

Interactive comment on “Remote sensing-based estimation of gross primary production in a subalpine grassland” by M. Rossini et al.

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Dear Reviewer, Thank you for the positive evaluation of the manuscript. The manuscript has been revised, according to the Reviewer's comments and suggestions. We have carefully considered each of them and have implemented the corresponding changes in order to improve the manuscript. We are confident to have fully answered all questions and incorporated all the recommendations in the revised paper. The Reviewer will find below the responses to the specific comments (typed in bold characters, while authors' replies are in italics).

Edits and comments for improvements: The introduction has to be strengthened. In particular a clearer argumentation on the importance of the proposed experiment and stated objectives is essential. In this context you could consider

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extending the discussion on advantages and disadvantages of present RS parameters or RS approaches used to estimate LUE (e.g., PRI, fluorescence, or the chlorophyll content). From this overview it could be concluded that the mechanistic understanding and knowledge of superimposing effects on RS proxies is currently insufficient and the outcome of the proposed research intents to partly clarify this issue.

We think that it could be very interesting extending the discussion on advantages and disadvantages of present RS parameters and approaches used to estimate LUE, but we would not lengthen too much the introduction. The reader can refer to recent review articles (Hilker et al. 2008b; Coops et al. 2010; Penuelas et al. 2011) to have a complete overview on advantages and disadvantages of RS approaches in LUE and GPP modeling. We added the following sentences at page 1716 line 19 in order to provide a clearer argumentation on the importance of the proposed experiment: “From this overview of RS approaches currently adopted to estimate GPP, it is evident that, although the ability to model GPP has increased considerably in recent years, a unique model for GPP estimation valid across different ecosystems and a wide range of environmental conditions has not yet been identified (Hilker et al., 2008b; Coops et al., 2010; Penuelas et al., 2011). The proposed research strives to improve our understanding of the links between optical and flux measurements to help developing models suitable for determination of global productivity from space.”

The discussion should reflect the representatives of the experiment in more detail. This is of particular importance as your findings might be interesting for several groups involved in observation activities (e.g., SpectNet). Please note that your findings are based on a small scale experiment by observing a structural less complex canopy. This of course has implications for your conclusions e.g., about the strength of PRI as proxy for LUE. PRI might work fine in your case but translating this approach to other sites, which are potentially characterized by a more complex structure, might be difficult. Please consider in your dis-

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discussion past studies highlight the strong structural dependency of the PRI (e.g., Hilker et al. 2008, *Science of the Total Environment* 404 or Grace et al. 2007, *Global Change Biology* 13). In analogy to this, please discuss the representativeness of the other components (i.e., NDVI as proxy for LAI and fIPAR; MTCI as proxy for CAB) needed to monitor GPP.

According to your suggestions and the indication of referee 2, the discussion has been reworded as:

“ Unattended high temporal and spectral resolution canopy spectra coupled with EC data were acquired for two consecutive years on a subalpine grassland to exploit different strategies for evaluating the potential of RS in estimating carbon uptake. Collected data were processed using automatic procedures which took into account a series of quality criteria related to the illumination conditions during the acquisition and the system performances and reliable time series of VIs providing useful information on the time course of different grassland variables have been obtained. In particular, MTCI was the index most related to Chl content and NDVI to fIPAR_g and LAI, confirming previous studies on different ecosystems (Dash and Curran, 2004; Huemmrich et al., 2010; Panigada et al., 2010). PRI indexes based on green reference bands (555 and 551 nm) were instead the indexes most related to LUE_g (Table 3). To our knowledge this is the first study showing the potential of PRI to estimate ϵ expressed in terms of LUE_g, representing a more physiologically realistic way of quantifying the PAR effectively used for photosynthesis compared to ϵ more widely computed as GPP/APAR or GPP/incident PAR (see the recent review by Garbalsky et al. (2011)). It is worth noting that, as opposed to PRI_{555/551}, PRI computed using a reference band positioned in proximity of the Chl absorption well (645 and 667 nm) were more related to leaf Chl concentration than LUE_g (Table 3). Therefore the choice of the reference band used to compute PRI appears to play a key role in the determination of the sensitivity of this index to photosynthetic efficiency. This result confirmed recent studies by Middleton et al. (2009) and Goerner et al. (2011), although we believe that further

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studies are needed to explore the best reference band for estimating PRI across vegetation types and temporal scales. Furthermore, the translation of these findings to more complex ecosystems (e.g. forests) is not trivial due to the effects of canopy structure on the relationship between PRI and LUE (Barton and North, 2001; Hilker et al., 2008a; Cheng et al., 2010, 2011). Most VIs peaked in the first half of July, in correspondence to maximum canopy development, attested by maximum values of LAI and GPP (Figs. 2, 3 and 4). However, due to the different sensitivity of VIs to grassland variables, their minimum and maximum values occurred at different DOYs and their slope changed in time. For example, PRI₅₅₅ and PRI₅₅₁ had a less distinct seasonal course and they reached minimum values about 10–20 days after full canopy development. This time-lag observed between the peak of PRI_{555/551} and indexes using red bands can be explained by considering selective light absorption by photosynthetic pigments. Chlorophyll controls the energy flux that can be transferred to the dark reaction of photosynthesis and, because of the lower Chl absorption of green light (Terashima et al., 2009), indexes based on green wavebands may therefore reach their peak later in the season compared to indexes involving a strong Chl absorption band in the red spectral region. The analysis conducted with LUE models indicated that GPP can be successfully modelled using RS indexes or combining RS indexes with meteorological data. Results of model 1 confirmed that VIs related to canopy greenness, and specifically to Chl content, explained most of the variability in GPP in an ecosystem characterized by a strong seasonality in green-up and senescence such as grasslands and crops (Gitelson et al., 2006; Wu et al., 2009; Peng et al., 2011). MTCI was the best predictor for both GPP_m and GPP_d, confirming its better performances with respect to EVI in estimating GPP in grassland ecosystems (Harris and Dash, 2010). However, as highlighted by Gitelson et al. (2008), this kind of models is not able to describe variations in GPP due to short-term (hours to days) variations of illumination or environmental stresses (such as temperature and water availability). This limitation was overcome by exploiting models 2 and 3, which take into account variations related to changing incident irradiance. Somewhat surprisingly, the inclusion of incident PAR in model for-

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mulation did not result in improved estimation of GPP. However, using $\ln(\text{PAR})$ instead of PAR in model parameterization, the accuracy of GPP estimation improved. This means that the grassland increases its efficiency at low values of incident PAR while, given its moderate LAI and erectophile leaf angle distribution, it is not able to fully exploit high radiation loads. This higher efficiency at low PAR can probably result from more diffuse light scattered within the canopy and less photoinhibition on the top of the canopy, which lead to a reduced tendency toward saturation (Chen et al., 2009). Furthermore, in our case, low PAR conditions can probably be associated with precipitation events, associated with high SWC and low temperatures, which are known to stimulate photosynthetic efficiency in alpine plants (Billings and Mooney, 1968; Korner and Diemer, 1987; Polley et al., 2011). To account for stress-induced changes in photosynthetic efficiency, the PRI was also tested to directly infer ϵ from RS data. The inclusion of PRI in model formulation showed slight improvement in GPP estimation, in particular for GPP_m . Physiologically, this means that in our ecosystem, APAR_g is coupled with ϵ , and the inclusion of the ϵ term in the model slightly improves its ability to track seasonal variations. Similar results were obtained by Rossini et al. (2010) and Gitelson et al. (2006) in other ecosystems characterised by strong seasonal variability (crops). Modelling ϵ as a function of meteorological conditions generally results in lower accuracy in GPP estimation (Table 5). To evaluate the effect of the temporal resolution of VI time series on GPP estimation, 16-day composite time series of MODIS (i.e. NDVI, EVI and PRI) and MERIS-derived (MTCI) products were then simulated and downscaled to daily frequency and results were compared. Short-term variability (hours to days) in both VIs and flux data is dampened out by averaging data over two weeks, thus leading to good performances when fitting GPP against resampled VIs (Tables 6 and 7). However, when these models are used to simulate annual GPP, they inevitably provide a decrease in the accuracy of total GPP estimation. The results from models driven only by RS and PAR variables were as good as, and in many cases better than, the more complex MOD17 GPP model which requires meteorological and vegetation type data inputs in addition to RS indexes. As with several previous studies

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on VIs, since the estimation of model coefficients is based on a semiempirical regression technique and is conducted only for a single site, further verification studies should be conducted under other vegetation and climatic conditions and at different sites potentially characterized by a more complex structure to fully explore the efficacy of this method and make general inferences. This study provides a conceptual background for GPP estimation using real satellite data and a better understanding of the spatio-temporal variations of productivity. The choice of the index depends on the spectral characteristics of the satellite sensor being used. In particular, MTCI can be derived from satellite systems with spectral bands in the red edge region (MERIS in this study), EVI and NDVI from satellites having blue, red and near-infrared bands (MODIS in this study) and PRI from satellites with a narrow green band centered at 531 nm (MODIS in this study). Our results show that red edge indexes like MTCI can be used both as single variables or in combination with PRI and meteorological variables to obtain accurate estimations of GPP in a grassland ecosystem. Unfortunately, the computation of MTCI and PRI from a single satellite is currently only feasible from the NASA Earth Exploring One (EO-1) Hyperion sensor, which is near the end of its lifetime with 12 years in orbit (launched November 2000). The launching of new image spectrometers, such as the NASA HypIRI or the DLR EnMAP, will allow the calculation of a greater number of indexes, including MTCI and PRI, thus offering significant potential to enhance the accuracy of the assessment of CO_2 uptake in terrestrial ecosystems from space. Finally, we remark that NDVI and EVI showed poorer performances when used as single variables to predict GPP and it is preferable to use these indexes in combination with PRI and meteorological variables to improve accuracy in GPP modelling."

We gave serious attention to all the minor revisions requested. Grammar was corrected and sentences rephrased as suggested.

Other editorial comments: Abstract Page 1713, line16: "... the NDVI showed better correlations with LAI ..." Better than what? Please complete the sentence.

According to the Reviewer's suggestion, the sentence was corrected as "In this study,

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the normalized difference vegetation index (NDVI) was the index best correlated with LAI and $fIPAR_g$ ($r = 0.90$ and 0.95 , respectively), the MERIS terrestrial chlorophyll index (MTCI) with leaf chlorophyll content ($r = 0.91$) and the Photochemical Reflectance Index (PRI_{551}), computed as $(R_{531} - R_{551}) / (R_{531} + R_{551})$ with LUE_g ($r = 0.64$)."

Page 1713, line 21: Please add: "based on Monteith's light use efficiency model"

This expression was corrected as the Reviewer indicated.

Introduction Page 1715, line 7: You wrote: "e.g., enhanced vegetation index, EVI, Huete et al. 2000". From this the reader could get the impression that Huete et al. is an index, which is of course not true. Please set brackets or so.

According to the Reviewer's suggestion, the sentence was corrected as "e.g., enhanced vegetation index (EVI), Huete et al. 2000".

Page 1716, lines 12–15: This argumentation would mean that crops per se are unstressed. I do not agree on this statement.

According to the Reviewer's suggestion, the sentence was corrected as "Successful results have been obtained in agricultural crops (Gitelson et al., 2008). In this study, the investigated crops didn't suffer short term environmental stresses. In such conditions, an independent estimate of ϵ can be unnecessary due to its correlation with chlorophyll content, allowing the use of chlorophyll-related VIs as a proxy of photosynthesis or primary productivity (Sims et al., 2006a)."

Methods Page 1718, line 7–8: Do you mean daily time series or annual time series?

The sentence was reworded as "The percentage of green components of the canopy derived from image classification was fitted with a 4th order polynomial to obtain the seasonal courses of greenness at daily time-step."

Page 1718, equation 2: Please introduce the abbreviations for PAR_i and PAR_t

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As suggested, the sentence "where PAR_i , PAR_t and PAR_r are the incident, transmitted and reflected PAR, respectively." was added.

Page 1719, line 9: Please reword: "...were partitioned into ecosystem respiration and GPP."

The sentence was modified.

Page 1719, line9: Please shortly introduce why a gap-filling is needed.

As suggested, the paragraph was reworded as "The turbulent vertical fluxes of CO_2 and latent and sensible heat were measured using the eddy covariance technique (Baldochi et al., 1996). According to EUROFLUX methodology (Aubinet et al., 2000), only half-hourly data in which the theoretical requirements of the EC technique are fulfilled were retained for the following analyses and gap filling techniques were used to re-create continuous NEE time series. To evaluate temporal variations of CO_2 fluxes and compare these data with spectral measurements, half-hourly measurements of NEE were partitioned into ecosystem respiration and GPP. For the gap-filling and partitioning, the marginal distribution sampling (MDS) method and the partitioning method described in Reichstein et al. (2005), implemented in the online tool (<http://www.bgc-jena.mpg.de/bgc-mdi/html/eddyproc/>), were used. Different CO_2 flux metrics were used in the analyses: midday mean GPP (GPP_m) for the same time period used for calculating spectral properties (11:00–13:00 local solar time) and daily sums of GPP (GPP_d). A detailed description of the EC flux measurements and flux footprint is reported in Migliavacca et al. (2011)."

Page 1721, line 28: Please reword to: "...averaging the index values collected between"

This expression was corrected as the Reviewer indicated.

Page 1723, line 3: Please reword to: "the model comparison"

This expression was reworded as the Reviewer indicated.

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Page 1723, line 11: Please define $\ln(\text{PAR})$.

As suggested, the definition “the logarithm of PAR ($\ln(\text{PAR})$)” was added.

Best regards,

Micol Rossini co-authors

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