



Remote estimation of grassland gross primary production during extreme meteorological seasons



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ABSTRACT

Different models driven by remotely sensed vegetation indexes (VIs) and incident photosynthetically active radiation (PAR) were developed to estimate gross primary production (GPP) in a subalpine grassland equipped with an eddy covariance flux tower. Hyperspectral reflectance was collected using an automatic system designed for high temporal frequency acquisitions for three consecutive years, including one (2011) characterized by a strong reduction of the carbon sequestration rate during the vegetative season. Models based on remotely sensed and meteorological data were used to estimate GPP, and a cross-validation approach was used to compare the predictive capabilities of different model formulations. Vegetation indexes designed to be more sensitive to chlorophyll content explained most of the variability in GPP in the ecosystem investigated, characterized by a strong seasonal dynamic. Model performances improved when including also PAR_{potential} defined as the maximal value of incident PAR under clear sky conditions in model formulations. Best performing models are based entirely on remotely sensed data. This finding could contribute to the development of methods for quantifying the temporal variation of GPP also on a broader scale using current and future satellite sensors.

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1. Introduction

Terrestrial plants play important roles in the global carbon sequestration as they fix carbon dioxide (CO₂) as organic compounds through photosynthesis. Terrestrial gross primary production (GPP), the total amount of CO₂ fixed by terrestrial ecosystems, is one of the determinants of land-atmosphere CO₂ exchange (Beer et al., 2010). Thus, accurate GPP estimates can provide valuable information for global carbon studies. Among terrestrial ecosystems, mountain grasslands show a high interannual variability of their productivity (Yi et al., 2012). This variability is enhanced by grassland vulnerability to extreme climate events, such as unusual spring warm temperature which can contribute to early snowmelt in mountain environments (Beniston, 2005). The melting of snow cover influences the start and length of the summer growing season, the amount and timing of nutrients and

water release from the snow pack and can contribute to changes in species composition (Wipf and Rixen, 2010). The expected increase of the occurrence of extreme events predicted by models and confirmed by observational data (Easterling et al., 2000; Meehl and Tebaldi, 2004) could hamper our ability to quantify ecosystem production. Hence, the development of models able to estimate ecosystem carbon cycle related processes across years characterized by markedly different meteorological conditions is necessary to increase our confidence of future model predictions.

Measurements of vegetation reflectance at eddy covariance (EC) sites have notably increased in recent years (Balzarolo et al., 2011) because remote sensing holds considerable potential for advancing our capabilities to estimate and monitor vegetation production at different temporal and spatial scales. Several studies demonstrated the effectiveness of empirical models driven by remote sensing inputs to model GPP on different ecosystems (Peng et al., 2011; Wu et al., 2009), including grasslands (Rossini et al., 2012). Nevertheless a general consensus about model formulations and input variables performing better, especially considering long term data

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series characterized by high inter-annual variability, has still to be achieved.

Previous studies reported the ability to model GPP using vegetation indexes (VIs) designed to be sensitive to chlorophyll (Chl) content. Chlorophyll content is a key variable for explaining GPP variability in vegetation characterized by strong seasonality, such as crops (Gitelson et al., 2006b; Peng et al., 2011; Rossini et al., 2010) or grasslands (Rossini et al., 2012). This is not surprising since Chl content is a main factor controlling the amount of light absorbed by green vegetation and also directly relates to the enhanced electron transport activity, which governs light use efficiency (LUE). The accuracy in GPP estimation may be improved taking into account high frequency changes in radiation conditions and light use efficiency modulation, through the inclusion of incident photosynthetically active radiation (PAR_i) and surrogate of LUE, the photochemical reflectance index (PRI, Gamon et al., 1992) in model formulation (Peng et al., 2011; Rossini et al., 2012; Sakamoto et al., 2011).

For the calibration of this kind of models an estimation of PAR_i is required. In the prospect of GPP monitoring from space-borne remote sensing sensors, an accurate proxy for PAR_i that can be measured remotely is needed. Shortwave radiation obtained from coarse scale meteorological data sets from the NASA Data Assimilation Office was used as a substitute for PAR_i by Sakamoto et al. (2011). However, these estimates of PAR_i have significant uncertainties; the coefficient of variation was 23.6% and mean normalized bias was 13.9% (Sakamoto et al., 2011). Alternatively PAR_i can be indirectly estimated by radiative transfer modeling approach (e.g., Liu et al., 2008) once the optical properties of the atmosphere have been retrieved. However, incorporating such radiative transfer calculations into the practical generation of standardized product providing regular observations of global PAR_i is still a challenging topic in remote sensing (Liang et al., 2006).

Gitelson et al. (2012) suggested using potential photosynthetically active radiation ($PAR_{potential}$), defined as the maximal value of incident PAR under clear sky conditions, rather than PAR_i for estimating GPP. Such approach has the advantage that $PAR_{potential}$ can be more easily estimated using radiative transfer models or look-up table-based algorithms (Lyapustin, 2003).

To our knowledge, such approach has been successfully applied in soybean and maize using Landsat and daily MODIS satellite images (Gitelson et al., 2012; Peng et al., 2013), but it has never been applied to simulate GPP using ground spectral reflectance measurements collected with daily resolution.

This paper provides an evaluation of the robustness of an approach based solely on remotely sensed data to estimate GPP over grasslands. We monitored spectral reflectance throughout the growth period of a subalpine grassland during three consecutive years (2009–2011), including a year (2011) characterized by the longest snow-free period on record (83 years) leading to changes in canopy structure and functioning with a strong reduction of the carbon sequestration rate during the carbon uptake period (Galvagno et al., 2013).

The specific objectives of this paper are (1) to evaluate the robustness of GPP prediction by remote sensing driven models using a three year dataset including one year with an exceptionally long growing season, (2) to assess the performance of the best model formulation, and (3) to test whether the use of $PAR_{potential}$ improves the accuracy in GPP estimation.

2. Methods

2.1. Site description and micrometeorological measurements

The study was conducted in an unmanaged grassland of the sub-alpine belt located in the North-Western Italian Alps (45°50'40" N, 7°34'41" E, Torgnon, Aosta Valley) at 2160 m a.s.l. during three

growing seasons (2009–2011). The vegetation of the site is composed mainly by matgrass (*Nardus stricta*) and, secondarily, by *Trifolium alpinum*, *Arnica montana*, *Poa alpina* and *Carex sempervirens*. The area is classified as an intra-alpine region with semi-continental climate with an annual mean temperature of 3.1 °C and mean annual precipitation of about 880 mm (Mercalli and Berro, 2003). The snow-free period lasts generally from late May to early November. This site is approximately 9 ha and it is equipped with an EC flux tower which provides continuous measurements of net ecosystem CO₂ exchange (NEE) from January 2009. Detailed descriptions of the EC flux measurements, the procedures used to partition the NEE to derive GPP and of the flux footprint are reported in Migliavacca et al. (2011) and Galvagno et al. (2013). Along with EC fluxes, the main meteorological variables (in particular PAR_i) are available with a time step of 30 min.

2.2. Radiometric measurements and spectral vegetation index computation

Hyperspectral reflectance measurements were collected in the proximity of the EC tower using the HyperSpectral Irradiometer (HSI, Cogliati, 2011; Meroni et al., 2011), designed for unattended high temporal frequency acquisitions. This instrument acquired spectra in the visible and near-infrared region (400–1000 nm) with a full width at half maximum of 1 nm.

HSI employs a rotating arm equipped with a cosine-response optic to measure alternately the sky (sensor pointing zenith) and the target irradiance (sensor pointing nadir), allowing the computation of the Bi-Hemispherical Reflectance factor (BHR, Schaepman-Strub et al., 2006). With this configuration the 97% of the total signal comes from a cone limited by a zenith angle of 80° and the maximum contribution to the measured signal comes from zenith angles around 45°. This means that with an installation height of 3.5 m above the investigated surface, the 97% of the total signal comes from a circular ground area of 40 m diameter (Meroni et al., 2011).

Hyperspectral reflectance measurements were acquired every 5 min from sunrise to sunset during the snow-free season in 2009, 2010 and 2011. The values of the VIs used in the following analyses are means of index values calculated for each reflectance spectrum collected between 11:00 and 13:00 local solar time to minimize changes in solar angle. For more details about spectral reflectance data acquisition and preprocessing see Rossini et al. (2012).

As a first step for scaling the results of this study to current and future Earth Observation systems, the VIs considered have been defined on the basis of MODIS (Moderate Resolution Imaging Spectrometer, NASA) and OLCI (Ocean and Land Colour Instrument on board of future Sentinel-3 satellite, ESA) spectral bands. In particular, we considered the following VIs: (i) the normalized difference vegetation index (NDVI) and the photochemical reflectance index (PRI) computed from MODIS simulated data, (ii) the red-edge chlorophyll index (CI_{re}), the green chlorophyll index (CI_g), the OLCI terrestrial chlorophyll index (OTCI) and the normalized difference red-edge (NDRE), computed from OLCI simulated data (Clevers and Gitelson, 2013). Their definitions using MODIS (M) and OLCI (O) spectral bands are provided in Table 1.

2.3. Data selection

Ground-observed PAR_i values were used to calculate $PAR_{potential}$ as the maximal PAR_i in 8-day- PAR_i windows (Gitelson et al., 2012; Peng et al., 2013). The relationship between maximal PAR_i and the day of the year (DOY) was fitted with polynomial functions to compute $PAR_{potential}$ at daily step. The best-fit functions, a second and a third order polynomial, were used to calculate mid-day and daily $PAR_{potential}$ respectively. Based on $PAR_{potential}$, the

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