more snow accumulation.

The magnitude and character of the responses of greenness metrics to seasonal snow and meteorological metrics differed among subregions (Fig. 7 and 8 and *Figure S3.5*, *S3.6* and *S3.7*). Like SOS and EOS, the regional differences could partly be explained by their differences in elevation. For instance, mean summer temperature explained most LAI_{mean} and $NDVI_{mean}$ values in the Eastern Swiss Alps, consisting of higher elevations than the other regions. The subregions also differ climatically, e.g., the eastern Swiss Alps are drier than the other subregions. This climatic difference may explain why the summer relative sunshine duration (MRSD) had high explanatory power in this region. Overall, our findings suggest that the influence of seasonal snow and meteorological metrics on greenness is different both among elevations and among subregions in the grassland areas of the Swiss Alps. However, the relative amount of pixels showing significant correlations was less than 20% between $NDVI_{mean}$ and investigated factors, and less than 40% between LAI_{mean} and investigated factors across elevations and subregions. On the one hand, this difference might be caused by the different saturation effects between NDVI and LAI (i.e., NDVI saturates earlier than LAI (Asam et al. 2013; Fensholt et al. 2004)). On the other hand, the limited impacts of investigated factors on greenness metrics might indicate that grassland growth is driven by additional factors beyond the metrics investigated in this study. Besides, the similar variation with elevations is partly caused by covariation between LAI_{mean} and $NDVI_{mean}$.

4.4. Limitations

As discussed above, disentangling how the vegetation-activity signal is influenced by absence or presence of snow versus the actual green-up of vegetation during the growing season is challenging. Several reports point out that the presence of snow cover in vicinity of green vegetation may result in uncertainty in the NDVI signal (Jönsson et al. 2010; Quaife and Lewis 2010). Consequently, the snow cover dynamics may impact satellite monitoring of greenness in vegetated areas (Beck et al. 2006; Busetto et al. 2010; Delbart et al. 2006; Jönsson et al. 2010; White et al. 2009). Some studies have proposed to use a winter baseline NDVI (i.e. NDVI of dormant but snow-free vegetation) to minimize the effect of snow cover (Beck et al. 2006; Busetto et al. 2010). This approach has been developed for evergreen needle-leaf trees that may continue to be photosynthetically active despite being snow covered (e.g. Walther et al. (2016)). In alpine grasslands, the winter baseline can be expected to be lower and therefore have limited influence on the amplitude-based SOS estimate. Also, the winter baseline in alpine grasslands is expected to be spatially more variable due to variations in fractional vegetation cover and therefore particularly difficult to estimate. For these reasons, we expect the use of a winter baseline NDVI to have minimal effect on the extracted phenological metrics in our study area.

The compositing scheme and medium spatial resolution of satellite data combined with the terrain complexity in the Swiss Alps make land surface phenology estimates complex. The link to driving factors is furthermore influenced by the different resolutions of the MODIS, SWE and meteorological data. Nevertheless, we were able to analyze year-to-year variation in climate and greenness data, which allowed us to better understand land surface phenology processes in alpine grasslands.

An important factor that remained beyond the scope of this paper is management practices (grazing, cutting) (Schmidt et al. 2018; Zeeman et al. 2010). Many land surface phenology metrics are influenced not only by climate but also by management type and intensity, and this especially at low elevation. It remains a challenge for future studies to disentangle land use from climate effects on greenness measures derived from remote sensing.

5. Conclusion and outlook

Based on NDVI-derived metrics investigated in alpine grasslands, we found positive association of the accumulation and melt date of seasonal snow with the start of season especially at elevations above 1500 m asl. Autumn temperature was positively correlated with the end of season below 2000 m asl, while autumn precipitation was associated with the end of season at elevations above 2000 m asl. The effects of seasonal snow and meteorological factors on the mean greenness of the growing season were complex and differed among regions, however, the mean greenness was more influenced by temperatures at high elevations and by snowmelt date at low elevations than by other factors.

Given the high sensitivity of alpine grassland ecosystems, our results suggest that the response of these systems to future changes of seasonal snow and warming climate depends on elevation. The growing period of grassland might become longer in a warmer future climate, with an advanced spring and delayed autumn phenology. However, our results also suggest that a longer growing season alone may not enhance greenness and productivity, rather in combination with sufficient water availability and high summer temperatures.

Future research in remote sensing of alpine land surface phenology should focus on disentangling the effects of greenness due to snow absence during melting and actual vegetation greening at the start of the growing season. Eventually, the detection of long-term trends in relationships among snow, temperature and greening will improve our understanding of climate change effects on vegetation.

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4.8 Supporting Information

S1 Start of season (SOS)

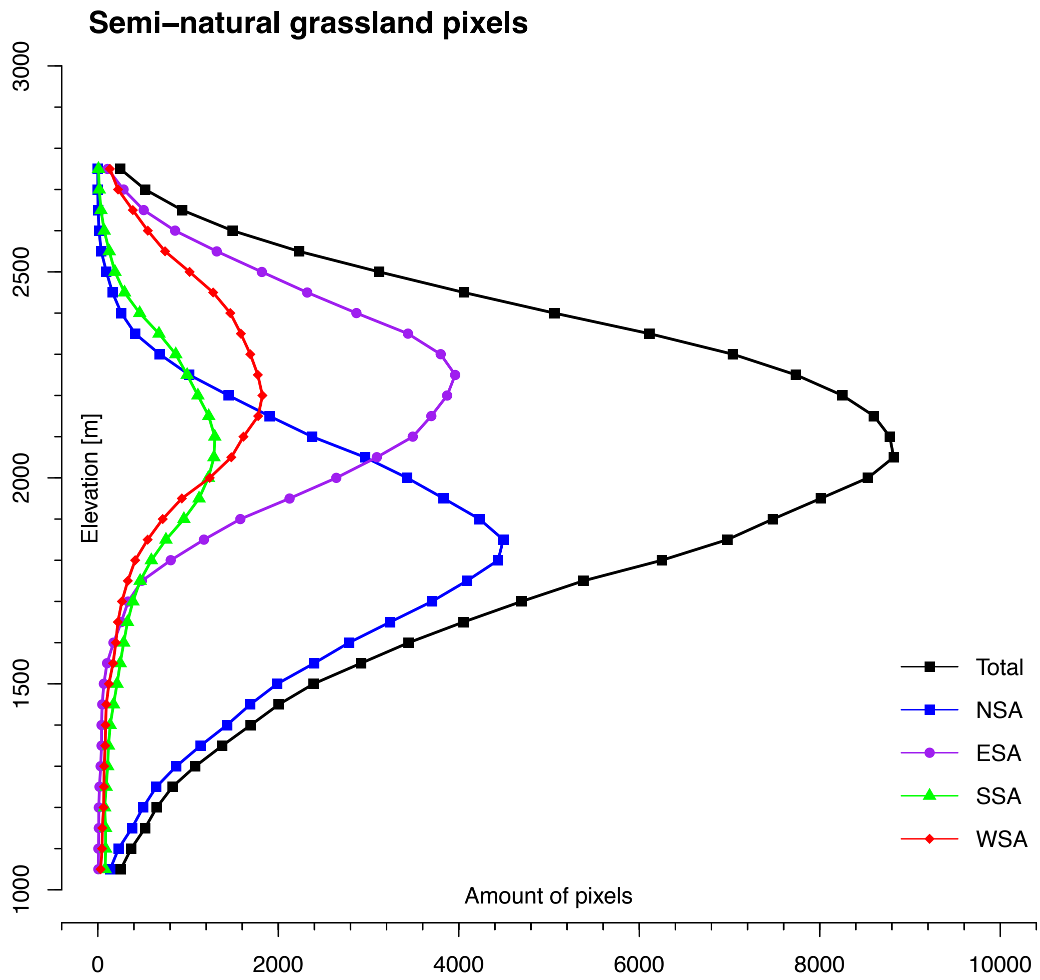

Figure S1.1. Elevational distribution of amount of pixels in semi-natural grassland for the entire Swiss Alps and the four subregions.

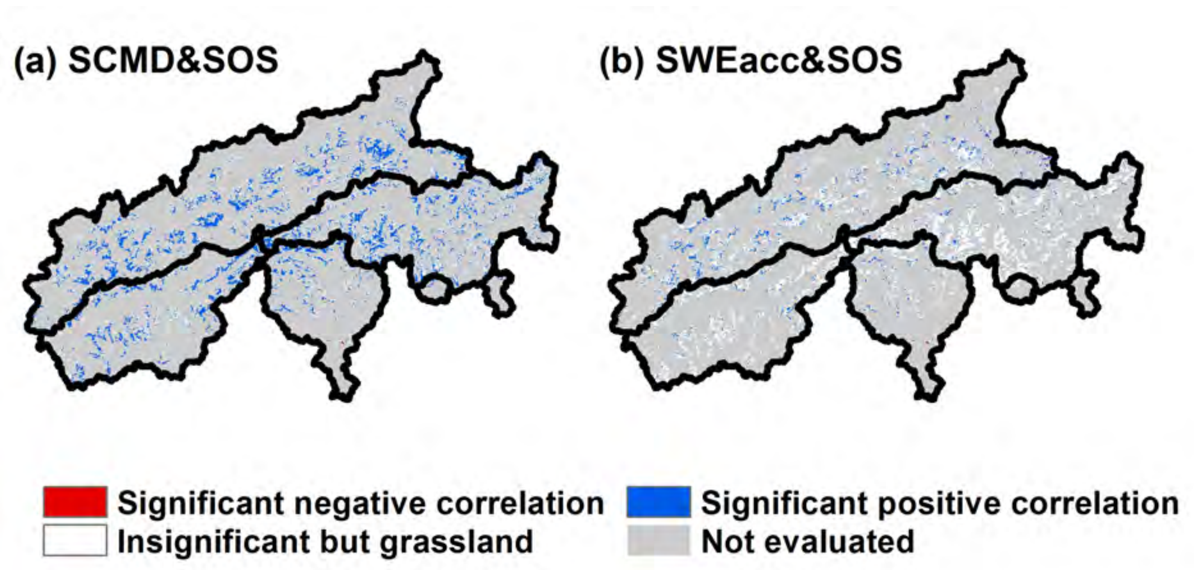

Figure S1.2. Spatial patterns of Spearman's correlation coefficients (*r*) between seasonal snow metrics and SOS (i.e., SCMD & SOS (a), and SWE_{acc} & SOS (b)) across the entire semi-natural grassland area in the Swiss Alps.

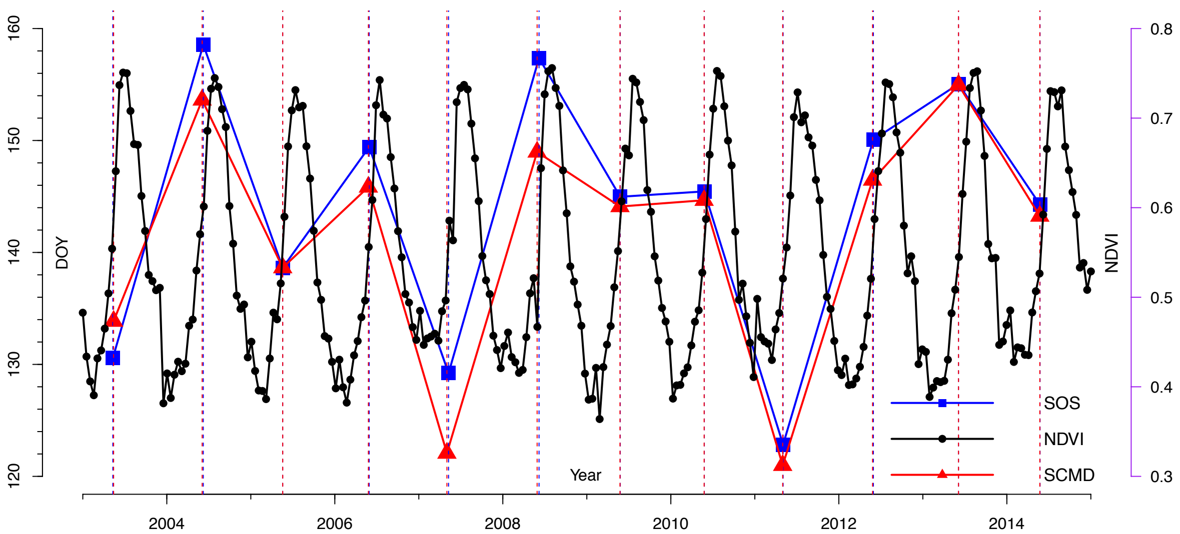

Figure S1.3. Average values of the inter-annual SOS, NDVI, and SCMD in semi-natural grassland for the entire Swiss Alps. The dashed line represents a mean DOY of SOS and SCMD.

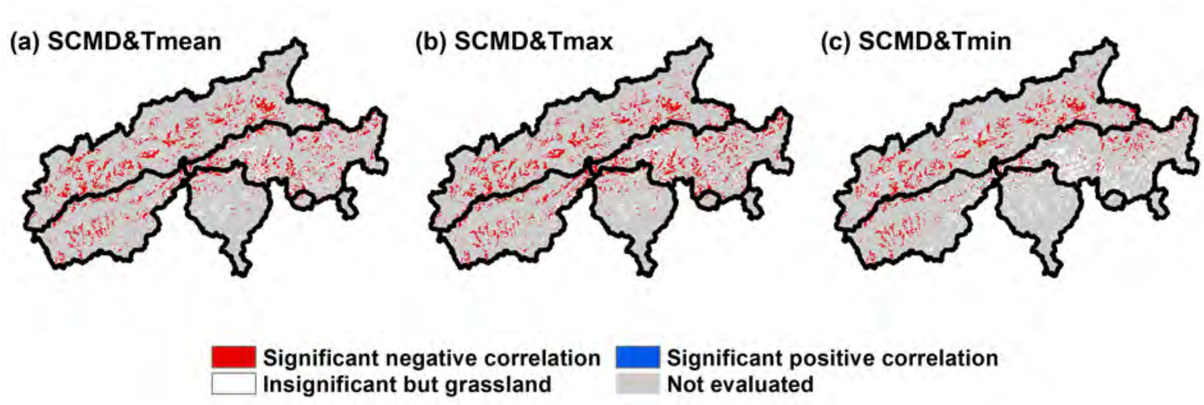

Figure S1.4. Spatial patterns of Spearman's correlation coefficients (r) between spring air temperature and SCMD (i.e., ST_{mean} & SCMD (a), ST_{max} & SCMD (b), and ST_{min} & SCMD (c)) across the entire semi-natural grassland area in the Swiss Alps.

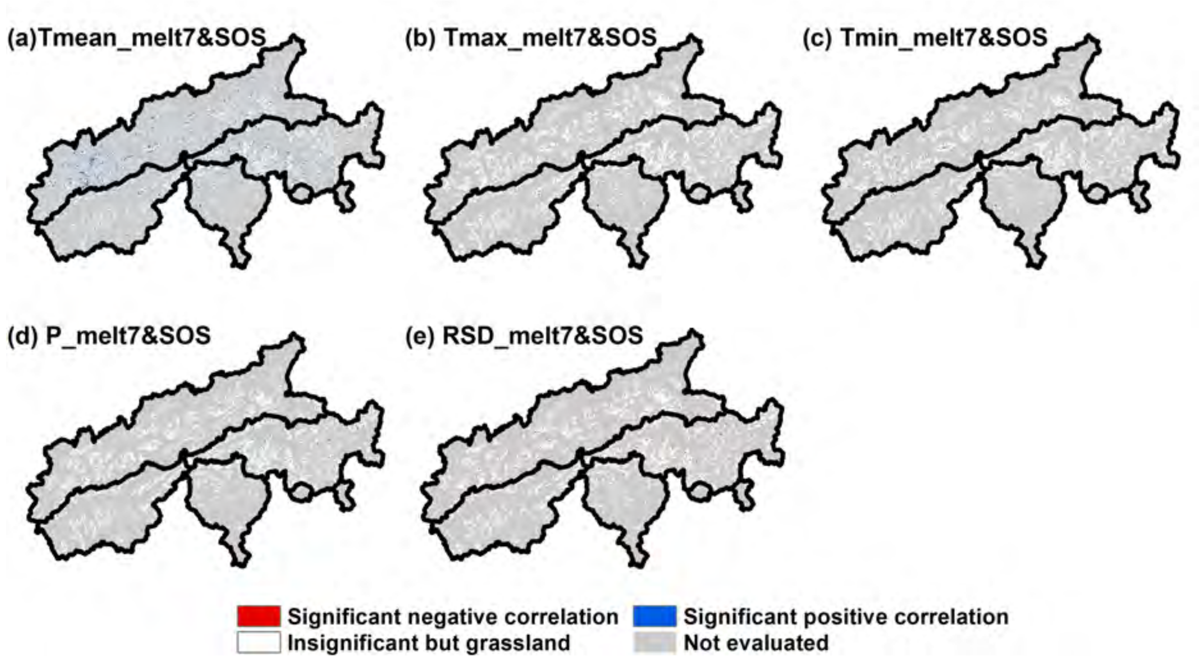

Figure S1.5. Spatial pattern of Spearman's correlation coefficients (r) between spring driving metrics after snow melt and SOS (i.e., T_{mean_melt7} & SOS (a), T_{max_melt7} & SOS (b), T_{min_melt7} & SOS (c), $P_{\_melt7}$ & SOS (d), and $RSD_{\_melt7}$ & SOS (e)) across the entire semi-natural grassland area in the Swiss Alps.

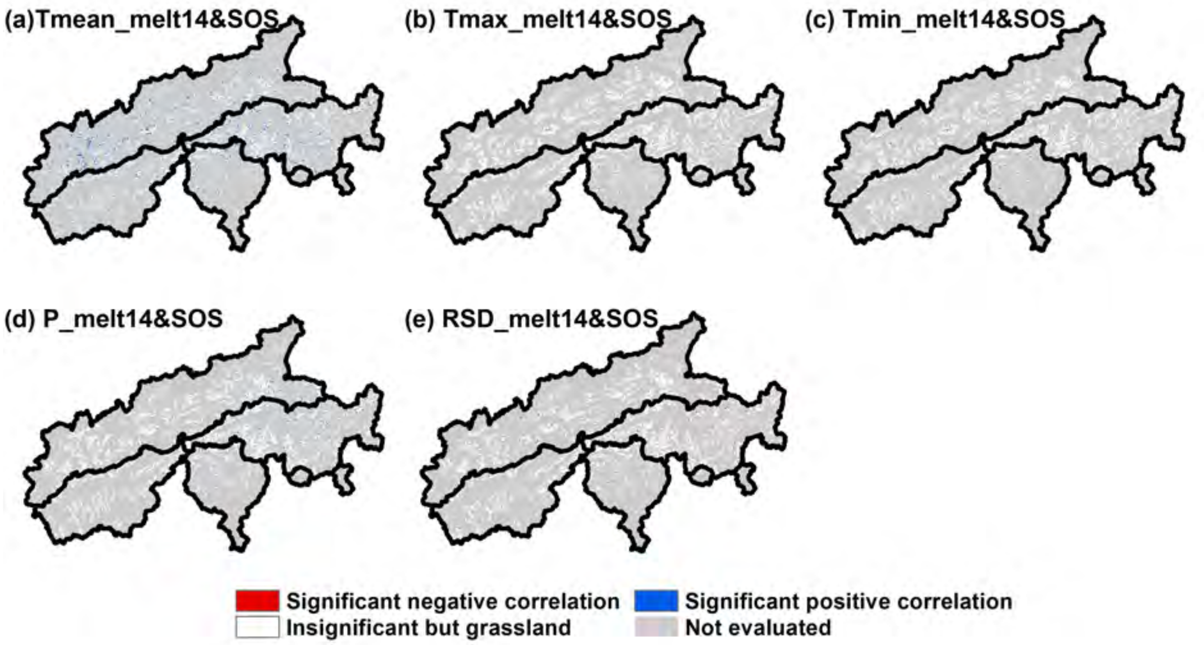

Figure S1.6. Spatial pattern of Spearman's correlation coefficients (*r*) between spring driving metrics after snow melt and SOS (i.e., T_{mean_melt14} & SOS (a), T_{max_melt14} & SOS (b), T_{min_melt14} & SOS (c), $P_{\_melt14}$ & SOS (d), and $RSD_{\_melt14}$ & SOS (e)) across the entire semi-natural grassland area in the Swiss Alps.

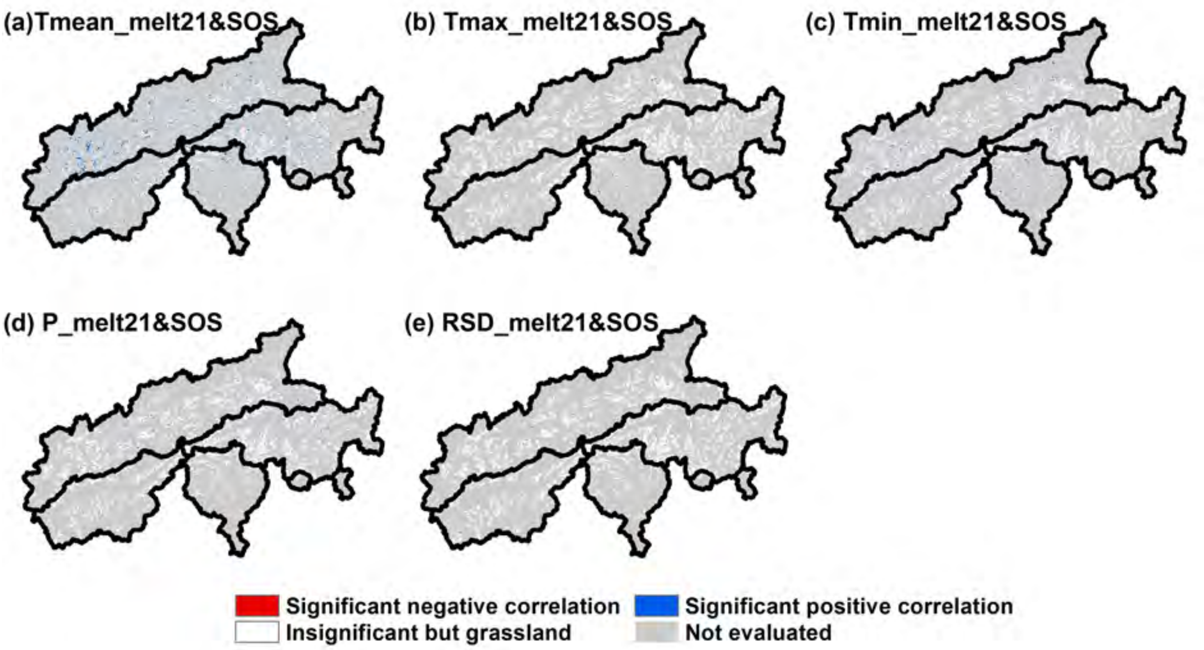

Figure S1.7. Spatial pattern of Spearman's correlation coefficients (*r*) between spring driving metrics after snow melt and SOS (i.e., T_{mean_melt21} & SOS (a), $T_{max\_melt121}$ & SOS (b), T_{min_melt21} & SOS (c), $P_{\_melt21}$ & SOS (d), and $RSD_{\_melt21}$ & SOS (e)) across the entire semi-natural grassland area in the Swiss Alps.

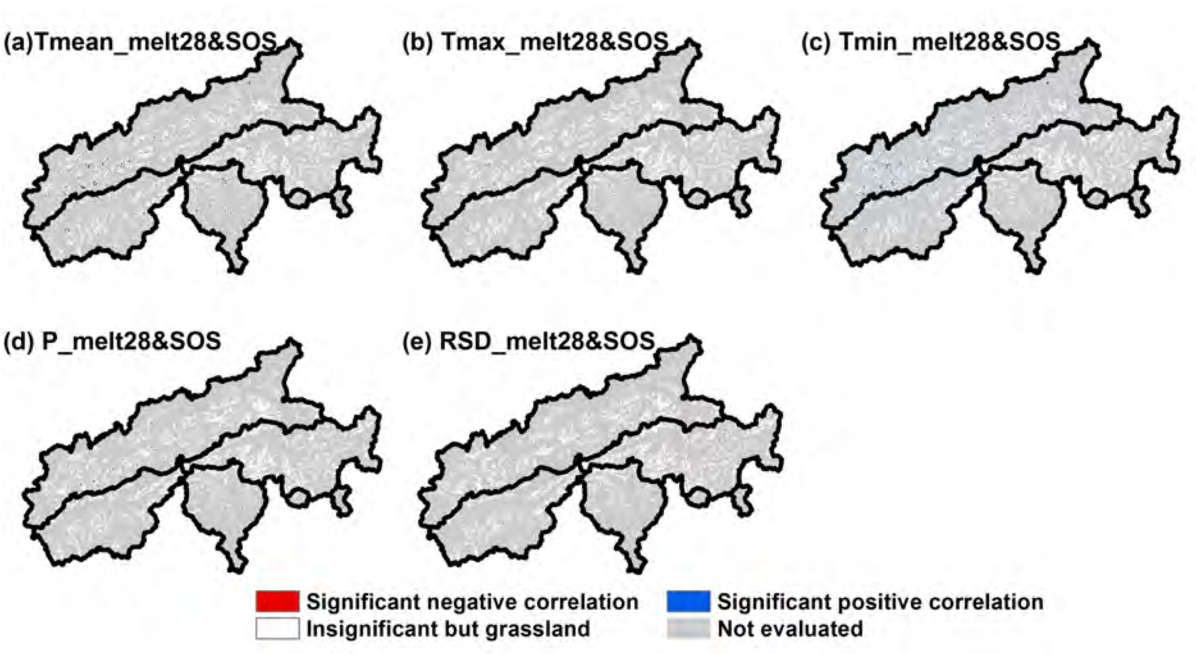

Figure S1.8. Spatial pattern of Spearman's correlation coefficients (*r*) between spring driving metrics after snow melt and SOS (i.e., T_{mean_melt28} & SOS (a), T_{max_melt28} & SOS (b), T_{min_melt28} & SOS (c), $P_{\_melt28}$ & SOS (d), and $RSD_{\_melt28}$ & SOS (e)) across the entire semi-natural grassland area in the Swiss Alps.

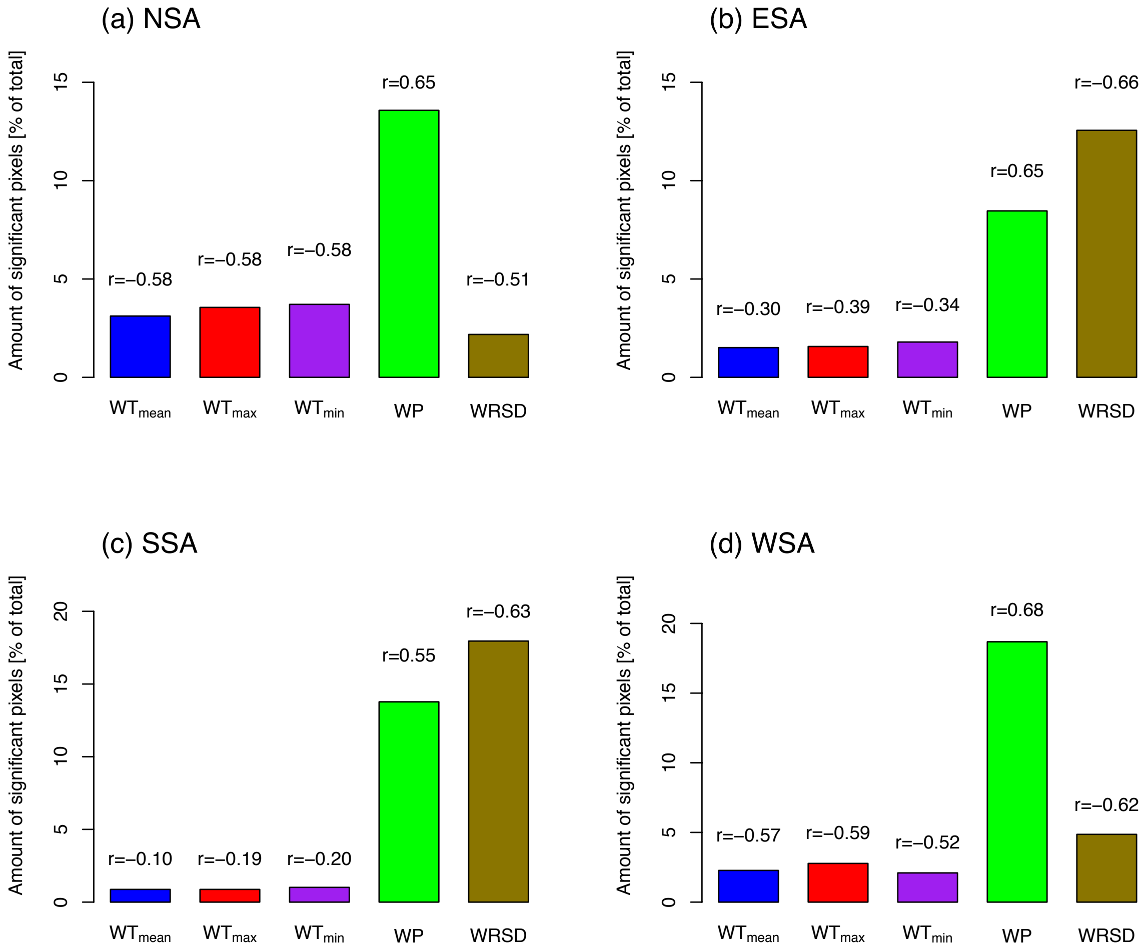

Figure S1.9. Average values of Spearman's correlation coefficients (*r*) between winter driving metrics and SOS (i.e., WT_{mean} & SOS, WT_{max} & SOS, WT_{min} & SOS, WP & SOS and WRSD & SOS) and the corresponding amount of significant pixels [% of total] for the four subregions (NSA (a), ESA (b), SSA (c), WSA (d)).

S2 End of season (EOS)

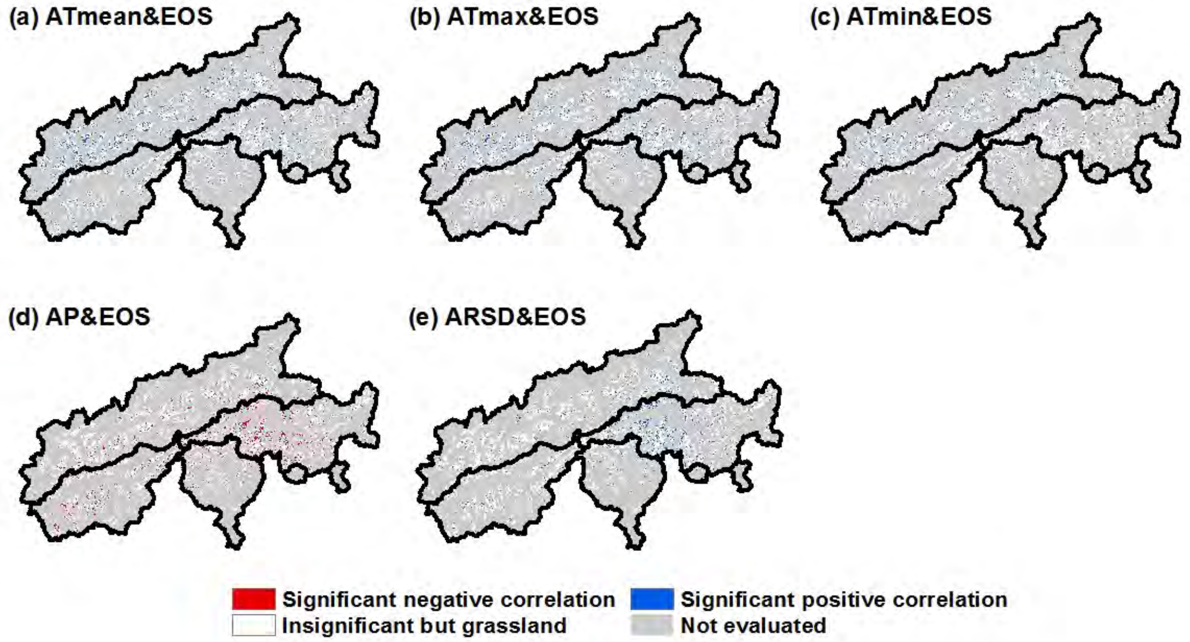

Figure S2.1. Spatial pattern of Spearman's correlation coefficients (r) between autumn driving metrics and EOS (i.e., AT_{mean} & EOS (a), AT_{max} & EOS (b), AT_{min} & EOS (c), AP & EOS (d), and ARSD & EOS (e)) across the entire semi-natural grassland area in the Swiss Alps.

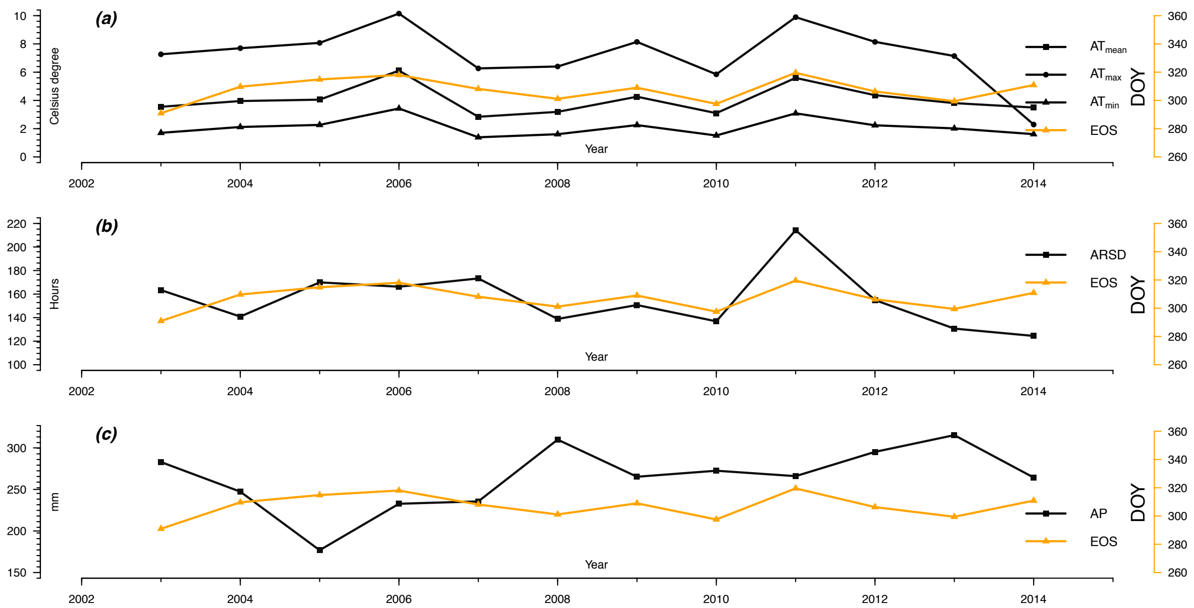

Figure S2.2. Average values of the inter-annual AT_{mean}, AT_{max}, AT_{min}, AP, ARSD, and EOS for the semi-natural grassland in the entire Swiss Alps.

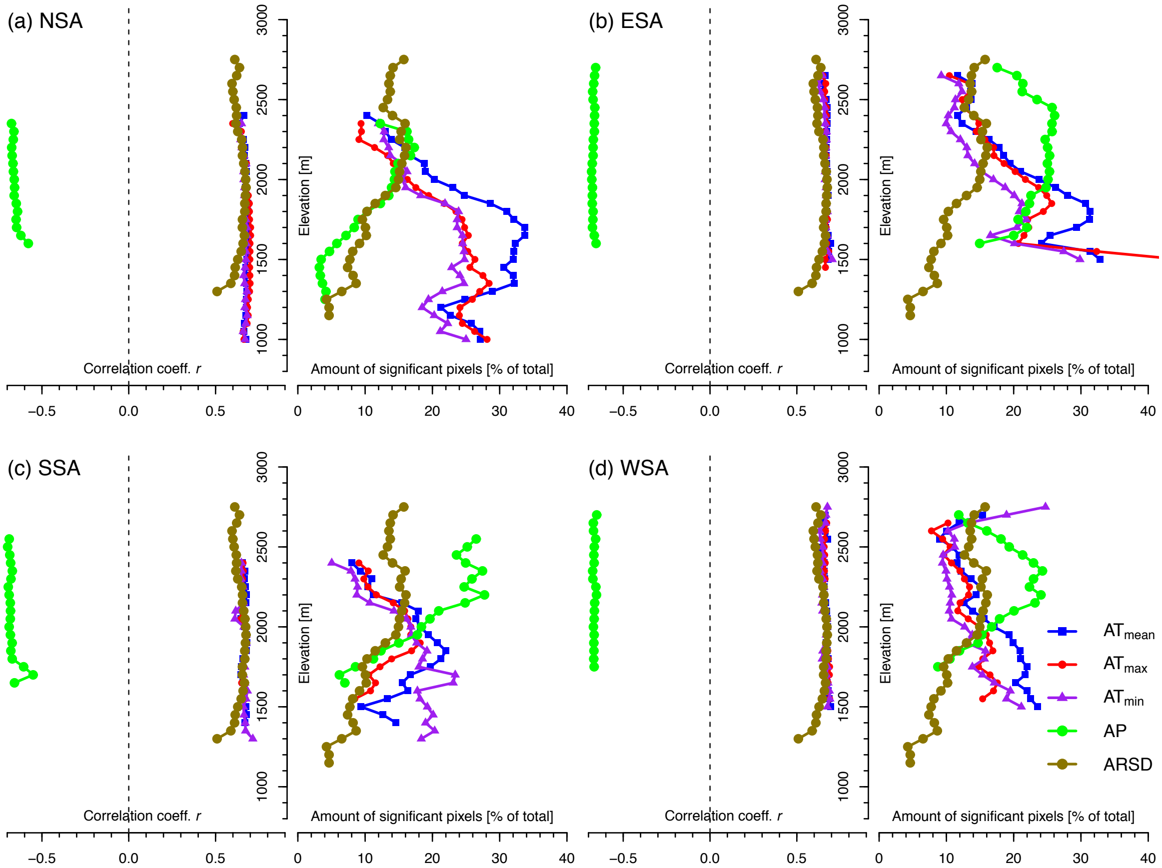

Figure S2.3. Elevational variation of mean Spearman's correlation coefficients (*r*) between autumn driving metrics and EOS (i.e., AT_{mean} & EOS, AT_{max} & EOS, AT_{min} & EOS, AP & EOS and ARSD & EOS) and the corresponding amount of significant pixels [% of total] for the four subregions (NSA (a), ESA (b), SSA (c), WSA (d)). The dashed grey line represents a mean correlation coefficient of 0.

S3 Greenness greenness

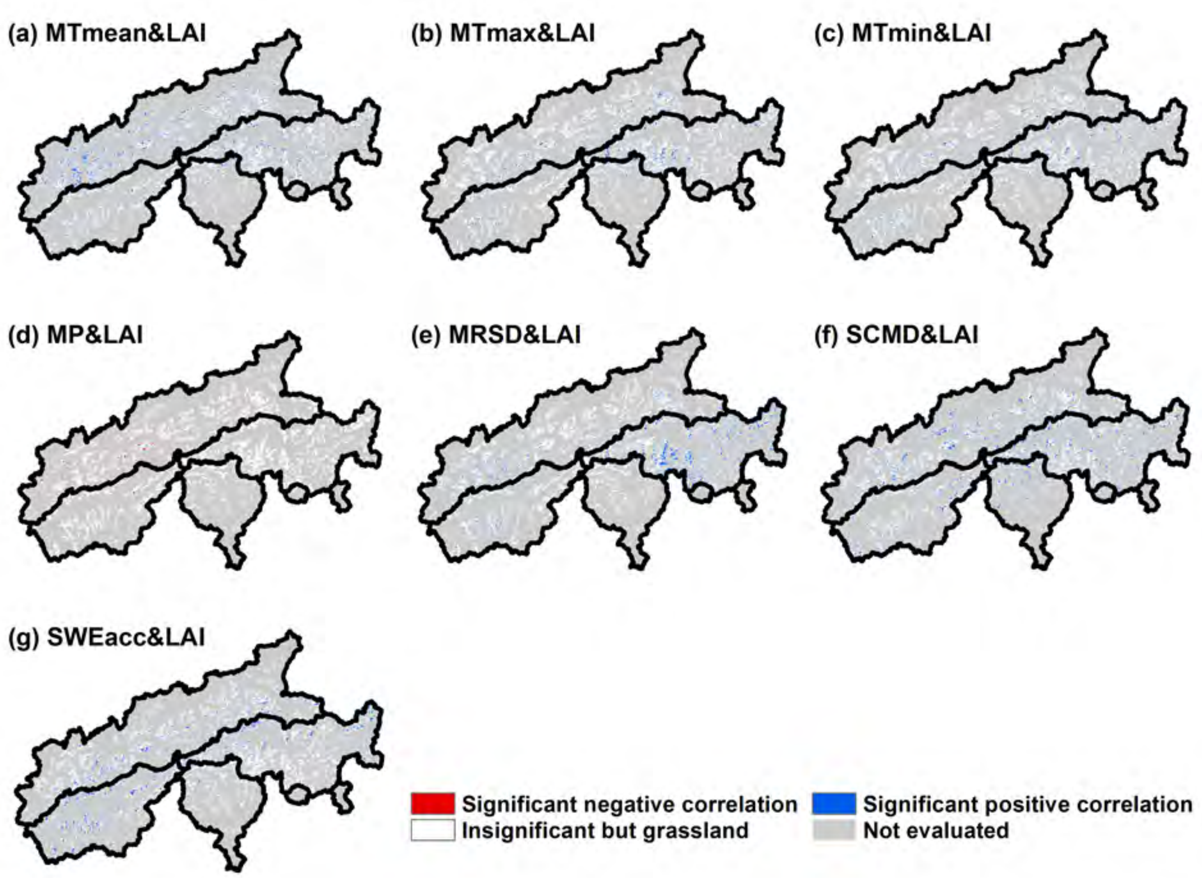

Figure S3.1. Spatial pattern of Spearman's correlation coefficients (*r*) between seasonal snow and summer driving metrics and LAI_{mean} (i.e., MT_{mean} & LAI_{mean} (a), MT_{max} & LAI_{mean} (b), MT_{min} & LAI_{mean} (c), MP & LAI (d), MRSD & LAI_{mean} (e), SCMD & LAI_{mean} (f), and SWE_{acc} & LAI_{mean} (g)) across the entire semi-natural grassland area in the Swiss Alps.

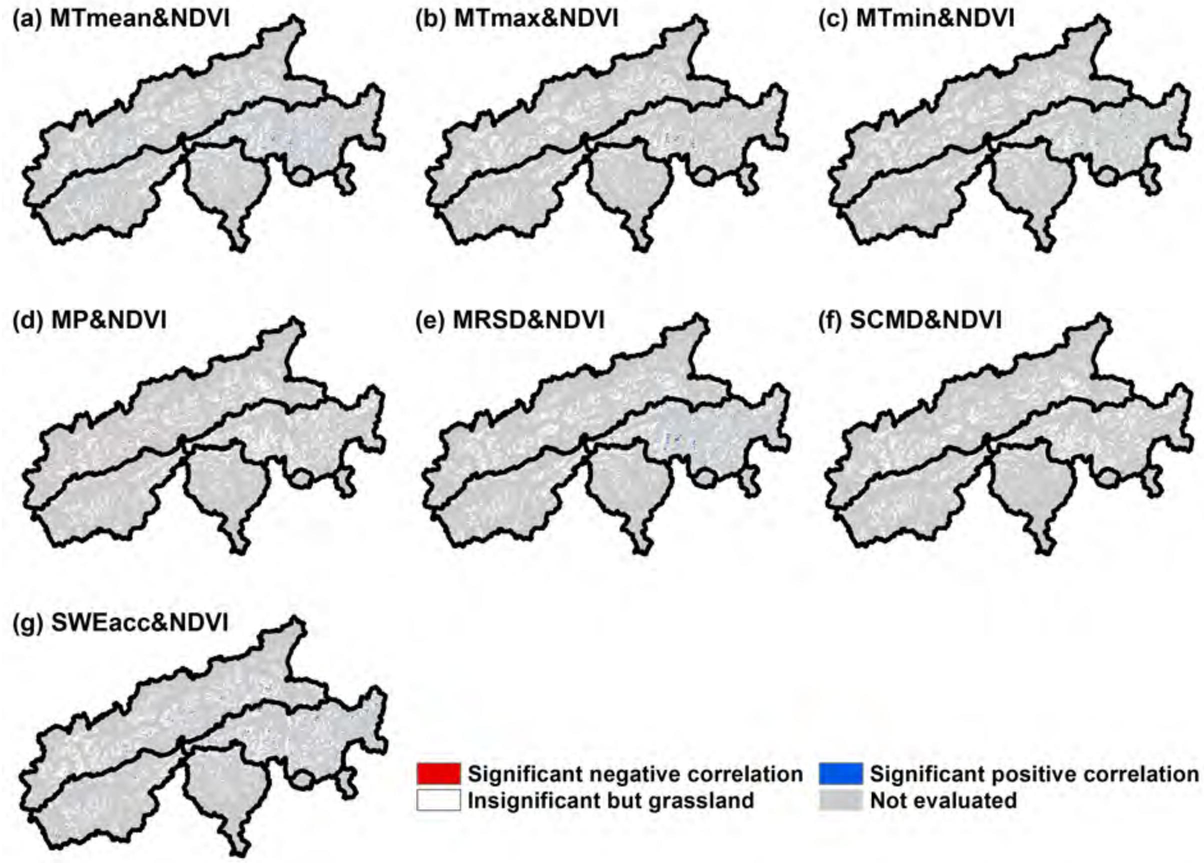

Figure S3.2. Spatial pattern of Spearman's correlation coefficients (*r*) between seasonal snow and summer driving metrics and $NDVI_{mean}$ (i.e., MT_{mean} & $NDVI_{mean}$ (a), MT_{max} & $NDVI_{mean}$ (b), MT_{min} & $NDVI_{mean}$ (c), MP & $NDVI_{mean}$ (d), MRSD & $NDVI_{mean}$ (e), SCMD & $NDVI_{mean}$ (f), and SWE_{acc} & $NDVI_{mean}$ (g)) across the entire semi-natural grassland area in the Swiss Alps.

Besides using mean NDVI values, we also computed the integrated NDVI (integrated NDVI $=\int_{SOS}^{EOS} NDVI(t)dt$, t is day of year) of the growing season between SOS and EOS. However, the integrated NDVI values did not show improved association with driving metrics. Besides, the integrated NDVI values and the mean NDVI values are highly correlated with each other.

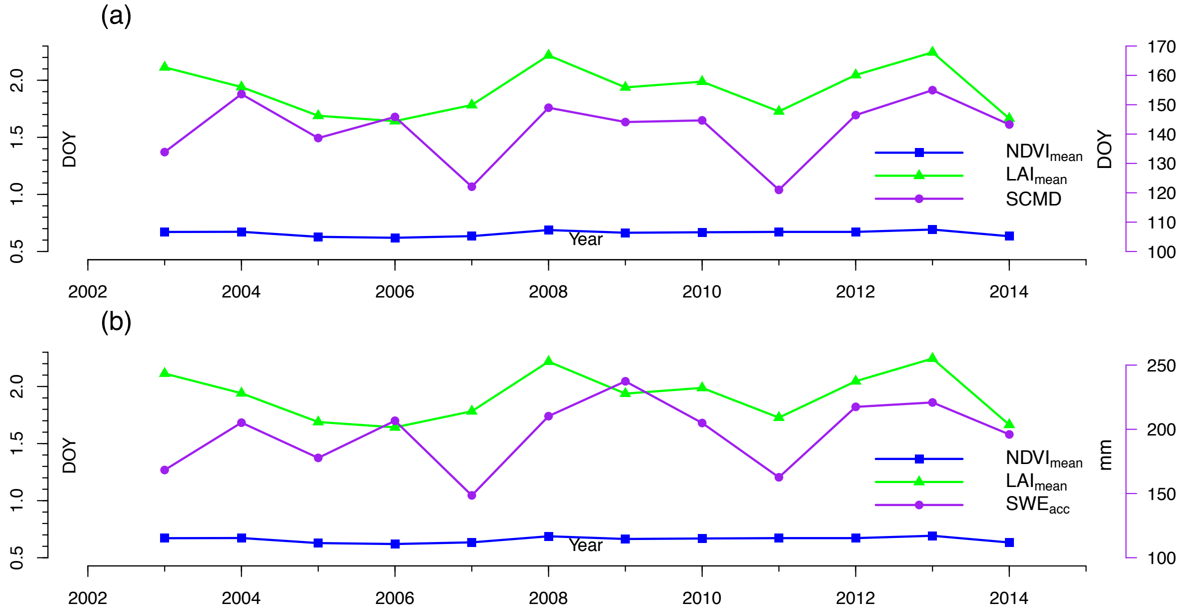

Figure S3.3. Average values of the inter-annual $NDVI_{mean}$, LAI_{max}, SCMD, and SWE_{acc} for the entire semi-natural grassland area in the Swiss Alps.

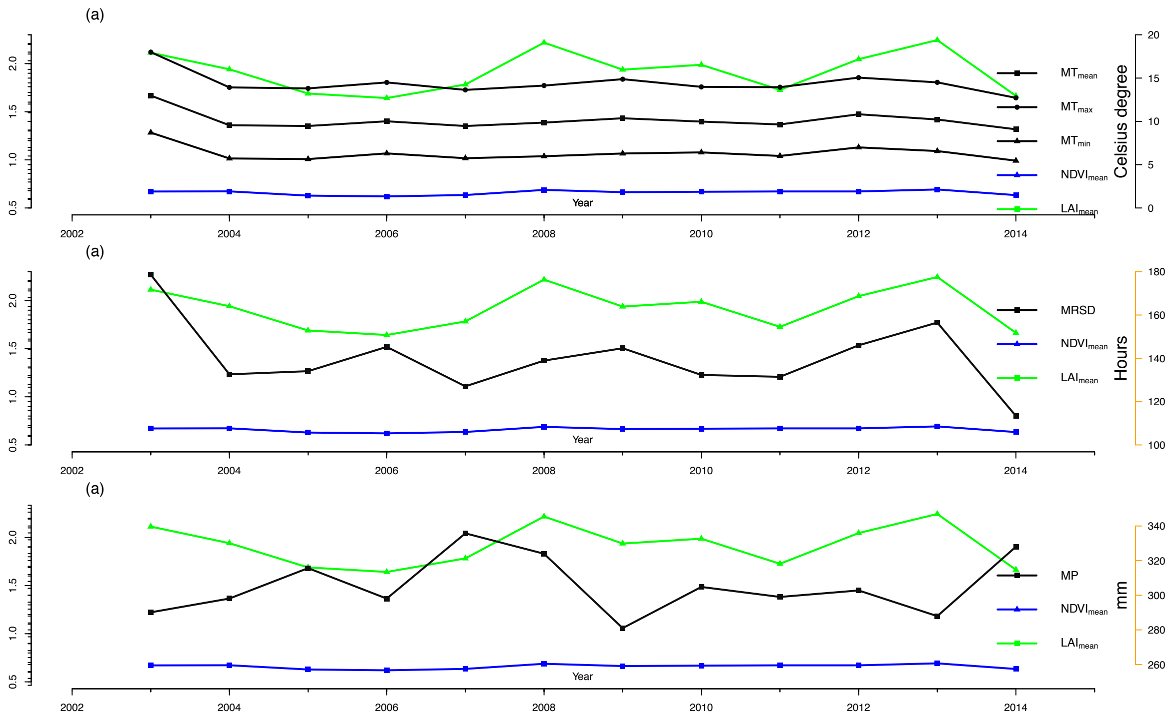

Figure S3.4. Average values of the inter-annual $NDVI_{mean}$, LAI_{max}, MT_{mean}, MT_{max}, MT_{min}, MP, MRSD and SWE_{acc} for the entire semi-natural grassland area in the Swiss Alps.

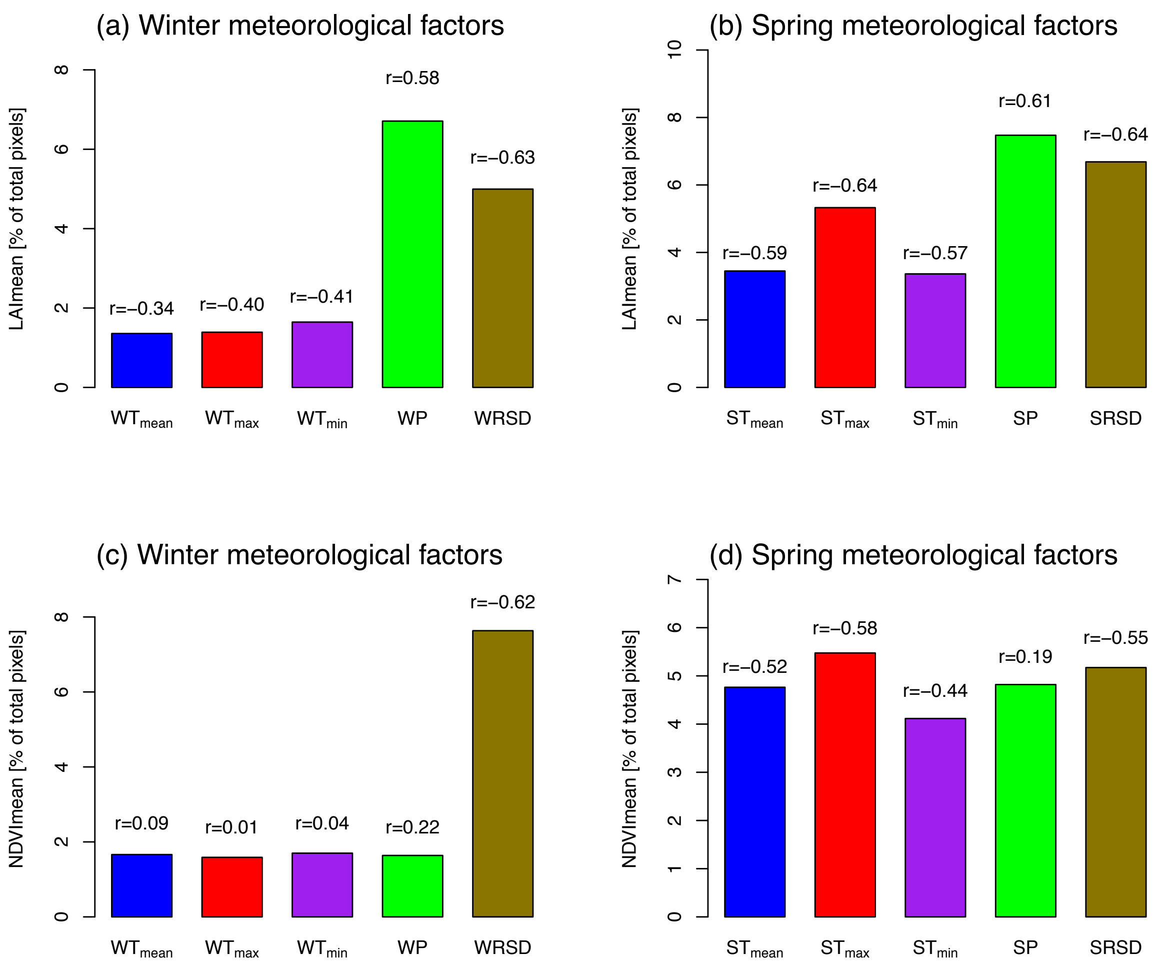

Figure S3.5. Mean Spearman's correlation coefficients (*r*) between winter (a and c) and spring (b and d) meteorological factors and greenness metrics (i.e., WT_{mean} & LAI_{mean}, WT_{max} & LAI_{mean}, WT_{min} & LAI_{mean}, WP & LAI_{mean} and WRSD & LAI_{mean}; ST_{mean} & LAI_{mean}, ST_{max} & LAI_{mean}, ST_{min} & LAI_{mean}, SP & LAI_{mean} and SRSD & LAI_{mean}; WT_{mean} & $NDVI_{mean}$, WT_{max} & $NDVI_{mean}$, WT_{min} & $NDVI_{mean}$, WP & $NDVI_{mean}$ and WRSD & $NDVI_{mean}$; ST_{mean} & $NDVI_{mean}$, ST_{max} & $NDVI_{mean}$, ST_{min} & $NDVI_{mean}$, SP & $NDVI_{mean}$ and SRSD & $NDVI_{mean}$) and the corresponding amount of significant pixels [% of total] for the entire semi-natural grassland area in the Swiss Alps.

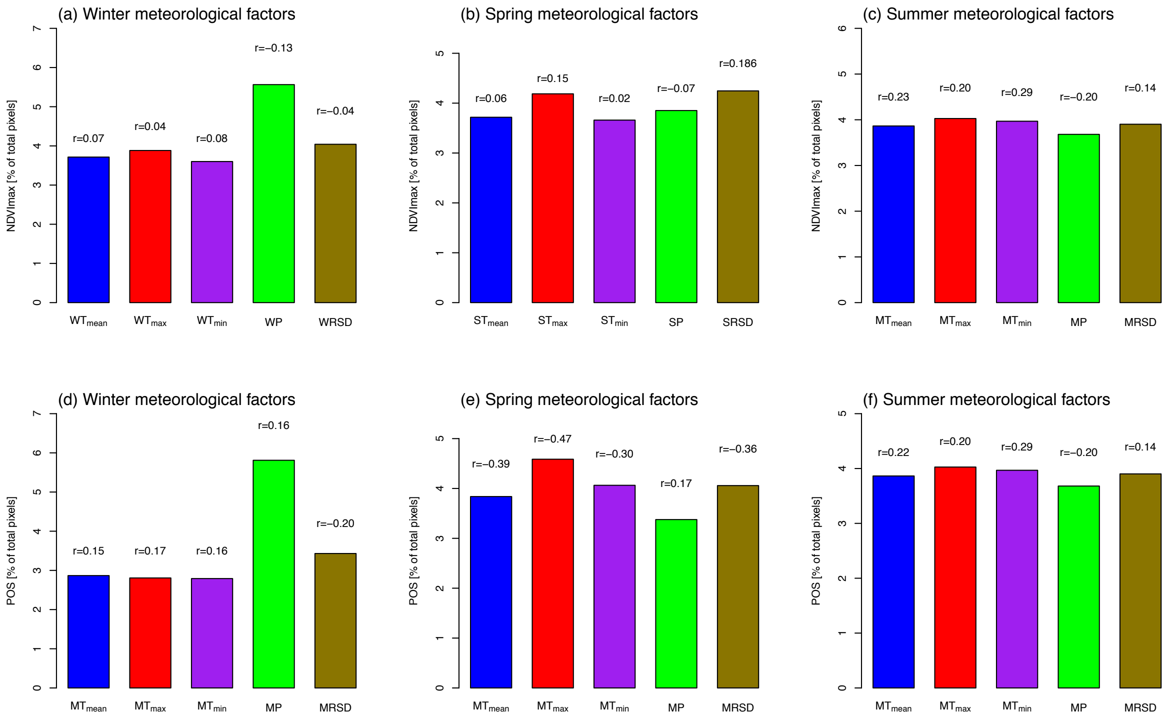

Figure S3.6. Mean Spearman's correlation coefficients (*r*) between winter (a and d), spring (b and e) and summer (c and f) meteorological factors and greenness metrics (i.e., WT_{mean} & $NDVI_{max}$, WT_{max} & $NDVI_{max}$, WT_{min} & $NDVI_{max}$, WP & $NDVI_{max}$, and WRSD & $NDVI_{max}$; ST_{mean} & $NDVI_{max}$, ST_{max} & $NDVI_{max}$, ST_{min} & $NDVI_{max}$, SP & $NDVI_{max}$, and SRSD & $NDVI_{max}$; MT_{mean} & $NDVI_{max}$, MT_{max} & $NDVI_{max}$, MT_{min} & $NDVI_{max}$, MP & $NDVI_{max}$, and MRSD & $NDVI_{max}$) and POS (WT_{mean} & POS, WT_{max} & POS, WT_{min} & POS, WP & POS, and WRSD & POS; ST_{mean} & POS, ST_{max} & POS, ST_{min} & POS, SP & POS, and SRSD & POS; MT_{mean} & POS, MT_{max} & POS, MT_{min} & POS, MP & POS, and MRSD & POS) and the corresponding amount of significant pixels [% of total] for the entire semi-natural grassland area in the Swiss Alps.

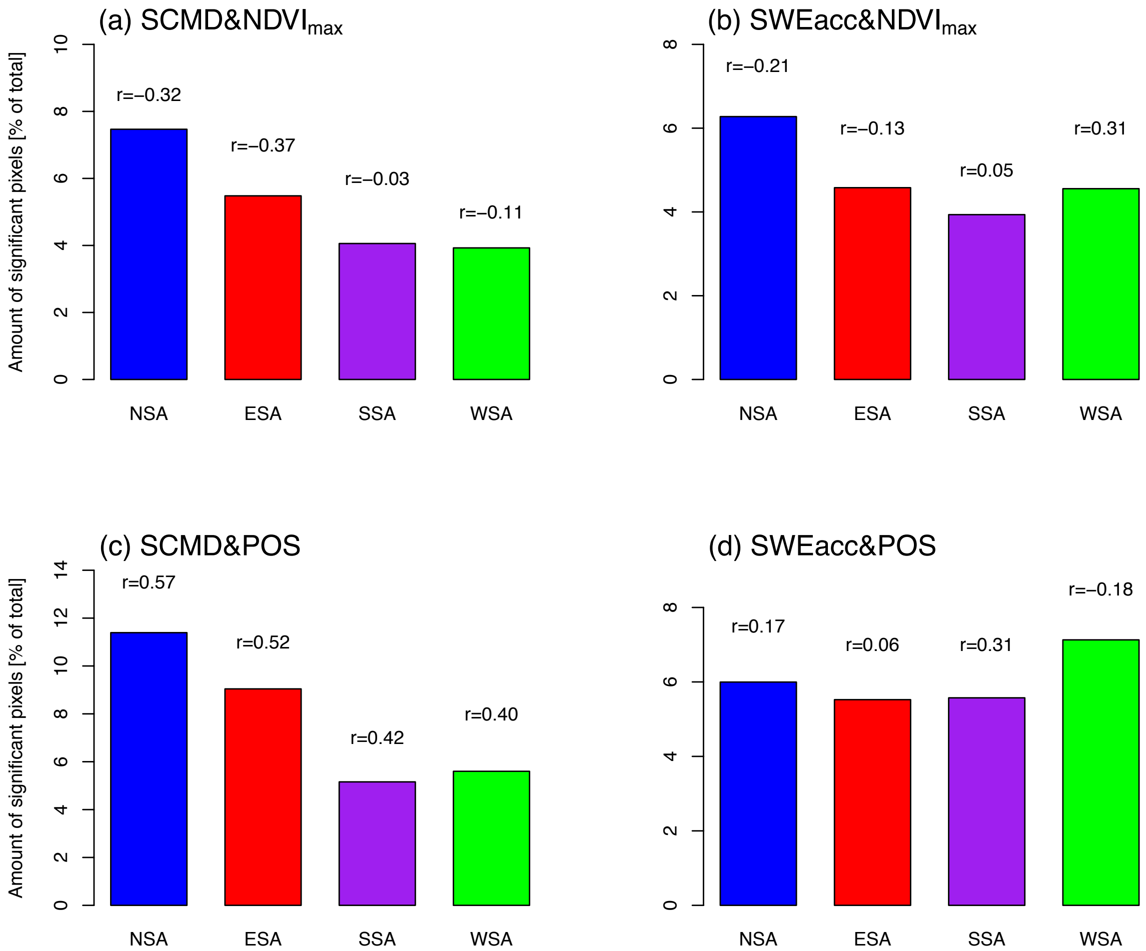

Figure S3.7. Mean Spearman's correlation coefficients (*r*) between snow driving metrics and peak greenness metrics (i.e., $NDVI_{max}$ & SCMD (a), $NDVI_{max}$ & SWE_{acc} (b), POS & SCMD (b), and POS & SWE_{acc} (d)) and the corresponding amount of significant pixels [% of total] for the entire study area.

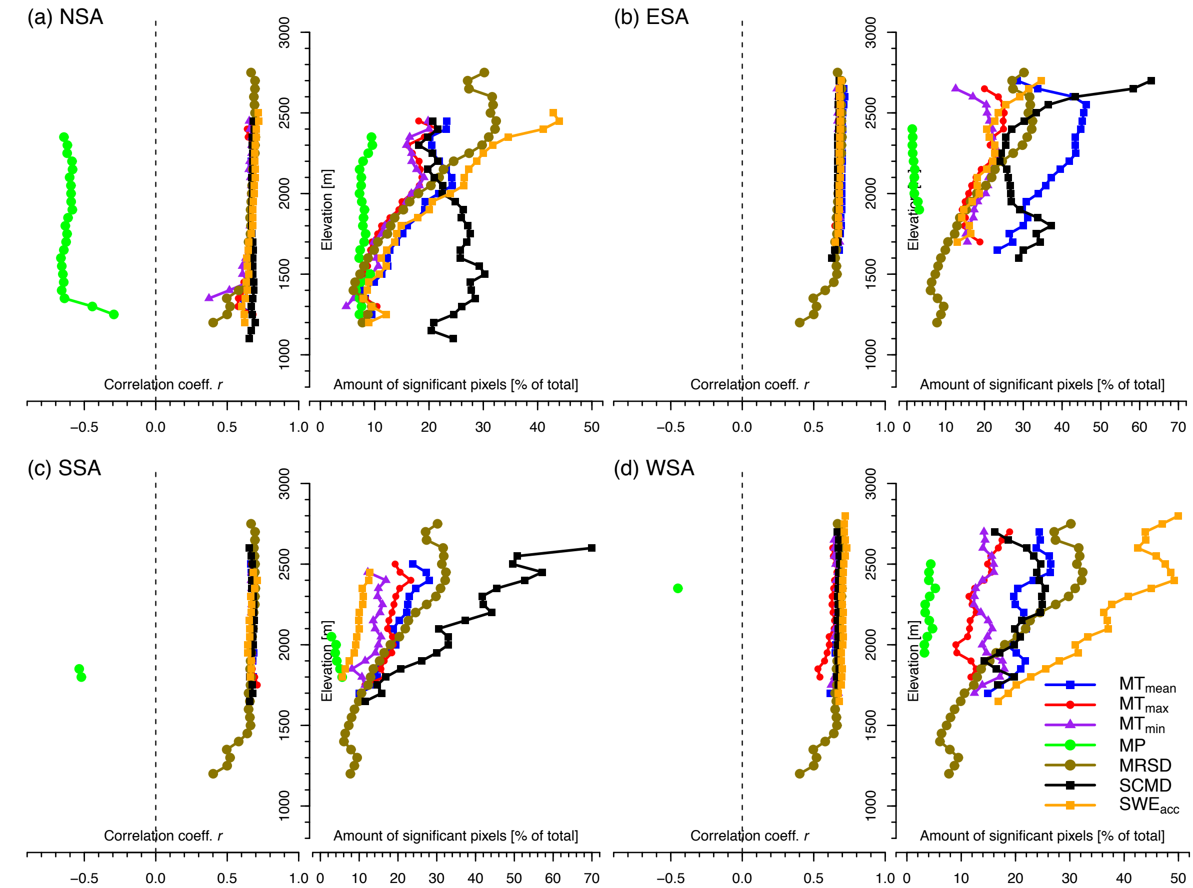

Figure S3.8. Elevational variation of mean Spearman's correlation coefficients (*r*) (left panel) between snow metrics and greenness (i.e., MT_{mean} & LAI_{mean}, MT_{max} & LAI_{mean}, MT_{min} & LAI_{mean}, MP & LAI_{mean}, MRSD & LAI_{mean}, SCMD & LAI_{mean} and SWE_{acc} & LAI_{mean}), and the corresponding amount of significant pixels [% of total] (right panel) for the four subregions (NSA (a), ESA (b), SSA (c), WSA (d)). The dashed grey line represents a mean correlation coefficient of 0.

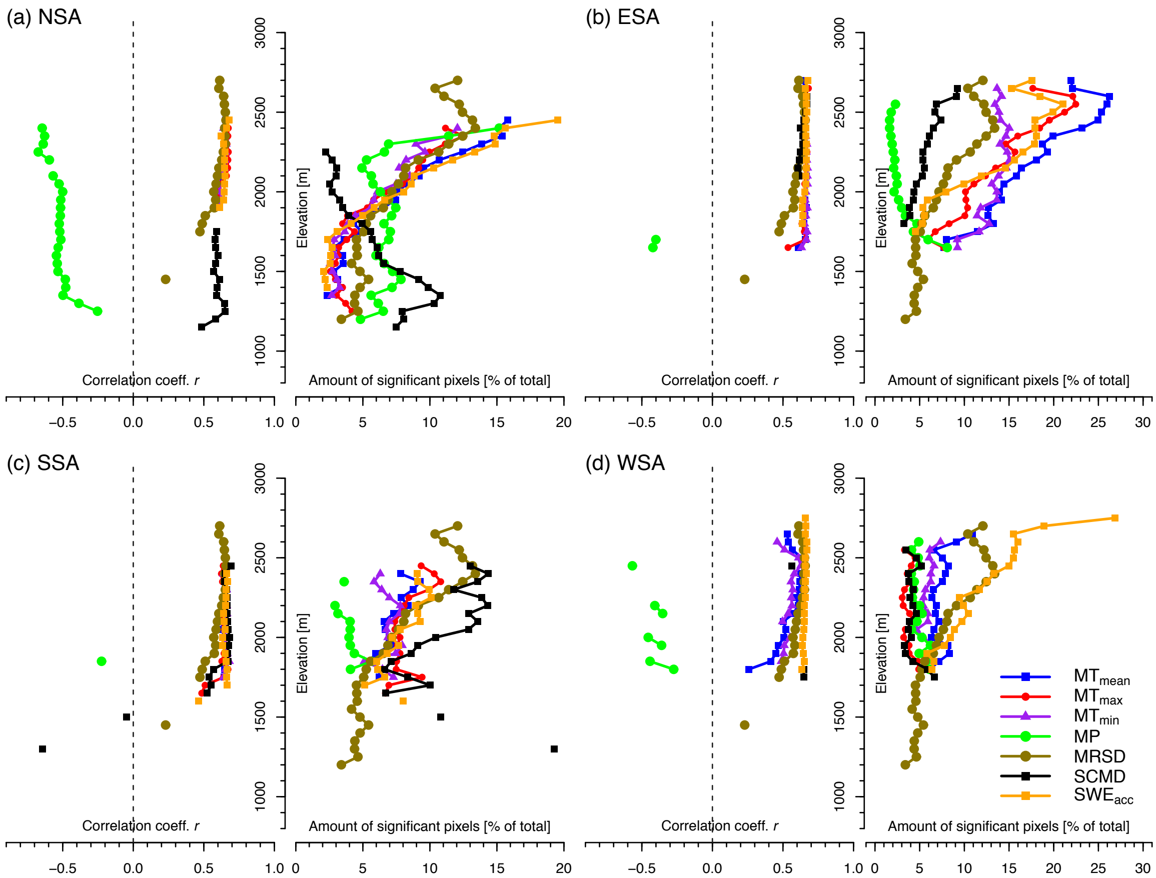

Figure S3.9. Elevational variation of mean Spearman's correlation coefficients (*r*) (left panel) between snow metrics and greenness (i.e., MT_{mean} & $NDVI_{mean}$, MT_{max} & $NDVI_{mean}$, MT_{min} & $NDVI_{mean}$, MP & $NDVI_{mean}$, MRSD & $NDVI_{mean}$, SCMD & $NDVI_{mean}$ and SWE_{acc} & $NDVI_{mean}$), and the corresponding amount of significant pixels [% of total] (right panel) for the four subregions (NSA (a), ESA (b), SSA (c), WSA (d)). The dashed grey line represents a mean correlation coefficient of 0.

Chapter 5

Synthesis

5.1 Main findings

The research field of mapping of snow cover phenology, snow accumulation, land surface phenology, and vegetation greenness and tracking of their spatiotemporal variations using remote sensing has developed rapidly in the alpine areas over the past decade. In particular, time-series optical remote sensing data plays a crucial role as a tool to implement spatially explicit seasonal snow and alpine vegetation phenology and greenness mapping and monitoring approaches.

This thesis (i) maps 250-m resolution snow cover phenology, snow accumulation, and land surface phenology, and tests the elevation-dependent relationships between snow cover phenology and land surface phenology of nature-vegetated areas for the entire European Alps, (ii) analyzes the elevation-dependent relative contributions of snow cover phenology and snow accumulation to land surface phenology of naturally-vegetated areas at landscape scale for the entire Swiss Alps, and (iii) identifies the influence of seasonal snow and meteorological factors on the land surface phenology and greenness in alpine grassland for the entire Swiss Alps.

The previous Chapters addressed the five Research Questions (RQs) formulated in Chapter 1. In this Chapter these RQs are discussed together with the five hypotheses.

5.1.1 How can time-series remote sensing be used to map Alpine land surface phenology and greenness metrics, as well as snow cover phenology and snow accumulation?

Remote sensing is one of the most widely used methods for the monitoring of vegetation phenological events at local and global scales (Cleland *et al*. 2007; Fisher *et al*. 2006; Garonna *et al*. 2016; Garonna *et al*. 2018; Piao *et al*. 2006). Chapter 2 adapts an approach (i.e., the Midpoint-pixel method (White *et al*. 2009)) to calculate the start of season and end of season using time-series optical remote sensing data. Based on the coarse optical remote sensing data practice in land surface phenology modeling at large scale (Garonna *et al*. 2014; Garonna *et al.* 2016; White *et al*. 2009), this thesis applied higher resolution time-series remote sensing data (i.e., MODIS13Q1) presenting guidelines for adapting the existing novel method across alpine regions with complex topography. It suggests mapping snow and vegetation metrics and analyzing snow-vegetation relationships directly using optical RS data.

Many studies have already used time-series remote sensing data to map and analyze alpine vegetation phenology and productivity (Julien and Sobrino 2009; Marshall *et al*. 2016; Verhegghen *et al*. 2014; White *et al*. 2009). However, these works were often only based on coarse- or mid-resolution remote sensing data or limited in analysis of a land cover and regional level (Badeck *et al*. 2004; Dong *et al*. 2015; Melaas *et al*. 2016; Prentice *et al*. 2005; Stueve *et al*. 2011; Zheng *et al*. 2015). There is still a lack of higher spatial resolution land surface phenology and greenness metrics and their relationships with seasonal snow and meteorological factors across elevation in the alpine regions (Xie *et al*. 2018; Xie *et al*. 2017).

The spatial variability in snow cover phenology (Chapter 2), land surface phenology (Chapter 2), mean snow water equivalent (Chapter 3), snow accumulation (Chapter 4), mean normalized difference vegetation index during growing season, maximum normalized difference vegetation index, and mean leaf area index during growing season (Chapter 4), and various meteorological metrics (Chapter 4) were detected across elevations and for subregions at the landscape scale using satellite-derived data and gridded data.

5.1.2 What are the spatial variation and temporal trends of land surface phenology and greenness, as well as snow cover phenology and snow accumulation, across the European Alps over 2003-2014?

Changes of land surface phenology and greenness, as well as snow cover phenology and snow accumulation, can occur for the different subregions. In chapter 2, results indicate that snow cover phenology metrics (i.e., first snow fall, last snow day, and snow cover duration) vary considerably between the four subregions (north-west, north-east, south-west and south-east subregion) of the European Alps. The snow cover duration in the south-west subregion is lower than in the north-east regions, and regional differences in snow cover duration disappear at higher elevations. These regional differences of snow cover duration are presumably due to different climatic influences, such as a stronger dependency of snow cover on precipitation at higher altitudes, and a higher sensitivity of snow cover to temperature in lower regions (Hüsler *et al*. 2014). Results show earlier first snow fall and later last snow day in regions with longer snow cover duration in the northern Alps (with more precipitation in winter) and at high elevations (with lower freezing temperature in winter) over the past decade. Land surface phenology (i.e., start of season, end of season, and length of season) shows a regular distribution with coupling to snow cover phenology across the European Alps. Namely, a later start of season, an earlier end of season and a shorter length of season often occur in climatic subregions with longer snow cover duration, and vice versa. Additionally, in chapters 3 and 4, it was found that mean snow water equivalent, snow accumulation, and snow cover melt day present a significant difference between the subregions in the Swiss Alps. Specifically, more mean snow water equivalent and snow accumulation, or later snow cover melt day, are observed in northeast regions and high elevations in the Swiss Alps.

Changes of land surface phenology and greenness metrics, as well as snow cover phenology and snow accumulation, vary with elevations. Snow cover phenology and land surface phenology metrics both showed significant relationship with elevations. Snow cover duration increases with elevation. Land surface phenology strongly depends on elevation across the entire European Alps, except for some forest-dominated low elevations. In chapters 3 and 4, it was also found that mean snow water equivalent, snow accumulation and snow cover melt day present significant variation depending on elevation in the Swiss Alps. These findings are in line with previous reports presenting the variation in the snow timing and accumulation with elevation in mountainous regions (Bormann *et al*. 2012; Hüsler *et al*. 2014). The elevational variation of land surface phenology confirms the dependency of phenological events on elevation in mountainous areas (Cornelius *et al*. 2013; Gottfried *et al*. 2012; Hwang *et al*. 2011a; Richardson *et al*. 2006a).

In chapter 3, the results present a significant positive correlation between snow cover duration and mean snow water equivalent across elevations in the Swiss Alps. This finding is in agreement with previous studies that showed snow cover being correlated with snow accumulation metrics such as snow depth and snow water equivalent (Metsämäki *et al*. 2012; Yu *et al*. 2013). However, the lack of significant correlations between snow cover duration and last snow day, and between last snow day and mean snow water equivalent, may be due to the fact that snow cover duration is closely linked to last snow day only in alpine regions with continuous snow cover (Bormann *et al*. 2012; Dedieu *et al*. 2014; Hüsler *et al*. 2014). This findings is in contrast to a study performed in the Sierra Nevada Mountains (Trujillo *et al*. 2012), where a strong correlation of snow disappear day with maximum snow water equivalent is reported, albeit under different climatic conditions than in our study area. Snow cover duration is closely linked to last snow day only in alpine regions with continuous snow cover (Bormann *et al*. 2012; Dedieu *et al*. 2014; Hüsler *et al*. 2014). These findings may further indicate that snow cover duration and mean snow water equivalent have no significant correlation with the multiple late season transient snow patterns and snowfall during snowmelt seasons in the study area.

Further to this, changes of land surface phenology and greenness, as well as snow cover phenology and snow accumulation, can occur at inter-annual time scales. In Chapter 2, no significant trend in snow cover phenology and land surface phenology metrics between 2003 and 2014 was found. In Chapter 3 and 4, there was no significant trend in mean snow water equivalent of the snow cover duration, snow cover melt day, mean snow water equivalent from January to April and greenness metrics (i.e., max normalized difference vegetation index, mean normalized difference vegetation index during growing season, and mean leaf area index during growing season) during 2003-2014. This was also the case for seasonal snow variation in previous studies over the period 1990-2011 (Hüsler *et al*. 2014; Marty 2008). However, this thesis' finding is in disagreement with Defila and Clot (2005) who reported significant trends of phenology metrics over the study region in recent decades, although they considered much longer time extents (50 years). This may be due to the fact that the strength and direction of a trend can strongly depend on the time periods considered (Marty *et al*. 2017).

5.1.3 What are the effects of seasonal snow and climatological drivers of change on alpine land surface phenology and greenness in the Alps?

This study examined how the spatiotemporal variability of snow cover and snow accumulation correlates with alpine land surface phenology and greening.

In Chapter 2, based on the analysis of 250-m satellite-derived snow cover phenology and land surface phenology in the European Alps, findings support hypothesis I: that the influence of snow cover phenology on alpine land surface phenology is different between climatic subregions, natural vegetation types and terrain aspects with varying elevations. In particular, it was found that snow cover duration plays a key role in the start and length of the growing season in mid and high elevations across the European Alps. These results are in line with previous studies that demonstrated that prolonged snow cover duration results in a delayed and reduced growing season (Cooper *et al*. 2011; Jonas *et al*. 2008; Julitta *et al*. 2014), whereas a shortened snow cover duration mostly advances and prolongs plant growing period (Galvagno *et al*. 2013; Wipf and Rixen 2010; Wipf *et al*. 2009). It was demonstrated that a change in snow cover duration has a greater impact on alpine land surface phenology at higher than at lower elevations, which may be due to a coupled influence of snow cover duration with underground conditions and air temperature. Alpine land surface phenology will react to changes in snow cover duration with the predicted increase of global temperatures, which influences and reshapes the alpine ecosystem. The magnitude of these responses will differ depending on vegetation types, climatic subregions and topographical factors such as elevation and terrain aspect, but will be more pronounced in regions with longer snow cover duration and in higher elevations. Moreover, although temperature strongly regulates the start of the growing season of both temperate deciduous broad-leaf and coniferous forest (Yu *et al*. 2013), the thesis' results consequently support the suggestion that phenological events of most temperate tree species are not solely driven by air temperature (Yu *et al*. 2013), but also by snow cover duration.

In Chapter 3, this study used a novel 250-m satellite-derived snow cover phenology and mountainous land surface phenology and 1-km modelling-derived mean snow water equivalent of the Swiss Alps (2003-2014). The results show that the variations in snow cover duration, last snow day and mean snow water equivalent explained 71.0% of the inter-annual changes in start of season of 21.5% natural vegetation pixels, and 70.0% in length of season of 14.5% natural vegetation pixels above 1500 m asl, where snow metrics were not mutually correlated. However, these effects differed with elevation and between subregions. Snow cover duration and mean snow water equivalent of snow cover duration had more influence on the start and length of season than last snow day across elevation. These results correspond well to the fact that both timing and accumulation of snow have a great effect on determining phenology in high-elevation regions (Huelber *et al*. 2006; Hülber *et al*. 2011; Wipf *et al*. 2009). Furthermore, these results are in agreement with the conclusion that the vegetative season can be reduced by longer lasting snow cover (Björk and Molau 2007; Cooper *et al*. 2011), and that a deep snowpack invariably leads to delaying and shortening the plant growing season (Borner *et al*. 2008; Löffler 2005). In addition, timing and accumulation of snow may influence the length of growing period through their effects on the spring start of growing (White et al. 2009) and greenness (Trujillo *et al*. 2012). These effects can be attributed to the fact that winter snow has an effect on soil water reserves, for example by keeping soils moist through the growing season (Hiller *et al*. 2005; Richardson *et al*. 2013; Trujillo *et al*. 2012). However, our result indicates that both start and length of season showed no significant responses to last snow day across both elevation and subregion. This finding is neither in agreement with Trujillo *et al*. (2012), nor with Paudel and Andersen (2013), where the last snow day was highly correlated with the spring phenology when tested in other high elevational regions. This may be due to the fact that the climate and other environmental factors in these regions are different from the Swiss Alps that were examined for this thesis.

The analysis in Chapter 3 concluded that

i) start of season and length of season was more sensitive to snow cover duration and mean snow water equivalent above 1500 m asl than below;

ii) the relationship of alpine land surface phenology with seasonal snow was more pronounced in high elevational regions such as the western and eastern Swiss Alps, as well as in alpine vegetation types such as natural grassland and sparsely vegetated areas as compared to other areas; and

iii) start of season was influenced primarily by snow cover duration and secondarily by mean snow water equivalent, while length of season showed equal effects from snow cover duration and mean snow water equivalent across elevations. In contrast, last snow day showed no significant effect on either start of season or length of season across elevation in the Swiss Alps.

The results presented in Chapter 3 further indicate that alpine ecosystems are significantly sensitive to timing and accumulation of snow variation associated with elevation. Moreover, changes in high-elevation vegetation activity and composition should be expected in response to changes in timing and accumulation of snow. However, along with extreme events and land-use practices, other factors such as soil water and nutrient availability might lead to linear or non-linear changes in vegetation phenology in the regions where snow plays a limited role.

In Chapter 4, this study employed start of season, peak of season, end of season, land surface phenology, mean normalized difference vegetation index during growing season, maximum normalized difference vegetation index, and mean leaf area index during growing season, in combination with snow accumulation and snow cover melt day and other meteorological factors such as air temperature, relative sunshine duration, and precipitation over the period 2003–2014. The results show that positive effects of snow cover melt day and snow accumulation on the start of season are more critical than other factors investigated in this study across elevations. However, these results are in disagreement with the previous statements that snowmelt has a high positive correlation with the spring phenology in grassland (Cooper *et al*. 2011; Filippa *et al*. 2015; Julitta *et al*. 2014; Suzuki 2014; Wipf *et al*. 2009; Zeeman *et al*. 2017). However, these results is in against with the previous common consensus that air temperature (Körner and Basler 2010; Li *et al*. 2016; Linkosalo *et al*. 2009; Menzel *et al*. 2006), sunshine duration (Liu *et al*. 2016) and precipitation (Piao *et al*. 2006) is considered to be of critical importance in spring phenology determinant. Considering the studied natural grassland areas dominated by snow in winter and spring, the spring air temperature may indirectly influence start of season via its influence on the snow cover melting.

Autumn temperature is more critical to the end of season below 2000 m asl, whereas autumn precipitation is more important above 2000 m asl. These results are in agreement with the previous reports that autumn phenology of grassland over permafrost regions is positively correlated with air temperatures (Jeong *et al*. 2011; Menzel *et al*. 2006; Sun *et al*. 2014) and relative sunshine duration (Migliavacca *et al*. 2011) and negatively correlated with precipitation (Choler 2015; Prevéy *et al*. 2014) in autumn. However, this fact is in opposition to the report by Liu *et al*. (2016) and Richardson *et al*. (2013) that precipitation is positively correlated with end of season and is the most relevant environmental factor in grassland. This special result might be because precipitation cools down the species growing environment through its influence on air and soil temperature at alpine grassland regions in autumn.

Snow cover melt day, snow accumulation, and summer temperature and precipitation show significant positive correlations with mean normalized difference vegetation index during growing season, maximum normalized difference vegetation index, and mean leaf area index during growing season. The grassland areas in northern and eastern regions and at elevations above 1800 m asl are more strongly sensitive to seasonal snow and meteorological factors. This evidence is firmly in parallel with the report that the snowmelt date and winter snow depth, as well as summer temperature, are positively corrrelated with higher NDVI values over high latitude areas (Grippa *et al*. 2005) and high elevation montian areas (Trujillo *et al*. 2012). However, these results are in disagreement with the previous statements that snow accumulation has an adverse effect on plant productivity (Wipf and Rixen 2010) whilst snowmelt has a minor impact on it (Suzuki 2014). This impact might be because accumulation and melt of snow can influence the grasses' roots by the supply of water and nutrient mobilization in spring (Clement *et al*. 2012; Julitta *et al*. 2014; Keller and Körner 2003; Suzuki 2014; Wang *et al*. 2013) to avoid drought stress (Fernandez-Pascual *et al*. 2017), meanwhile, the grasses roots take account of up to 90% of productivity in grassland (Mokany *et al*. 2006; Steinaker and Wilson 2005). Snow provides frost-damage protection and shields the grasses' roots from harsh winds in winter (Chen *et al*. 2015; Groffman *et al*. 2006; Pintaldi *et al*. 2016; Wahren *et al*. 2005; Wipf *et al*. 2006) for the grasses roots. Thin and early melting snow may lead to frost-damage of species through their exposure to cold air temperatures (Julitta *et al*. 2014; Wipf *et al*. 2006), hence later snowmelt could be more beneficial to the above-ground biomass during the growing season in alpine grassland.

Chapter 4 further suggests that more accumulation and later melt of snow delays the spring phenology and shortens the growing period but enhances the productivity in alpine grassland. Alpine ecosystems in grassland might be particularly sensitive to the future change of seasonal snow.

5.1.4 Limitation of this work

As discussed above, disentangling how the vegetation-activity signal is influenced by absence or presence of snow versus the actual green-up of vegetation during the growing season is challenging. Several reports point out that the presence of snow cover in the vicinity of green vegetation may result in uncertainty in the NDVI signal (Jönsson *et al*. 2010; Quaife and Lewis 2010). Consequently, the snow cover dynamics may have an impact on satellite monitoring of greenness in vegetated areas (Beck *et al*. 2006; Busetto *et al*. 2010; Delbart *et al*. 2006; Jönsson *et al*. 2010; White *et al*. 2009). Some studies have proposed the use of a winter baseline NDVI (i.e. NDVI of dormant but snow-free vegetation) to minimize the effect of snow cover (Beck *et al*. 2006; Busetto *et al*. 2010). This approach has been developed for evergreen needle-leaf trees that may continue to be photosynthetically active despite being snow covered (e.g. Walther *et al*. (2016)). In alpine grasslands, the winter baseline can be expected to be lower and therefore have limited influence on the amplitude-based SOS estimate. Also, the winter baseline in alpine grasslands is expected to be spatially more variable due to variations in fractional vegetation cover and therefore particularly difficult to estimate. For these reasons, we expect the use of a winter baseline NDVI to have minimal effect on the extracted phenological metrics in our study area.

Given the compositing scheme and spatial resolution of satellite data, as well as terrain complexity, the land surface phenology estimates derived from normalized difference vegetation index still differ with the election of techniques (White *et al*. 2009) which thus affects the computation of mean normalized difference vegetation index and mean leaf area index between start of season and end of season. Meanwhile, the compositing scheme and medium spatial resolution of satellite data combined with the terrain complexity in the Swiss Alps make land surface phenology estimates complex. The link to driving factors is furthermore influenced by the different resolutions of the mid-resolution remote sensing (i.e., MODIS), snow water equivalent, and meteorological data. Nevertheless, this thesis was able to analyze year-to-year variation in climate and greenness data, which allowed us to better understand land surface phenology processes in alpine vegetated lands.

Satellite-derived snow cover duration and last snow day can be error prone, especially in conditions when snow cover and clouds are spectrally difficult to distinguish (Xie *et al*. 2017). Uncertainties in mean snow water equivalent estimates according to snow cover duration arise with snow under critical illumination conditions and snow in forested regions (Thirel *et al*. 2012).

The 12-years length correlation test in this study is a limitation remaining due to the fact that 250-m resolution MODIS13Q1 NDVI (normalized difference vegetation index) data are only available for a relatively short time-series from the year of 2002. Unfortunately, it is difficult to make future predictions based on short-term analyses.

An important factor that remained beyond the scope of this paper is management practices (grazing, cutting) (Schmidt *et al*. 2018; Zeeman *et al*. 2010). Many land surface phenology metrics are influenced not only by climate but also by management type and intensity, and this especially at low elevation. It remains a challenge for future studies to disentangle land use from climate effects on greenness measures derived from remote sensing.

The plant species are affected by nutrient and water supply (Peter *et al*. 2008) and soil temperature (Fernandez-Pascual *et al*. 2017). However, soil environmental factors, which may influence the roots' growing conditions in the alpine vegetated areas, were not possible to investigate in this study. The role of the above factors in the future, combined with possible climate change scenarios in mountainous regions, was beyond the research scope of this study and remains to be investigated.

5.2 General contributions

Due to the alpine research need for mapping seasonal snow and land surface phenology and evaluating the influence of timing and accumulation of snow on land surface phenology in the field, this thesis is the first systematic attempt to track elevational variation in mid spatial resolution (250 m) land surface phenology and greenness metrics derived from remote sensing data, and to test their relationships with seasonal snow and climatic factors for the entire European Alps and specifically, for the Swiss Alps.

This work investigates five important steps towards systematic snow-vegetation relationships analysis: (i) mapping of snow cover phenology, land surface phenology and greenness metrics, (ii) spatiotemporal monitoring of snow cover phenology, snow accumulation, land surface phenology and greenness metrics, (iii) elevation-dependent influence of snow cover phenology on land surface phenology, (iv) relative influence of timing and accumulation of snow on start of season and length of season, and (v) investigation of the relationships of snow cover melt day, snow accumulation and meteorological factors with land surface phenology and greenness metrics over time. All above aspects demonstrate that the practice of remote sensing is valuable to conducting alpine seasonal snow and land surface phenology and greenness metrics mapping and monitoring.

The main contributions of this thesis are three-fold.

In Chapter 2, in the European Alps, this thesis found that snow cover melt day shows strong correlation with start of season and length of season at high elevations above 2000 meters; the correlation (between snow cover duration and start of season and between snow cover duration and length of season) differs between climatic sub-regions and terrain aspects are more pronounced at elevations below 2000 meters than above; the correlation of start of season and length of season with snow cover duration is strongest in natural grasslands. Snow metrics are known to co-vary under certain conditions.

This study includes first snow fall and last snow day metrics, which do not necessarily represent the last and first date of the continuously snow covered winter period but allow us to account for potential late season transient snowfall events occurring in the Alps. The results of Chapter 2 indicate that last snow day and first snow fall have no influence on alpine phenology. However, this designed analysis is the first test of the effects of first and last snow date on end and start of land surface phenology across the European Alps.

In snow sensitive regions with weak or no interdependence between timing and accumulation of snow, the relative importance of these parameters remains to be assessed, in finding the most relevant metrics for studying snow-vegetation dynamics. In Chapter 3, in the Swiss Alps, this work found that mean snow water equivalent shows strong correspondence with snow cover duration across elevations; the influence of snow cover duration and mean snow water equivalent on start of season and end of season are more pronounced at elevations above 1500 meters above sea level than below; snow cover duration plays a more significant role than mean snow water equivalent on alpine start of season and length of season.

Based on the work in Chapter 2 and 3, alpine grassland is the most sensitive region, where land surface phenology significantly correlates with snow cover phenology metrics and mean snow water equivalent. However, together with other meteorological factors, knowledge about the elevation-dependent character and magnitude of these effects of the accumulation and melt of snow on the land surface phenology and greenness are still limited, and need further investigation in alpine grasslands. Thus, in Chapter 4, in the alpine grassland of the Swiss Alps, positive effects of snow cover melt day and snow accumulation on the start of season are more critical than factors investigated in this study across elevations. Autumn temperature is more critical to the end of season below 2000 m asl, however, autumn precipitation is more important above 2000 m asl. The grassland areas are sensitive to seasonal snow and meteoroloigcal factors, showing a pronounced response in northern and eastern regions and at elevations above 1800 m asl.

The findings of Chapter 2 confirm Hypothesis I and provide interesting insights into the spatial variability of snow cover phenology and land surface phenology across elevations at landscape level. The findings of Chapter 3 confirm Hypothesis II that snow cover phenology plays a more important role than snow accumulation on start of season, but an equal role on length of season, in the Swiss Alps. Chapter 4 tested Hypotheses III, IV and V, and found that snow accumulation and snow cover melt day play a dominant role on start of season and positively influence greening of the growing season. The relative influences of meteorological factors on end of season vary with elevation.

5.3 Final considerations and future directions

This study presents an overview of elevation-dependent correlation of timing and accumulation of snow with alpine land surface phenology and greening. Increased combination of long-term *in situ* observations and remote sensing for detailed long-term investigations should be envisaged in future research.

Further to the findings of this thesis and its main contributions, open issues remain for discussion, and as the focus of future research. Specifically, two key scientific issues need to be resolved and two major technical issues need to be overcome, as well as other open issues, such as herbarium phenology records.

5.3.1 Open issues based on this thesis

Resulting from this Ph.D. project research, two scientific questions have arisen that demand further research.

First, this thesis found that in the European Alps, the sensitivity of land surface phenology to various environmental factors varied with elevation, terrain-aspect, vegetation type, and climatic subregion. For instance, the sensitivity of start of season and length of season to snow cover and snow accumulation in the vegetated areas was more pronounced at higher elevations in the Swiss Alps (Xie *et al*. 2018) and in the north-eastern European Alps (Xie *et al*. 2017). The relative effects of snowmelt, sunshine duration, and temperature on land surface phenology and on the average greenness showed significant differences depending on elevation in the Swiss Alps. Thus, the key effects of environmental triggers on land surface phenology and productivity might be worth clarifying over large spatial scales.

Second, investigations on the response of land surface phenology and productivity of vegetated areas to climate change derived from higher resolution remote sensing data at continental and global scales are still limited and need to be tested in the field. Higher resolution MODIS NDVI and EVI data sets tested in the Chapter 2 may however contain further valuable information for a more detailed investigation of the vegetation response to climate change on a larger scale. Understanding the variation of these responses based on geographic factors, bioclimatic regions, and vegetation types with a particularly intense response to global climate change are essential to understand and predict the influence of changing climate in detail. These scientific issues lead on to two technical issues resolved to achieve them.

This work found that land surface phenology of vegetated areas depict unresolved differences in its calibration resulting from atmospheric interference depending on elevations and on climatic subregions. For instance, the start of season and end of season metrics (between 2003-2014) of vegetated areas derived from MODIS NDVI (Xie *et al*. 2017) and EVI (Oehri *et al*. 2017) showed significant differences due to topography (below 2000 m asl), despite using the same relative threshold method across the Swiss Alps. The method adapted in the applicant's study (originally from (White *et al*. 2009) to derive land surface phenology from MODIS NDVI, is limited by a lack of field observations (Garonna *et al*. 2016; Hufkens *et al*. 2012).

Furthermore, the need for more accurate land surface phenology metrics, as well as the estimation of productivity metrics depending on land surface phenology, with higher spatial resolution is emphasized as a research gap, which would affect future ecological studies (Fisher and Mustard 2007; Melaas *et al*. 2016). The work has worked with the fusion of MODIS and Landsat data for tracking vegetation indices in the eastern Swiss Alps (for the years 1982-2014), which forms the basis of the future study. These datasets need to be complemented by acquisitions of field observed surveys. Thus, MODIS data and the fusion of MODIS and Landsat data sets (Walker *et al*. 2014; Walker *et al*. 2012) contain a vast potential for high-resolution ecological studies, especially when validating (Fisher and Mustard 2007) and combining with biome-scale ground surveys (Fisher *et al*. 2006) on a global scale.

5.3.2 Scientific issues

The first scientific question, identifying the controls that primarily determine land surface phenology over large spatial scales, needs a thorough understanding of the geographical variation and the relative importance of various environmental factors on land surface phenology. The effects of climate and climate-related factors on land surface phenology and productivity are different between geographical conditions (Ide and Oguma 2013) and between climatic regions (Dye and Tucker 2003; Peng *et* *al*. 2010). These effects also vary depending on topographic conditions (Trujillo *et al*. 2012; Walker *et al*. 2014) and land cover, such as vegetated areas (Cavanaugh *et a*l. 2014; Hu *et al*. 2010; Jönsson *et al*. 2010). The sensitivity of phenology and vegetation growth to environmental factors, including temperature (Körner and Basler 2010; Kucharik *et al*. 2006; Richardson *et al*. 2006b), precipitation (Chang et al. 2015), photoperiod (Caldararu *et al*. 2014), freezing in winter (Keenan 2015), snow (Xie *et al*. 2017), rainfall (Clinton *et al*. 2014), and hydrology (Forkel *et al*. 2015; Zhang *et al*. 2017a), etc.) are assumed to be complex and to result in significant differences in plant leafing phenology and productivity depending on elevation, bioclimatic zones and vegetation types. In addition, the relative influence of environmental factors on land surface phenology may also vary seasonally (Jolly *et al*. 2005). Thus, identifying the key climatic controls and environmental triggers to the leafing phenology in vegetated areas needs a thorough understanding of the geographical variation and the relative importance of various environmental factors on determining land surface phenology around the globe.

The second scientific question - the inter-annual trends of land surface phenology and their response to global climate change, particularly the identification of significant responding regions - still need detailed assessment, which will allow us to better quantify the vegetation responses to the changing climate. Inter-annual trends in time-series of land surface phenology are assumed to be primarily caused by climate change (Cleland *et al*. 2007; Garonna *et al*. 2016; Garonna *et al*. 2018; IPCC 2007; Menzel *et al*. 2006; Piao *et al*. 2015). Several large-scale studies have mapped the land surface phenology and productivity metrics of vegetated areas, tracked their inter-annual trend, and investigated their response to climate change over past decades (Garonna *et al*. 2016; Julien and Sobrino 2009; Verhegghen *et al*. 2014; Vicente-Serrano *et al*. 2016; White *et al*. 2005). However, previous work has focused on coarse optical remote sensing, and high-resolution analyses are lacking for quantifying the phenological responses to climate change, which allows us to more comprehensively quantify the vegetation responses to the changing climate. More specifically, there is a need for an in-depth investigation of the effects of climate change on vegetation types at a higher spatial resolution and more accurate geolocation in different bioclimatic zones. Studying the response of land surface phenology and greenness to climate change can have implications for forest management and contribute to more accurate forecasting of responses of vegetation ecosystems to climate change.

5.3.3 Technical issues

Before these two scientific questions can be addressed, two major technical issues need to be overcome: improved ground truthing and spatial resolution.

Land surface phenology estimated from space is yet to be carefully calibrated and validated using field-based observations, except in a few studies (Chen *et al*. 2015; Parmesan 2007; Schwartz *et al*. 2006; White *et al*. 2009). Atmospheric interference has led to unresolved differences between land surface phenology modeling and relevant biome-scale verification with regard to elevation, latitude, longitude, and region. For instance, most analyses of land surface phenology derived from satellite platforms use threshold values to detect spring greening (Jönsson *et al*. 2010) but field validation is lacking (Badeck *et al*. 2004; Fisher and Mustard 2007; Richardson *et al*. 2012). The thresholds for modeling start and end of season and thus the estimation of growing season may change with topography (Hwang *et al*. 2011a; Hwang *et al*. 2011b), vegetation types (Buitenwerf *et al*. 2015; Maignan *et al*. 2008), and bioclimatic regions due to different vegetation types showing different life cycle affected by the environment (Buitenwerf *et al*. 2015; Maignan *et al*. 2008). For instance, recent studies computing the start and end of season from remote sensing for the Swiss Alps (Oehri *et al*. 2017; Xie *et al*. 2017), Europe (Garonna *et al*. 2014), and the global scale (Garonna *et al*. 2016) revealed systematic differences between their predictions, which were based on nonlinear modeling. Therefore, the start and end of season need improved threshold definition based on field-based plant phenology records, before the approach can make accurate predictions at large scales.

Most current studies of land surface phenology are based on coarse-resolution imagery but mixtures of vegetation types within pixels can create bias, making it important to develop new data with higher resolution imagery. Most published studies of greenness phenology use coarse-scale satellite data, such as 8-km pixels available from AVHRR (Julien and Sobrino 2009; Marshall *et al.* 2016; Verhegghen *et al*. 2014; White *et al*. 2009), which have absolute differences in data values and therefore phenological events compared to higher-resolution MODIS (Zhang *et al*. 2017b). Vegetation indices from coarse satellite data in vegetated areas have been shown to lead to an ill-defined land surface phenology and have limitations resulting in mixed signals from multiple biomes and in shifts in human-related land cover such as agricultural practices, urbanization, and disturbances (White *et al*. 2005). Consequently, it is hard to disentangle a clear signal of climate change from of land-use change dynamics within the large pixels. Satellite datasets with a higher resolution contain an enormous potential for more comprehensive ecological studies (Badeck *et al*. 2004; Dong *et al*. 2015; Melaas *et al*. 2016; Prentice *et al*. 2005; Stueve *et al*. 2011; Zheng *et al*. 2015), especially when validated (Fisher and Mustard 2007) and combined (Fisher *et al*. 2006) with biome-scale ground records and surveys. Therefore, future research can develop robust approaches to monitor land surface phenology at a high spatial resolution (e.g., using MODIS with 250-m resolution and the fusion of MODIS and Landsat data). This will provide more track land surface phenology and greenness of vegetated areas, which can then be applied in ecological studies, leading to increased accuracy and improved monitoring of uncertainty traceability in the field.

5.3.4 Outlook of other open issues

Phenological events of a diversity of plant species can be also estimated by herbarium specimens, which are increasingly being recognized as a reliable source (Willis *et al*. 2017a). But, currently, there are only limited works published that tracks phenology using herbarium specimens (e.g., Davis *et al*. (2015), Willis *et al*. (2017b), Everill *et al*. (2014), Panchen *et al*. (2014), Zohner and Renner (2014)). Herbarium specimens have huge potential practice in tracking phenology and productivity of vegetation and its response to climate warming. Well-sampled herbarium records, producing similar tracks of phenological variations to those estimated by field-based observation (Chen *et al*. 2015; Pellerin *et al*. 2012), can accurately report on plant phenology (Davis *et al.* 2015; Everill *et al*. 2014; Panchen *et al*. 2014; Willis *et al*. 2017b; Zohner and Renner 2014) at species and community level. Furthermore, through integration with remote sensing data, herbarium specimens provide the novel insights and potential approach for future studies into plant phenology and ecosystem processes under future climate change at a large geographic scale (Primack and Gallinat 2017; Willis *et al*. 2017a). However, the practice of using herbarium specimens combined with satellite-derived data for the phenology and productivity of vegetation study is still a huge research gap. This is because there are only several relevant publications (e.g., Park (2012), Vaclavik *et al*. (2017)) in the field. In other words, it is a super research gap with potential broad space for studying the phenology and productivity of vegetation using herbarium specimens combined with satellite-derived data. Thus, in combination with assessment and validation from species surveys (Fisher *et al*. 2006) such as phenology observation net and herbarium specimens, remote sensing can provide new opportunities for reliable system analyses of land surface phenology and greenness.

In addition, future research in remote sensing of alpine land surface phenology should focus on disentangling the effects of greenness due to snow absence during melting and actual vegetation greening at the start of the growing season. Eventually, the detection of long-term trends in relationships among snow, temperature and greening will improve our understanding of climate change effects on vegetation. Moreover, snow cover melt date could be used to estimate the spring land surface phenology of the alpine natural grassland in the Swiss Alps, since a highly significant positive correlation was found between timing of snow melt and spring phenology in Chapter 4 of this thesis.

Soil environmental factors, which had not been investigated in this thesis, should be considered in the future studies. In addition, a combination of long-term *in situ* observations and time-series remote sensing of snow and vegetation phenology will be necessary to better investigate the relationships between snow metrics and land-surface phenology in future research in the European Alps.

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Education

2013-2018	Ph.D. candidate in Remote Sensing, Department of Geography, Remote Sensing Laboratories, University of Zurich (CH).
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2006-2010	B.Sc. in Resources and Environment and Urban Planning, Northwest University, Xi'an, China. Dissertation carried out at Northwest University, supervised by Prof. Dr. Haijuan Yang. Title: Association Analysis between Road Transportation and Economic Development in Northern Shaanxi in the Transition Periods.
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Previous research experience

2011-2013 Research Assistant in Northeast Institute of Geography and

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Teaching

2014-2017 Teaching assistant for various courses within the Department of Geography, University of Zurich. Namely: Modul exams of GEO123, June 2015; URPP GCB, September 2015; Master Exams, Fall semester 2016; Small Group Teaching HS 2016; Small Group Teaching FS 2017; Remote Sensing Colloquium, Spring 2017; Modul exams of GEO123, August 2017.

Graduate courses and training

2014-2013 PhD Seminars I & II

Principles and Theory in Geography

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Scientific writing

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Data analysis with R; R for spatial data analysis and visualization

PSC course: Scientific Writing Practice II.

Writing research papers for publication: Natural science and engineering C1-C2.

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Peer-reviewed publications (selected)

Xie, J., *et al.* (2018). Land surface phenology and greenness in Alpine grasslands driven by seasonal snow and meteorological factors. *Remote Sensing of Environment*. Under revision.

Xie, J., *et al.* (2018). Relative influence of timing and accumulation of snow on alpine land surface phenology. *Journal of Geophysical Research: Biogeosciences*, 123. 561-576.

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Xie Jing, *et al.* Analysis of seasonal changes of wetland landscape - Patterns derived from Remote sensing data. *Acta Ecologica Sinica* (in Chinese), 2014,34 (24).

Conference contributions (selected)

2017 AGU Fall Meeting Abstracts, December 2017: *Effects of seasonal snow and climatic controls on spring and autumn phenology in Alpine forest regions*.
2017 15th Swiss Geoscience Meeting in Davos (CH): *Influence of meteorological factors on the autumn land surface phenology in alpine grasslands*.
2017 10th EARSeL SIG Imaging Spectroscopy Workshop in Zurich (CH): *Altitude-dependent Influence of Snow Cover and Accumulation on Start of Alpine Phenology*.
2016 14th Swiss Geoscience Meeting in Geneva (CH): *Altitude-dependent correlation of snow cover duration with alpine spring phenology*.

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