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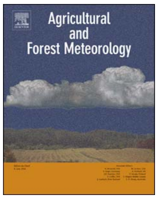

Heat wave hinders green wave: The impact of climate extreme on the phenology of a mountain grassland

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ABSTRACT

Climate extremes can have tremendous impacts on the terrestrial biosphere and their frequency is very likely going to increase in the coming years. In this study we examine the impact of the 2015 summer heat wave on a mountain grassland in the Western European Alps by jointly analyzing phenocam greenness (GCC) trajectories, proximal sensing, CO_2 flux data and structural canopy traits. Phenocam effectively tracked the impact of the heat wave, showing 39% of reduction in maximum canopy greenness and a senescence advance of 32 days compared to mean values. The same patterns (*i.e.* reduction of maximum values and senescence advance) were observed for all considered canopy traits and photosynthetic ecosystem functional properties, in particular the maximum light-saturated rate of CO_2 uptake (A_{max}), LAI and PRI. Pixel-level analysis of phenocam images allowed us to further highlight that forbs were more heavily impacted than grasses. Moreover the effect of the extreme event on greenness seasonal course was evaluated testing new formulations of the Growing Season Index (GSI) model. Results demonstrate that a combination of water and high temperature stress was responsible for the observed reduction of canopy greenness during the heat wave.

1. Introduction

Global warming is occurring fast in the European Alps (Beniston, 2012) and an increase of climate extremes is likely going to occur in this region (Gobiet et al., 2013; IPCC, 2013) hosting some of the most ecologically sensitive ecosystems of the planet (Seddon et al., 2016). Climate extremes are known to have exceptional impacts on the terrestrial biosphere that can result in ecosystem productivity reduction (Reichstein et al., 2013; Bahn et al., 2014; Frank et al., 2015; Rammig et al., 2015), altered ecological dynamics, community composition modification and biodiversity losses (Smith, 2011; Jung et al., 2014; Fuchslueger et al., 2014).

Phenology is one of the most effective biological indicators of climate change impacts on the terrestrial biosphere (Scheffers et al., 2016). Many studies highlighted the relationship between climate change and phenology (*e.g.* Buitenwerf et al., 2015; Richardson et al., 2013), as well as the impact that climate extremes can have on spring events such as flowering and foliar development or senescence (Reyer et al., 2013; Menzel et al., 2015; Hufkens et al., 2012a).

By providing continuous sub-daily images of canopy development, phenocams (*i.e.* repeat digital photography) are useful tools for phenology monitoring (Richardson et al., 2009) leading to an increase in phenocam deployment in the last years worldwide (Brown et al., 2016; Wingate et al., 2015; Nasahara and Nagai, 2015). Indeed, greenness index (Richardson et al., 2007) derived from phenocam imagery is used to track the green wave (*i.e.* the seasonal greening phenology, Schwartz, 1998) of many terrestrial ecosystems such as forests (Sonnentag et al., 2012; Hufkens et al., 2012a; Nagai et al., 2011), grasslands (Migliavacca et al., 2011; Hufkens et al., 2016; Inoue et al., 2015), peatlands (Peichl et al., 2013) and crops (Sakamoto et al., 2012; Wingate et al., 2015). Other authors analyzed the relationship between greenness index and ecosystem productivity (Toomey et al., 2015; Saitoh et al., 2012; Mizunuma et al., 2013; Knox et al., 2017), canopy functional and structural properties (Keenan et al., 2014; Yang et al., 2014) and disturbance events (Nagler et al., 2014; Zhou et al., 2017). Recently Menzel et al. (2015) and Hufkens et al. (2012b) demonstrated that phenocams can also be used to infer the impact of climate extremes on spring canopy development. Phenocam analysis is generally based on the extraction of canopy greenness information from specific regions of interest of the scene. In the last years, pixel-level analysis of

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phenocam imagery has been proposed as a new very promising approach to infer the spatial distribution of phenologically different individuals or species within the canopy and their differential response to climate cues (Julitta et al., 2014; Filippa et al., 2016; Snyder et al., 2016). Moreover, Migliavacca et al. (2011) demonstrated that phenocam canopy greenness can also be used to constrain phenological models such as the Growing Season Index model (GSI, Jolly et al., 2005) for the simulation of canopy development and for the identification of the main meteorological factors controlling plant phenology. Indeed the GSI model offers opportunities to disentangle the influence that meteorological drivers can have on canopy greenness during climate anomalies.

The relationship between the phenology of tree species and climate drivers has been thoroughly investigated by means of long-term data (*e.g.* Menzel et al., 2006; Fu et al., 2015; Zohner et al., 2016), while less studies focused on alpine grassland phenology (*e.g.* Vitasse et al., 2016; CaraDonna and Inouye, 2015; Filippa et al., 2015; Wipf and Rixen, 2010). Mountain grasslands are ecosystems vulnerable to climate extremes like early or delayed snowmelt, heat waves and droughts (De Boeck et al., 2015; Galvagno et al., 2013; Choler, 2015). The impacts of these extremes mainly depend on their intensity and timing (Sippel et al., 2016), ecosystem species composition and diversity and the interaction of biotic and abiotic factors (Hoover et al., 2014; Kreyling et al., 2011; Vogel et al., 2012; Ernakovich et al., 2014).

In 2015 heat records were broken worldwide (Heffernan, 2016; Tollefson, 2015) and in particular in July 2015, Europe experienced extremely hot temperatures and low precipitations (World Meteorological Organization, 2016). In this study we take advantage of this event to evaluate the impact of a climate extreme on the phenology of a mountain grassland in the Western European Alps using phenocam data. The main objectives of the study are: (i) to analyze heat wave impact on canopy green wave and relate it to other functional and structural canopy traits, (ii) to evaluate the occurrence of differential effects on plant functional types using pixel-level analysis and (iii) to disentangle the role of meteorological drivers on greenness during the heat wave.

2. Materials and methods

2.1. Study site

The study is conducted in an abandoned subalpine grassland (Torgnon, Italy, Galvagno et al., 2013) in the Western European Alps located at 2160 m asl (45°50′40″ N, 7°34′41″ E). Dominant vegetation mainly consists of grasses, (*Nardus stricta*) with co-dominant forbs species like *Arnica montana*, *Trifolium alpinum* and *Geum montanum*. The site is characterized by a mean annual temperature of 3.1 °C and mean annual precipitation of about 880 mm. A thick snow mantle generally covers the site from the end of October to late May limiting the growing season length to an average of five months. The peak value of Leaf Area Index (LAI) is on average 2.2 $m^2 m^2$ and maximum canopy height is 20 cm. The site is characterized by undulating terrain with a heterogeneous microtopography (< 50 cm); following snowmelt spatial patterns, forbs species tend to be located in concave areas, while grasses occupy convex areas (Pintaldi et al., 2016).

2.2. Data collection and processing

2.2.1. Phenocam and meteorological data

Phenocam images are collected using a Nikon D5000 digital camera controlled by a raspberry-Pi computer. Following Richardson et al. (2007), the camera is installed 2.5 m above the ground, pointing north and set at an angle of about 20° below horizontal. Images, collected hourly from 10.00 to 16.00 with exposure mode and white balance set respectively to automatic and fixed, are saved in JPEG format at a resolution of 1024 × 2048 pixels. The present study is based on images covering the period 2013–2015. Canopy greenness (green chromatic coordinate, GCC, Richardson et al., 2007), is computed following Eq. (1) for a selected region of interest (ROI) located in the foreground portion of the images.

$$\mathrm{GCC} = \frac{G_{\mathrm{DN}}}{R_{\mathrm{DN}} + G_{\mathrm{DN}} + B_{\mathrm{DN}}} \tag{1}$$

where R_{DN}, G_{DN} and B_{DN} are the red, green and blue digital numbers (DN) of each color channel in JPEG images, respectively. Daily filtered GCC time series are obtained using the phenopix R package (Filippa et al., 2016), following the filtering approach suggested by Sonnentag et al. (2012). The entire phenocam dataset of the site is available at https://phenocam.sr.unh.edu/webcam/sites/torgnon-nd/. Since 2008, a weather station provides 30-min averaged records of air temperature (HMP45, Vaisala), photosynthetically active radiation (LI-190, LI-COR), precipitation (OTT Pluvio2, OTT Hydromet) and soil water content (CS-616, Campbell Scientific).

2.2.2. Gross primary productivity and photosynthetic ecosystem functional properties

Eddy covariance measures of CO_2 fluxes are carried out continuously since 2008. Details on instrumental setup, measurements and data processing are provided in Galvagno et al. (2013, 2017). Estimates of gross primary productivity (GPP) are obtained following Reichstein et al. (2005) and Lasslop et al. (2010) approaches implemented in the online tool available at http://www.bgc-jena.mpg.de/~MDIwork/eddyproc/index.php. Ecosystem functional properties related to photosynthesis (Reichstein et al., 2014) are estimated using the light-response curve of photosynthesis (Eq. (2)) describing the relationship between Net Ecosystem Exchange (NEE) and photosynthetically active radiation (PAR). The rectangular hyperbolic light-response function (Falge et al., 2001) is used:

$$\mathrm{NEE} = \frac{A_{\max}\,\alpha\mathrm{PAR}}{\alpha\mathrm{PAR} + A_{\max}} + R_{\mathrm{eco}} \tag{2}$$

where A_{max} (μmol CO_2 m^{-2} s^{-1}) is the maximum light-saturated rate of CO_2 uptake, α (μmol CO_2 $\mu mol^{-1}_{photons}$) is the canopy light use efficiency representing the initial slope of the light-response curve, and R_{eco} (μmol CO_2 m^{-2} s^{-1}) is the ecosystem respiration. Model parameters are estimated by fitting Eq. (2) to non gap-filled, daytime half-hourly NEE data with a 15-day moving window shifted each 5 days and assigned to the central day of the moving window. Daily midday averages (average of all data from 11.00 to 13.00 LST) of GPP and daily A_{max} and α values are used for further analysis.

2.2.3. Spectral vegetation indexes

Canopy spectral properties are measured with SKR1800 sensors (Skye Instruments) collecting spectral signatures of the canopy every 5 min. Spectral data are used to compute vegetation indices (VIs) related to canopy structure such as the Normalized Difference Vegetation Index (NDVI, Rouse et al., 1974, Eq. (3)) and to canopy functioning such as the Photochemical Reflectance Index (PRI, Gamon et al., 1997, Eq. (4))

$$\mathrm{NDVI} = \frac{\rho_{860} - \rho_{640}}{\rho_{860} + \rho_{640}} \tag{3}$$

$$\mathrm{PRI} = \frac{\rho_{531} - \rho_{570}}{\rho_{531} + \rho_{570}} \tag{4}$$

where ρ_x is the reflectance computed at the x wavelength in nm. The fraction of the photosynthetically active radiation absorbed by the canopy (F_{apar}) is calculated using incident, reflected and below canopy PAR measures following Eklundh et al. (2011) and Olofsson and Eklundh (2007). For consistency, daily midday averages of VIs and F_{apar} are used for further analyses.