Dear Editor,

We really appreciate the detailed and constructive comments given by yourself and the two Reviewers. We respond below to each of the comments, indicating how they have been integrated into the revised version of the manuscript. Main comments are numbered (1), (2), (3),… and our response is indicated by the sign (->). The corrected manuscript with "Track Changes" is attached at the end of the response.

With best regards,

Albert Porcar-Castell

**Comments by the Editor (G. Wohlfahrt) and Response by the Authors**

**(1)** The authors nicely work out the crucial role that in situ measurements play in upscaling by linking between eddy covariance flux tower footprints and remote sensing. However, how to achieve this link receives much less attention in the paper (altogether around 20 lines on p. 13093-13094), compared to technical, technological and deployment issues of in situ measurements. The major conclusion I draw from this section is that the present approach of in situ flux tower sampling actually is unable to provide this link due to the mismatch in footprints and that new tools are required to establish this link. Does that mean that all previous and ongoing measurements on flux towers where in situ measurements were made on just a small fraction of the flux tower footprint are useless in providing this link except for the most homogeneous sites? Is there a way/are there examples of quantifying the associated uncertainty? The authors push UAVs as the 'silver bullet' to resolve the footprint mismatch dilemma. However, UAVs share some of the problems of satellite remote sensing, that is typically measurements from UAVs will provide data with poor temporal resolution compared to in situ continuous measurements. How to link between periodic UAV and continuous in situ measurements and further to the eddy covariance flux footprint?

In summary, I think that the issue of linking between in situ spectral and eddy covariance flux measurements, which is one of the central questions of EUROSPEC, provides much more which could and should be discussed and encourage the authors to think about how to expand the corresponding section in the paper. Ideally, this would be shown on the basis of some case study, but a conceptual treament of the necessary steps would also be useful.

-> We thank the Editor for this critical and justified comment. We agree that the issue of upscaling deserved more explanation. Also, the drawbacks posed by the mismatch between footprint and optical data were unjustly presented in a too negative tone in the previous version. The mismatch between footprint and optical data may add noise or bias to the seasonal relationship between flux and optical data but the relationship will still remain a powerful tool for upscaling activities. We have completely rewritten this section and clarified these points.

In turn, UAVs represent a tool that can be used to characterize the footprint/pixel variability, the BRDF of the target surface, and to conduct robust statistical sampling. These are issues that do not require high temporal resolution but rather, spatial versatility. Linking flux data with satellite data is complicated both by the temporal and spatial mismatch between datasets. Subsequently, while in situ spectral measurements help us elucidate the link between optical and flux data across time, punctual UAV measurements will help us study the impact of scale, complementing *in situ* spectral data. We present these points in the edited Section 3.4 and included also a new figure that we hope will help clarify the role of *in situ* spectral measurements and UAVs in upscaling activities.

**Comments by Referee 1 (J. Moreno) and Response by the Authors**

The paper represents a review of achievements and conclusions derived from the EUROSPEC COST activity, and contains relevant recommendations for implementation of networks of proximal optical measurements in flux towers to complement/validate satellite data in the context of global carbon cycle research.

The content of the paper can probably be taken as a reference in the field, particularly due to the useful recommendations provided towards the implementation of a network of optical spectral measurements, operated in continuous mode in association with flux tower sites and other ecological monitoring sites, serving then as a tool for the validation of modelling approaches and other type of observations, particularly satellite data. The review character of this contribution makes this paper quite relevant and of general interest.

**(2)** The structure of the paper is adequate and in general it is quite well written. The main aspects in the paper are the identification and description of the sources of variability in the measurements and the derived recommendations. Three sources of variability are described, but one source of variability which is only indirectly addressed, and which is critical for this type of measurements, is the temporal stability in the measurements and temporal stability in calibration. Issues such as the heating of instruments along a diurnal cycle can bias the measurements, as well as long-term drifts in instrument behaviour of instrument calibration. Given the experience of the authors during EUROSPEC and related studies, it would be adequate to show more explicitly (maybe through a new dedicated Section 3.2.4) how relevant are such stability effects, quantifying the changes experienced.Temperature-controlled equipment is complex and expensive, and guidelines can be provided on when such temperature stability becomes more critical and when other simple methods can be used, giving guidelines about the amount of error that would be expected. At the same time, it would be adequate to indicate the different stability effects on absolute terms and on relative inter-band calibration (i.e., for multispectral sensors, indicate which bands or spectral ranges are more sensible to instabilities). Some indication about the frequency needed for crosscalibration of instruments, typical order of magnitude of the accuracy in radiometric calibration achieved for these types of instruments, typical temporal drift of calibration, etc. can be details than can provide more quantitative information useful for the readers.

-> We thank the reviewer for raising this very relevant point. We agree on the importance of the sensor stability and in that we had not dealt with it with sufficient detail. Unfortunately, we were not able during EUROSPEC COST Action to conduct a systematic and quantitative analysis of the multiple stability effects and accordingly we cannot go into the subject with the level of detail that the topic deserves. This is probably a subject for a Review paper by itself which hopefully comes out sometime in the future. We have however followed the advice of the Reviewer and written a whole new section (3.2.4) introducing the subject. Although the section does not present a detailed analysis with a checklist and guidelines, due to the reasons mentioned earlier, we try to introduce the main tradeoffs and list a number of questions that the users should keep in mind when planning and designing long-term *in situ* spectral measurements, as well as calibration and subsequent data processing protocols.

**(3)** Section 3.2.3 is named “Field-of-view heterogeneity”, which seems to be related to the heterogeneity of observations inside the field of view of the instrument. In fact, the description is not about surface heterogeneity within the field-of-view, which is unavoidable at all observation scales and depends very much on the objective of the measurements. What is addressed in Section 3.2.3 corresponds in fact to two different issues: (a) the knowledge of the actual instantaneous field-of-view (optical) of the instrument, related to the PSF/MTF and related optical characterization, basically given by a 2D response function over the observation area; and (b) the case of sensors having focal-plane separation of spectral bands (either by the spatial disposition of detector in the focal plane, or by aberrations in the optical acquisition of the signal), causing that the instantaneous field-of-view is different for each spectral band. The first aspect (a) can be compensated by a dedicated laboratory characterization of the instrument for any kind of design, while the second aspect (b) requires a proper design of the instrument. Implications are different and have different impact on the data processing and interpretation.

->The reviewer is right in that the title was not consistent with the contents of this section. The title is now changed to "The fields-of-view of field spectrometers and multispectral sensors".

The purpose of this section was to highlight that the FOV of spectrometers needs more than cursory consideration when instruments and fore optic combinations are being selected for field use and to direct readers' attention to Mac Arthur et al 2012 and Eklundh et al 2011 for a full discussion of the subject.

Field spectrometer manufacturers normally specify an included solid angle for an instrument/fore optic combination FOV inferring that it is conical and (from the references provided in the text) it is usually assumed that all points from within the surface area delimited by the FOV are weighted equally in the integrated measurement recorded. As field spectrometers are not imaging instrument PSF or MTF are not normally discussed or used in spectrometer specifications. A more appropriate term is the Directional Response Function (as defined in "Methods of characterizing illuminance meters and luminance meters," Comm. Int. L'Eclairage, Vienna, Austria, Tech. Rep. 69, 1987). The use of this term recognizes that points within the FOV (as the reflectance form each point within the FOV will be received by the instrument from different angles) will have different weightings in the integrated measurement recorded. This weighting is a function of the fore optic and the optical design of the spectrometer as explained in detail in the (Mac Arthur et al 2012). The revised version has been modified accordingly to clarify that we are dealing with non-imaging spectrometers and give more details on the DRF. This was clearly confusing in the previous version as the Reviewer was referring to terminology usually applied to in imaging systems.

**(4)** An aspect which is not discussed in the paper, and that becomes essential to analyse scaling issues from single flux tower measurements to spatially continuous remote sensing data, is the role of spatial statistics and statistical sampling issues. Ground sampling following statistical basis is essential to properly formalize a mean value for the averaged measurement and the associated statistical error, which depends on the sampling strategy followed. The opportunity to use UAVs in such ground sampling provides a method to follow different possible statistical sampling procedures of the ground area (tower footprint) or the remote sensing pixel. Some comment about statistical background should be included when analysing upscaling aspects in Section 3.4.

-> We treat the statistical sampling issues and the role of UAVs in connection with comment (1) above.

**(5)** Box 1 is particularly relevant, but some potential changes can be implemented: (a) Change "high signal to noise" by "High signal-to-noise ratio" (b) Change "Ideal cosine directional response function" by "Optimal cosine directional response function" (the ideal one is probably not achievable) (c) The "Low temperature-sensitivity" condition probably means thermal stability in the measurements (for a temperature sensor one would like to have high temperature sensitivity!) (d) "Operating temperature range matching the wide thermal distribution of terrestrial plant species" means in fact the range of environmental conditions, but probably for a given site the overall range is more limited than the overall range when all potential sites are considered together. No necessarily every single instrument will operate in the full range of conditions. This can be clarified.

-> Changes (a), (b) and (c) have been made to Box 1 as suggested by the Reviewer. For point (d) we have edited the text as follows: For global networks: Operating temperature range matching the wide thermal distribution of terrestrial plant species, from -50ºC to 50ºC. For local measurements: temperature range matching local variation.

The purpose of considering a wide temperature range during sensor design is to cover the demands of standardized measurements across global networks. For such applications, the same sensor design/type would need to be deployed across sites, which may include arctic and tropical sites.

**(6)** In Table 1, for SFOV it is stated "Need for temperature control to derive radiometric quantities in absolute units", but in fact the temperature control does not guarantee calibration in absolute units. Here reference should be to consistent time series of measurements, but not necessarily absolute units, which imply calibration to a reference. The same is true for DFOV given as "Need to temperature control to derive both radiometric quantities in absolute units and reflectance ratios". Difference between absolute units (calibration to a reference) and temperature control for stability (consistency in calibration) should be clarified.

-> We thank the reviewer for picking up this inconsistency. We have rephrased these points as:

SFOV (disadvantages): "Either temperature control, or characterization of the temperature sensitivity of the instrument and post-processing, are needed to acquire consistent time series of radiometric measurements".

DFOV (disadvantages): "Either temperature control, or characterization of the temperature sensitivity of each of the instruments and post-processing, are needed both for derivation of reflectance factors and to acquire consistent time series of radiometric measurements".

**(7)** Also in Table 1, it is stated that hyperspectral systems have "Option to process the data with radiative transfer models", but this is true for all data type, multispectral or hyperspectral, and not exclusive of hyperspectral.

-> The reviewer is right. Our point here was to indicate that hyperspectral data provides more information, compared to multispectral data, which can be used to better constrain the inversion of radiative transfer models. We have reformulated this sentence as: "Increased range of possibilities for inversion of radiative transfer models"

**(8)** In page 13078, lines 22-23 it is stated that "Spectral measurements can be classified into multispectral or hyperspectral depending on the number of bands." In fact, the number of bands is a bad criteria to classify sensors, and has been misleading sometimes. Better refer to spectral resolution versus spectral range covered, contiguous spectral coverage versus discrete coverage, etc.

and

**(9)** Figure 2 is not particularly appropriate. As it is, it looks like multispectral data (discrete data) is a subset of the continuous sampling (same Gaussian response, but different number of Gaussians). In fact, discrete cases tend to be wide filters that show a response far from a Gaussian. The continuous case shown corresponds typically to a spectrometer, but the discrete case looks like the case where some bands of the spectrometers are used (i-e, case of MERIS or OLCI). The general case, however, is not the one illustrated in the figure.

-> The terminology we used is consistent with previous work cited in that section, in particular that of Balzarolo et al. (2011). However, we agree that the differences between multispectral and hyperspectral measurements can be sometimes misleading as they may overlap. We have clarified these aspects in the revised version and formatted also Figure 2 following the advice from the reviewer, which we hope will help to clarify this point.

"Accordingly, spectral measurements can be classified into multispectral or hyperspectral ~~depending on the number of bands."~~

The bandwidth of these sensors (in terms of full width at half the maximum response, FWHM) is in the order of 10 nm or greater and the sampling across a specific spectral range is typically discrete (Fig. 2)

Some other minor editorial aspects:

Page 13071, line 21: change "carbon cycle" by "terrestrial components of the carbon cycle", or "terrestrial carbon balance" or more directly "GPP". The problem comes from the fact that carbon cycle includes other temporal and spatial scales and contains also carbon exchanges in oceans, etc., just to be more precise.

->Rephrased: "…estimates of GPP over terrestrial ecosystems."

Page 13074, line 20: change "recent technological and technical advances" by "recent technical advances"

->Done

Page 13078, line 12: change "down-welling and up-welling reflectance" by "downwelling and up-welling radiances"

->Done

Page 13080, line 22: change "in situ field measurements to measure: : :" to avoid word repetition.

->"measure" replaced by "quantify"

Page 13081, line 1: change "at or off-nadir" (not clear the meaning, should be "at nadir or off-nadir" ?)

->Changed by "at nadir or off-nadir"

Page 13083, line 21: change "Because the situation where the same sensor is used in all sites is not: : :" by "Because the use of the same type of sensor in all sites is not: : :"

->Done

Page 13084, line 25: change "instrument readout" by "instrument readout time"

->Done

Page 13085, line 14: change “angular-dependent time degradation” by “angulardependent time degradation at such wavelengths”.

->Done

Page 13086, line 7: change “the response across that area is the same at all points” by “the response across that area is the same for all points inside the given FOV”.

->Done

Page 13086, lines 14-15: change “Even when less optically complex spectrometers, measuring only across the VNIR region are considered, the Earth Surface: : :” by “Even when less optically complex spectrometers are considered, for instance measuring only across the VNIR region, the Earth Surface: : :”

->Done

Page 13087, line 13: change “science and industry was suggested” by “science and industry was suggested, particularly to produce prototypes for new instruments”

->Done

Page 13094, line 22: change “resolution” by “resolutions” (plural)

->Done

Page 13095, line 13: change “Network” by “network” (no need for capital)

->Done

Page 13095, line 25: change “Tools” by “tool” (no need for capital)

->Done

Page 13096, line 3: change “Networking” by “networking” (no need for capital)

->Done

Page 13097, line 1: change “has” by “have”

->Done

Page 13098, line 24: here the word “drones” is used, when previously they were referred as UAVs or RPAs. Better use a consistent wording or clarify differences, if any, between drones and UAVs.

->Replaced it by UAVs for consistency

Page 13099, line 5: change “community” by “communities”

->Done

Figure caption of figure 2: change “spectra” by spectral”.

->Done

In Table 1, Configuration hemispherical-conical: change “Small Sampling area” by “Small sampling area”.

->Done

**Comments by Referee 2 (J. Gamon) and Response by the Authors**

This review of recent EuroSpec advances represents a valuable contribution to the emerging field of integrated optical - flux sampling and to the larger topic of ecosystem monitoring within the context of the global carbon cycle. The paper provides a broad context, nicely summarizes the recent history of EuroSpec and similar efforts elsewhere, and describes the recent formation of the Optimise program to carry the work forward. The manuscript includes a useful and insightful discussion of recent technical advances, helpful critiques of current limitations (e.g. gaps in current international efforts as well as technical challenges), and suggestions for future progress in the field of proximal remote sensing. It also provides a solid argument for developing a concerted sampling and data approach to better link the flux tower network to remote sensing.

Overall, this is a well-written and comprehensive review.

A few points to consider for possible addition/clarification:

**(10)** Page 13073, line 6 - The statement that optical estimates of fAPAR are affected by canopy structure is not uniformly true for all optical methods. Broadband measurements clearly have trouble, but spectral methods can distinguish green from non-green, using transmitted or reflected light, and this is largely the basis for using vegetation indices like NDVI. However, it is true that ground validation methods of fAPAR (e.g. using light bars based on PAR that do not distinguish color) are often strongly confounded by non-green canopy materials, and the literature has often been vague on this point. So this is probably more of a problem for our ground validation than for our satellite indices.

-> We apologize for the lack of clarity in our previous version. What we had in mind in this sentence was indices such as the NDVI obtained with multiband sensors rather than fAPAR estimates using PAR sensors. We agree with the reviewer that hyperspectral methods will be less affected by canopy structure compared to broadband measures using PAR sensors or other broadband sensors. Yet, NDVI estimates are still affected by the reflectance properties of non-green elements in the canopy, like bark or senescing leaves, (e.g. Campbell & Borden, 2005, Can. Entomol. 137:719-722; di Bella et al. 2004, Int J Rem Sens, 25:5415-5427) or wavelenght-dependent scattering effects within the canopy (e.g. Knyazykhin et al. 2012). The effect of structure on VI-based estimates of fAPAR is also mentioned in Gamon 2015. We have reformulated the paragraph as:

“It is important to note that fAPAR in Eqn 1 corresponds to green fAPAR, in contrast to total canopy fAPAR where both photosynthetic and non-photosynthetic elements such as wood contribute to PAR absorption. Green fAPAR has been widely estimated using reflectance-based vegetation indices as proxy, notably the Normalized Difference Vegetation Index (NDVI) derived from red and near-infrared (NIR) reflectance (Rouse et al., 1973; Tucker, 1979). These vegetation indices correlate better with green fAPAR than with total fAPAR because their spectral formulation can significantly discriminate green from non-green elements (Gamon et al. 1995). However, canopy structural factors, background properties, or sun-target-sensor geometry can complicate the estimation of green fAPAR with vegetation indices (Di Bella et al. 2004; Gamon 2015, Knyazikhin et al.2012)”

**(11)** Page 13073, line 9 – vegetation indices (e.g. NDVI) are more closely related to green fAPAR (i.e. the fraction of PAR absorbed by green canopy material) than total fAPAR, and this should probably be clarified.

-> See Response to comment (10)

**(12)** Page 13073, lines 22-23 – It may be true that other indices besides NDVI are better related to LAI, but are these any better related to green fAPAR? Green fAPAR, not LAI, is the real concern in the LUE model, so these discussions of saturation and LAI may not so terribly important from this perspective. Since LAI is non-linearly related to fAPAR, LAI may not be a meaningful metric for the LUE model. Given that LAI is ill-defined for much of the world's vegetation (think bryophytes, evergreen conifers, or most desert plants), it may be best to avoid a reliance on LAI-based approaches, at least when determining canopy light absorption. Optical approaches like fAPAR (or NDVI) that can provide a more direct measurement of light absorption by green tissues may actually be more relevant and useful than this discussion of LAI non-linearity suggests.

-> It is true that if we stick to the formal LUE paradigm green fAPAR is the main concern and we should not talk about LAI. However, we cannot rule out the fact that LAI and spectral indices related to LAI may be more efficient for estimating GPP particularly in dense canopies. This illustrates the need to keep the way open for alternative interpretations, models and hypothesis to relate optical data to flux data in addition to the LUE model. To avoid confusion, we rewrote and moved the following paragraph so that it is separated from the description of the LUE model:

"Noting that the relationship between NDVI and fAPAR tends to saturate at high canopy densities (Myneni and Williams, 1994; Olofsson and Eklundh, 2007) also other approaches have been used to estimate vegetation carbon uptake. For example, the Enhanced Vegetation Index (EVI) (Huete et al., 2002) efficiently describes the seasonal variability in GPP across both dense and sparse vegetation canopies (Schubert et al., 2010, 2012; Sims et al., 2006; Sjöström et al., 2011; Xiao et al., 2004a, 2004b; Xiao et al., 2010). More recently, the plant phenology index (PPI) (Jin and Eklundh, 2014) has been shown to be linearly related to green leaf area index (LAI), and better related to seasonal GPP variations than NDVI and EVI of coarse-resolution MODIS data at northern latitudes. This illustrates the value of investigating the relationship between carbon uptake and spectral information in flux footprint areas beyond the LUE model depicted in Eqn 1."

**(13)** Page 13073, lines 5-6 – Efficiency variation is considered indirectly through meteorologically-based variables (which may not be available for a given site).

-> We agree that a significant part of the inter-seasonal variation in LUE can be reproduced via the instantaneous effect of an environmental scalar. What we wanted to emphasize is that the slow dynamics in physiology and phenology are not considered. We have rephrased accordingly:

"while inter-seasonal variability due to plant phenology and photosynthetic dynamics (Lagergren et al., 2005) is only considered via the instantaneous effect of the environmental scalar, which cannot reproduce the slow response dynamics of vegetation."

**(14)** Page 13081, lines 19-21 - By "averaging out" these effects, aren't bi-hemispherical measurements LESS sensitive to BRDF effects than hemispherical-conical by? Can you provide a citation to support this point?

-> We are aware of a few studies providing a comparison of the sensitivity to BRDF effects of bi-hemispherical and hemispherical-conical measurements. In Meroni et al. (2011) the bi-hemispherical reflectance collected with the HSI was compared with the hemispherical-conical reflectance collected with a traditional field spectroscopy set-up with nadir viewing geometry (FOV f 25° and white reference panel to estimate incident irradiance). The bi-hemispherical and hemispherical-conical reflectance differed both in intensity and shape of the diurnal cycle. In particular the bi-hemispherical reflectance was less affected by BRDF effects for measurements collected around solar noon but reflectance markedly increases at large illumination zenithal angles. The effect of large illumination angles on the bi-hemispherical reflectance is also reported in Strub et al. (2003, Geoscience and Remote Sensing, IEEE 41:1034-1042, doi: 10.1109/TGRS.2003.811555 ).

We thank the reviewer for this justified comment. The text in the previous version of the manuscript was confusing because the comparison in Meroni et al. (2011) refers only to hemispherical-conical measurements collected with a nadir view. We have modified the text as:

"bi-hemispherical measurements tend to be more sensitive to variations in illumination geometry compared to hemispherical-conical measurements collected with a nadir view particularly for large illumination zenith angle ~~, as affected by the bi-directional reflectance function (BRDF) of the surface~~."

**(15)** Page 13085, lines 12-13 - Some brief mention of the panel options here (and their pros/cons) would be helpful. For example, most are made of teflon (PTFE) and users can purchase Spectralon (for a high price) or can make panels from virgin white teflon (at considerable cost savings but slightly reduced performance).

-> Thanks for pointing out to this improvement. We have added the following paragraph:

"Selection of reference panel material is also very important. Manufacturers of reference panels for spectroscopy such as LabSphere (Spectralon ®) or SphereOptics (Zenith polymer ®) use a sintered fluoropolymer manufactured to have a very high reflectance, possibly in excess of 96% and approximate a Lambertian reflectance across the 400 nm to 2,500 nm spectral. Alternatively, low cost PTFE sheets (i.e. Teflon) can be purchased at lower cost. However, PTFE sheets have lower reflectance, approximately 80%, and have higher specular reflection. Also, because PTFE sheets are not manufactured to be used as 'references' there may be variability between individual sheets and wavelength dependent reflectances may be unknown. Overall, PTFE sheets are not recommended as field spectroscopy reference standards."

# EUROSPEC: At the interface between remote sensing and ecosystem $CO_2$ flux -measurements in Europe

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## Abstract

Resolving the spatial and temporal dynamics of gross primary productivity (GPP) of terrestrial ecosystems across different scales remains a challenge. Remote sensing is regarded as the solution to upscale point observations conducted at the ecosystem level, using the eddy covariance (EC) technique, to the landscape and global levels. In addition to traditional vegetation indices, the photochemical reflectance index (PRI) and the emission of solar-induced chlorophyll fluorescence (SIF), now measurable from space, provide a new range of opportunities to monitor the global carbon cycle using remote sensing. However, the scale mismatch between EC observations and the much coarser satellite-derived data complicates the integration of the two sources of data. The solution is to establish a network of *in situ* spectral measurements that can act as bridge between EC measurements and remote sensing data. *In situ* spectral measurements have been already conducted for many years at EC sites, but using variable instrumentation, setups, and measurement standards. In Europe in particular, *in situ* spectral measurements remain highly heterogeneous. The goal of EUROSPEC Cost Action ES0930 was to promote the development of common measuring protocols and new instruments towards establishing best practices and standardization of ~~*in situ* spectral~~these measurements. In this review we describe the background and main tradeoffs of in situ spectral measurements, review the main results of EUROSPEC Cost Action, and discuss the future challenges and opportunities of *in situ* spectral measurements for improved estimation of local and global estimates of GPP over terrestrial ecosystems.~~carbon cycle.~~

Keywords: Carbon balance, Chlorophyll Fluorescence, COST Action, Flux Measurements, ICOS, Optical Sampling, Proximal Sensing, Remote Sensing, Spectral Reflectance, Greenness, SpecNet, FluxNet, Vegetation Indices.

## 1. Introduction

Accurate quantification of carbon fluxes across space and time is of primary importance to climate scientists, land use managers, and policymakers (Beer et al., 2010; Ciais et al., 2014; Joos et al., 2001). Carbon budgets can be estimated with high accuracy at the ecosystem level (e.g. Clement et al., 2012; Grace et al., 2006; Zanotelli et al., 2015) but global estimates of Gross Primary Productivity (GPP) and carbon balance in terrestrial ecosystems still have high levels of uncertainty (Alton, 2013; Balzarolo et al., 2014; Beer et al., 2010; Enting et al., 2012; Jung et al., 2011; Keenan et al., 2012; Piao et al., 2013). The primary method used to measure the net flux of carbon dioxide ($CO_2$) between the Earth's surface and the atmosphere is eddy covariance (EC) (Aubinet et al., 2000; Baldocchi, 2008; Goulden, 1996). The EC technique has dramatically improved our understanding of inter and intra annual variations in the carbon fluxes at the ecosystem level (Baldocchi, 2008). However, upscaling these local observations to the landscape and regional level remains a challenge. Because EC measurements require sites with moderate to low slopes, there is a bias towards certain topography and ecosystem types (Göckede et al., 2008). In addition, the footprint of EC measurements is not constant and varies with wind direction and speed, measurement height, and vegetation structure (Schmid, 2002; Vesala et al., 2008). Although footprint size can be controlled to some extent with tower height, the resulting data may still represent different vegetation communities depending on time-varying wind direction. Footprint analysis (e.g. Kormann and Meixner, 2001) is required to cope with this source of variability that complicates the interpretation of flux data. Despite these limitations, the global number of active flux sites exceeds 500 and is constantly increasing (Schimel et al., 2015). The question remains as to how to better upscale these point measurements to the landscape, regional and global scale.

Given that ~~many~~ most of the factors affecting carbon fluxes have strong spatial and temporal components it is difficult to envisage upscaling without the use of remote sensing data, the only means to provide regular and spatially continuous observations of the Earth surface. One of the most widely applied approaches to assimilate remotely sensed data is to estimate GPP through a light use efficiency (LUE) model (Monteith, 1972; Reichstein et al., 2014; Ruimy et al., 1994):

$$GPP = PAR \ x \ fAPAR \ x \ LUE \qquad (1)$$

where GPP is expressed as a function of the incident photosynthetically active radiation (PAR), the fraction of this PAR that is eventually absorbed by vegetation (fAPAR), and the efficiency by which absorbed PAR is used to assimilate atmospheric $CO_2$, termed the light use efficiency (LUE) (Hilker et al., 2008a). The fAPAR in Eqn 1 is a function of canopy chlorophyll content or green biomass (i.e. more chlorophyll results in more absorption). It is important to note that fAPAR in Eqn 1 corresponds to green fAPAR, in contrast to total canopy fAPAR where both photosynthetic and non-photosynthetic elements such as wood contribute to PAR absorption. Green fAPAR has been widely estimated using reflectance-based vegetation indices as proxy, notably the Normalized Difference Vegetation Index (NDVI) derived from red and near-infrared (NIR) reflectance (Rouse et al., 1973; Tucker, 1979). These vegetation indices correlate better with green fAPAR than with total fAPAR because their spectral formulation can significantly discriminate green from non-green elements (Gamon et al. 1995). However, canopy structural factors, background properties, or sun-target-sensor geometry can all complicate the estimation of green fAPAR with vegetation indices (Di Bella et al. 2004; Gamon 2015, Knyazikhin et al.2012). ~~However, optical estimates of fAPAR are also affected by canopy structure (i.e. the amount and disposition of photosynthetic and non-photosynthetic elements such as wood, and their effect on light absorption and scattering inside the canopy).~~ Vegetation indices (VIs) ~~related to fAPAR~~ have been successfully used to track seasonal dynamics in GPP in ecosystems characterized by strong seasonal dynamics in green biomass such as croplands, grasslands, broadleaf forests (Gitelson et al., 2006, 2008, 2012; Harris and Dash, 2010; Peng and Gitelson, 2012; Rossini et al., 2010). ~~The Normalized Difference Vegetation Index (NDVI) (Rouse et al., 1973; Tucker, 1979) is perhaps the most common vegetaion index, derived from red and near infrared (NIR) reflectance. In addition, because the relationship between NDVI and fAPAR tends to saturate at high canopy densities (Myneni and Williams, 1994; Olofsson and Eklundh, 2007), other vegetation indices have been developed and used to estimate fAPAR, and by extension GPP. For example, the Enhanced Vegetation Index (EVI) (Huete et al., 2002) efficiently describes the seasonal variability in GPP across both dense and sparse vegetation canopies . More recently, the plant phenology index (PPI) (Jin and Eklundh, 2014) has been shown to be linearly related to green leaf area index (LAI), and better related to seasonal GPP variations than NDVI and EVI at northern latitudes.~~

In ecosystems dominated by evergreen species, the seasonal variation in GPP can be strongly controlled by LUE in addition, or instead of, fAPAR (e.g. Garbulsky et al., 2008). The LUE term is usually estimated as the product of the potential maximum LUE ($\varepsilon_{max}$) and an environmental scalar (*f*) expressing the influence of one or several environmental stress factors constraining $\varepsilon_{max}$. For example, in the MODIS GPP product (Running et al., 2004), LUE is estimated by using a plant functional type or biome-dependent $\varepsilon_{max}$, and climate variables describing the environmental scalar *f* (i.e. air temperature and vapour pressure deficit). The problem of this approach is that maximum

LUE depends only on vegetation type (Xiao et al., 2004a,b; Zhao et al., 2005), while inter-seasonal variability due to plant phenology and photosynthetic dynamics (Lagergren et al., 2005) is ~~not considered.~~only considered via the instantaneous effect of the environmental scalar, which fails to reproduce the slow dynamics of biological systems.

Importantly, LUE generates optical signatures that can be measured with optical remote sensing instruments mounted on airborne or satellite platforms. These signatures are the photochemical reflectance index (PRI), and the emission of solar-induced chlorophyll-a fluorescence (SIF) by vegetation. The PRI uses the reflectances at 531 and 570nm to capture the temporal dynamics in LUE via variations in the xanthophyll-cycle pigments and the relative ratio of carotenoids to chlorophyll found in foliage (Gamon et al. 1992; Porcar-Castell et al. 2012; Wong and Gamon 2015). The PRI has been successfully estimated from sensors mounted on multiple platforms including towers, aircrafts and satellites (e.g. Drolet et al., 2005; Garbulsky et al., 2008; Nichol et al. 2002). In contrast, SIF are photons of red/far-red light (660-800nm) emitted during the first steps of photosynthesis. Accordingly, the emission of SIF is expected to depend on both fAPAR and LUE (Porcar-Castell et al. 2014). Despite the challenge of measuring SIF, due to the small intensity of the signal relative to that of the reflected light, recent ~~technological and~~ technical advances make it now possible to estimate SIF from towers, aircrafts and satellites (Frankenberg et al., 2011; Guanter et al. 2007; Joiner et al., 2011; Porcar-Castell et al., 2014; Rossini et al., 2010; 2015). Overall, the growing number of satellite missions with enhanced capacity to retrieve PRI and SIF at increasing spatial and temporal resolutions (e.g. Clevers and Gitelson, 2013; Frankenberg et al., 2014; Guanter et al. 2015; Guan et al., 2015) open up new possibilities to improve carbon models and upscale EC data.

Noting that the relationship between NDVI and fAPAR tends to saturate at high canopy densities (Myneni and Williams, 1994; Olofsson and Eklundh, 2007) also other approaches have been used to estimate vegetation carbon uptake. For example, the Enhanced Vegetation Index (EVI) (Huete et al., 2002) efficiently describes the seasonal variability in GPP across both dense and sparse vegetation canopies (Schubert et al., 2010, 2012; Sims et al., 2006; Sjöström et al., 2011; Xiao et al., 2004a, 2004b; Xiao et al., 2010). More recently, the plant phenology index (PPI) (Jin and Eklundh, 2014) has been shown to be linearly related to green leaf area index (LAI), and better related to seasonal GPP variations than NDVI and EVI of coarse-resolution MODIS data at northern latitudes. This illustrates the value of investigating the relationship between carbon uptake and spectral information in flux footprint areas beyond the LUE model depicted in Eqn 1.

~~However, i~~Integrating satellite and EC data into large scale carbon models is not straightforward. The spatial mismatch between EC measurements and coarser grid-cell information in models and most satellite-derived remote sensing data adds significant uncertainty (Chen et al., 2012; Oren et al., 2006). The large viewing angle of many satellite products, e.g. MODIS, results in ill-defined and variable footprint areas leading to additional geometric uncertainties (e.g. Tan et al., 2006). Furthermore, airborne and space-borne data needs to be corrected for atmospheric absorption and scattering effects (Karpouzli et al., 2003; Richter, 2011), a process that again can add further uncertainty (Drolet et al., 2005; Hilker et al., 2009). All these physical limitations could be substantially reduced by including *in situ* long-term spectral measurements to the network of EC flux sites (Gamon et al., 2010; Hilker et al., 2009).

Coordinated *in situ* spectral measurements require a network of stable sensors that follow the same measurement standards, calibration protocols, and have traceable technical specifications to allow across-site comparisons. Following the example of the EC Fluxnet community (http://fluxnet.ornl.gov/), SpecNet (www.specnet.info) was set to cover the needs for networking and standardization of optical measurements across flux sites (Gamon et al., 2006, 2010). Although the geographical coverage of SpecNet collaborators is constantly increasing the network was until very recently strongly biased towards North American sites. The European community of scientists conducting optical measurements remained highly dispersed and heterogeneous. It is in this context that the EUROSPEC COoperation in Science and Technology (COST) Action ES0903 (http://cost-es0903.fem-environment.eu/) originated in 2009 and operated until 2013. European COST Actions are four year projects aimed at promoting trans-national cooperation and networking among scientists and engineers across Europe and beyond (see www.cost.eu for further details).

The goal of EUROSPEC COST was to promote the development of common measuring protocols and new instruments for *in situ* spectral measurements, bringing together scientists and industries in order to increase the reliability, value and cost-efficiency of such measurements. This was done so that field-installed spectral sensors could be used as "bridge" between the EC and optical remote sensing communities.

The Action was divided in four Working Groups (WG): WG1, network and state-of-the-art characterization. The goal was to characterize the variability of spectral measurements and methods being used across flux sites in Europe. WG2, intercomparison and standardization of instruments. The goal was to characterize the sources of variability between sensors, methods and protocols.

WG3, New instruments. The goal was to promote the development of new instruments that better match sensor design, specifications, cost and purpose. And WG4, upscaling methods. The goal was to evaluate challenges and tools to upscale point observations to the footprint area and beyond.

The main objective of this review is to contextualize and synthesize the accomplishments made during EUROSPEC and to identify a number of challenges and opportunities for the near future. We review the main outcomes from EUROSPEC. We describe the background of *in situ* long-term spectral measurements and their main tradeoffs, followed by presenting the main results of each EUROSPEC WG and by a final discussion on future challenges and opportunities of these measurements.

## 2. *In situ* long-term spectral measurements: principles and trade-offs

Remote sensing measurements can be collected from platforms that may operate at variable distance from the Earth's surface: from satellites for regional-global extent measurements, to field spectrometers mounted on top of towers for close-range *in situ* measurements. In between these two scales are airborne platforms including piloted and unpiloted aircraft, kites and blimps that can measure at multiple scales depending on height. In EUROSPEC we focused on long-term *in situ* optical measurements conducted from EC towers.

There are a number of important differences between close-range *in situ* measurements and the traditional remote sensing from aircraft or satellites. *In situ* measurements, sometimes referred to as proximal sensing, are conducted at short distances and are to a large extent free from the atmospheric absorption and scattering effects that affect traditional remotely sensed data (Cheng et al., 2006; Meroni et al., 2009; Thenkabail et al., 2002). *In situ* measurements can be used to track the spectral properties of individual biological elements (leaves, shoots, plants, homogeneous canopies) while traditional remote sensing tends to measure at coarser scales where multiple species, soil and non-vegetated areas may contribute to the measured signals. Most importantly, *in situ* measurements can provide data at high-temporal resolution, something that cannot be accomplished with traditional remote sensing. All these characteristics make *in situ* measurements ideal to study and disentangle the link between optical signals and carbon flux dynamics, as well as for calibrating and validating satellite data and atmospheric correction algorithms (Brook and Ben-Dor, 2015; Czapla-Myers et al., 2015; Hilker et al., 2009).

*In situ* spectral measurements involve the measurement of the down-welling (incoming) and up-welling (both reflected and emitted) radiation fluxes from the Earth surface. These measurements can be conducted with variable setup and approaches and the optimal solution will depend on the purpose, characteristics of the site and amount of resources available.

## 2.1 Single *vs* Dual Field of View (SFOV *vs* DFOV)

Measurements of down-welling and up-welling radiation can be carried out either in sequence (when a single sensor or spectrometer is used), or simultaneously (when two separate sensors or spectrometers are used) (Fig. 1). These are also addressed as single beam/field-of-view (SFOV) or dual beam/Field of view (DFOV) configurations, respectively, and have their own advantages and disadvantages (See Table 1). A SFOV system is generally configured with a single sensor (or spectroradiometer) and will be generally cheaper to set up than a DFOV using two sensors. Having a single sensor means also that there is no need to inter-calibrate the sensor pair. However, long-term and unattended measurements with a SFOV system face the challenge of automating a single sensor/spectrometer to measure both down-welling and up-welling radiation. This automation usually involves moving parts (e.g Meroni et al., 2011; Sakowska et al., 2015), which may become a problem for long-term field operation under certain environments and entail a time delay between up-welling and down-welling measurements, which in turn may generate noisy data under cloudy conditions. Similarly, DFOV systems have also associated advantages and disadvantages. Because radiometric measurements are temperature-sensitive (Saber et al., 2011), DFOV based on two spectrometers are particularly sensitive to temperature. A practical solution is to keep the two sensors at constant temperature, e.g. by housing them in a temperature-controlled enclosure (e.g. (Drolet et al., 2014), but this might not be always possible due to power limitations. Also, regular intercalibration of the two sensors will be essential in DFOV measurements (see e.g. Anderson et al., 2006; Gamon et al., 2015; Jin and Eklundh, 2015). Additionally, long-term measurements with a DFOV may be constrained by aging-dependent degradation of the two sensor heads. These limitations were partly overcome with new DFOV systems developed during EUROSPEC that include a single spectrometer (see Section 3.3). The advantage of a DFOV system is that it guarantees quasi simultaneous measurements of down-welling and up-welling ~~reflectance~~radiances, each within a few hundred milliseconds of the other and may be easier to automate because do not require moving parts to shift from up-welling to down-welling measurements. Importantly, systems such as the Piccolo and SIF-Sys (developed during EUROSPEC and described in section 3) share the benefits from both SFOV and DFOV systems as they include a single spectrometer but make use of bifurcated fibre optics to sample two fields of view (Fig.~~ure~~ 1~~2~~).

## 2.2 Multispectral *vs* Hyperspectral Sensors

Spectral information can be acquired at different spectral resolution, which depends on the sampling intervals (discrete or continuous) and the width of the spectral bands (Fig. 2). Accordingly, ~~S~~spectral measurements can be classified into multispectral or hyperspectral ~~depending on the number of bands~~. Multispectral sensors measure a limited number of spectral bands, from two to five bands found for example in the SKYE SKR-1800 or 1860 sensor series (Skye Instruments Ltd, UK) the Decagon-SRS series (Decagon devices Inc, WA, USA) or the Cimel five-band sensors (Cimel Electronique, FR), or up to 16 bands found in the Cropscan MSR16R (Cropscan Inc. MN, USA) (Balzarolo et al., 2011; Sakowska et al., 2014). The bandwidth of these sensors (in terms of full width at half the maximum response, FWHM) is in the order of 10 nm or greater and the sampling across a specific spectral range is typically discrete (Fig. 2). These sensors are typically manufactured using optical filters, light emitting diodes (LEDs) and photodiode detectors (Norton, 2010; Ryu et al., 2010). These sensors are characterized by relatively low cost (from a few hundred to a few thousand euros/dollars), ease of maintenance, weather-proof design, and low power consumption. Hence, they are useful and affordable instruments for deployment at flux tower sites for extended periods of time. In addition, their relatively low cost allows mounting of several sensors in different positions to study spatial heterogeneity. Multispectral sensors can be deployed to measure a number of vegetation indices (e.g. NDVI or PRI) to track and study vegetation phenology and seasonality. They can also be used to produce satellite calibration and validation data, provided that their spectral configuration can be related to that of the spaceborne sensor.

In contrast, hyperspectral sensors (more often addressed as spectrometers, or spectroradiometers when they are radiometrically calibrated) can measure hundreds of spectral bands, often 250 or more, with bandwidths usually less than 10 nm full width at half maximum (FWHM) and sampling intervals from less than 1 nm to 10 nm depending on configuration (Fig. 2). The obvious advantage of hyperspectral sensors is that they can resolve more detailed features of the vegetation (Milton et al., 2009) and serve to estimate parameters that require higher spectral resolution, such as the emission of chlorophyll fluorescence (Meroni et al., 2009). Moreover, since hyperspectral information can be resampled to coarser spectral resolutions, data from hyperspectral systems can be flexibly convoluted to match spectral bands of different remote sensors (Olsson et al., 2011) increasing its value as a source of satellite calibration and validation data. In addition, hyperspectral data can be used to mine new spectral band combinations to match different ecosystem variables (e.g. Balzarolo et al., 2015; Heiskanen et al., 2013; Inoue et al., 2008; le Maire et al., 2008; Milton et al., 2009; Tagesson et al., 2015; Wang et al., 2011; Yao et al., 2010). Milton and coworkers

(2009) presented an extensive review of how hyperspectral proximal sensing, or field spectroscopy, has developed and listed the most commonly available field spectrometers. Spectrometers are very complex opto-electro-mechanical instruments and tend to be expensive, from a few thousand Euros/dollars for optical benches measuring in the VNIR, to several tenths of thousands for field instruments measuring in the VNIR and the SWIR. The common limitation of all these spectrometers is that they are not designed for unattended or long-term field operation. Accordingly, users need to build their own weatherproof housing, power supply, automatic datalogging, and control units (see next section). As a result, the overall cost of these user-made systems is difficult to quantify because in addition to off-the-shelf components they involve plenty of in-house skilled technician hours. Field spectrometers are also more susceptible to physical damage (due to their inherent complexity), and are more difficult and expensive to automate for continuous or periodic logging applications. In addition, these systems tend to be considerably larger and heavier than their multispectral counterparts, presenting a structural challenge to their deployment on flux towers. Despite these limitations, the number of such measurements is rapidly increasing (Drolet et al., 2014; Huber et al., 2014; ~~Pacheco-Labrador and Martin, 2014;~~ Pacheco-Labrador and Martín, 2015; Rossini et al., 2012; Sakowska et al., 2015).

## 2.3 Instrument Configurations: hemispherical-conical, bi-conical and bi-hemispherical

Reflectance factors relate the radiant flux reflected by a target surface to the radiant flux incident on it and they can be measured using different instrument configurations (see Schaepman-Strub et al., 2006 for a full mathematical explanation of the different factors and terms). Three main instrument configurations have been applied to *in situ* field measurements to ~~measure~~ quantify incoming and reflected radiation and estimate reflectance factors: bi-conical, hemispherical-conical and the bi-hemispherical configurations (Fig. 1).

Hemispherical-conical measurements use a foreoptic diffuser assembly, designed to have a cosine response at changing solar zenith angle to estimate down-welling irradiance, and a conical foreoptic for upwelling measurements which can be installed at nadir or off-nadir. The hemispherical-conical configuration lends itself to both multispectral and hyperspectral measurements from flux towers.

Bi-conical measurements rely on a diffuse white reference panel, typically of Spectralon® (Labsphere Inc., NH, USA), reflecting down-welling solar radiant flux, normally viewed from nadir through a fixed angularly limited (conical) field-of-view foreoptic, to provide the reference measurement. The potential limitation of using a reference panel is that it needs to be kept clean and stable over time which may become a challenge in the field due to particle deposition (but see Sakowska et al., 2015 in Section 3). In practice, because both direct and diffuse light contribute to the up-welling signal reflected from the reference panel when measuring under field conditions, field data obtained in a bi-conical instrument configuration can be used to derive hemispherical-conical reflectance factors (HCRF) (Schaepman-Strub et al., 2006).

Bi-hemispherical measurements use a foreoptic diffuser to capture both down-welling and up-welling irradiance. Bi-hemispherical measurements require a nadir-view installation for both sensor heads and have the great advantage of enabling the sampling of a wider area. The main limitation of this configuration is that while the hemispherical-conical measurements can be taken by observing the canopy at nadir or off nadir, all viewing directions (both nadir and off-nadir) contribute to the bi-hemispherical measurements (Meroni et al., 2011). For this reason, bi-hemispherical measurements tend to be more sensitive to variations in illumination geometry compared to hemispherical-conical measurements collected with a nadir view particularly for large illumination zenith angles. ~~as affected by the bi-directional reflectance function (BRDF) of the surface.~~

## 3. EUROSPEC Main Results

### 3.1. Network and State-of-the-art characterization

When research questions become global, as in the case of global carbon cycle monitoring, networking becomes a key methodological element to ensure consistent implementation of measuring protocols, data sharing and management. One of the objectives of EUROSPEC was to contribute to build up a distributed European spectral sampling network to foster data sharing in order to better understand relationships between optical responses of vegetation and carbon cycle.

*In situ* long-term spectral measurements at flux towers are still accomplished with instruments that are of variable design and performance, use different configurations, are installed with contrasting geometries, and are conducted with different calibration or quality assessment regimes. In EUROSPEC, we conducted a detailed review of proximal sensing measurements based on the responses to a questionnaire obtained from groups working at 40 flux tower sites in Europe including two sites from Africa and Australia (Balzarolo et al., 2011). *In situ* measurements included SFOV and DFOV systems; bi-hemispherical or hemispherical-conical configurations, and both multispectral and hyperspectral sensors. The study portrayed the lack of consensus on what are the most suitable proximal sensing systems and methods to support EC measurements. No standards were being applied in terms of system performance (e.g. non-linearity in response, signal-to-noise ratios, and cosine response of down-welling radiant flux foreoptics); measurement geometries (e.g. hemispherical vs conical and their combinations); different foreoptic field-of-views; installation geometry (e.g. nadir or off-nadir; height of sensor above target surface), or calibration regimes (e.g. regularly calibrated by manufacturer, calibrated *in situ* or even not regularly calibrated) (Balzarolo et al., 2011). The lack of regular calibrations was presented as a fundamental limitation to overcome in order to produce high quality data, reliability of time series analysis and to enable inter-comparison of results between network sites, e.g. Integrated Carbon Observation System (ICOS) sites (https://www.icos-ri.eu/). At the end of EUROSPEC, the need to standardize these measurements still exists.

Balzarolo et al. (2011) suggested also that two possible levels of instrumentation could be considered. The first; termed the Basic Standard, would include only multispectral broadband sensors to estimate selected vegetation indices. The second, termed Advanced Standard, would augment these multispectral sensors sites with hyperspectral sensor systems. The question remains as to what specific instruments and sensors would be more appropriate in each case. Anderson et al. (2013) conducted a field intercomparison experiment to assess the reproducibility of measurements collected by different sensors used at flux tower sites. The analysis showed that lower-cost spectroradiometer systems performed similarly to more costly models and suggested that cost-effective and accurate measurements in the PAR range can also be acquired using lower-cost instrumentation. Similar conclusions were obtained by Harris et al. (2014) when they compared the performance of lower-cost multispectral sensors with a reference spectroradiometer to estimate the photochemical reflectance index (PRI). Another conclusion of these studies was the importance of characterizing sensor properties to allow inter-comparison of results between sensors and sites (see next section). Further long-term field instrument intercomparisons will be needed before final conclusions can be drawn from these studies.

EUROSPEC managed to establish an active network including scientists from 28 countries from Europe and beyond. This network remains active under a new COST Action (OPTIMISE-ES1309) and under the umbrella of SpecNet. Together we hope to continue promoting the standardization and implementation of optical measurements across flux sites.

### 3.2 Sources of variability

Limited consideration had been given to the comparability of spectral measurement protocols and systems before EUROSPEC (but see Castro-Esau et al., 2006; Pfitzner et al., 2011). Because the use of the same type of sensor in all sites is not ~~situation where the same sensor is used in all sites is not~~ realistic, and perhaps neither desirable as it would undermine the development of new sensors, we need to examine the factors that influence the variability in the data collected with different sensors. In EUROSPEC we dealt with a number of these factors: linearity of spectrometer response, impact of cosine diffusers and reference panels, ~~and~~ effect of sensor FOV, and ~~.~~temporal stability of measurements and calibrations.

### 3.2.1 Linearity of spectrometer response

Linearity refers to the linear relationship between the signal generated by a radiation sensor and the impinging light power. Any dependence of this relationship on third or more variables leads to a systematic error in the measurements which needs to be characterized and corrected. Pacheco-Labrador et al. (2014) and Pacheco-Labrador and Martín (2014) assessed the linearity of one of the commercial field portable spectroradiometers, the Unispec-DC (PP Systems) currently used in unattended systems at EC sites (Hilker et al., 2010; Pacheco-Labrador and Martín, 2015), finding that both the gray level measured and also the integration time had an effect on linearity. They showed that non-linearity could be a significant problem in hyperspectral proximal sensing, especially for *in situ* and long-term unattended measurements. The impact of gray level-dependent non-linearities may be significant when estimating narrow band indices, such as the photochemical reflectance index (PRI), and therefore cannot be left uncharacterized and uncorrected (Pacheco-Labrador and Martin, 2014). The impact of non-linearity can be minimized avoiding the most non-linear region of the dynamic range. In turn, non-linearities related with the integration time affected also the characterization of other instrumental artifacts (Pacheco-Labrador et al., 2014). This dependence, previously reported in cameras (Ferrero et al., 2006) but not in field spectroradiometers, is significant when the integration time is close to the readout time of the sensor (i.e. a photodiode continues to collect photons during the time when the signal is being processed (the readout time), producing an extra signal that is added to that obtained during the integration time). Despite that integration-time dependent non-linearities have been characterized only in the Unispec-DC (Pacheco-Labrador and Martín, 2015) it would be recommendable to avoid integration times close to the instrument readout time, unless the integration-time dependent non-linearity has been characterized.

### 3.2.2 Cosine diffusers and reference panels

Irradiance (i.e. downwelling radiant flux) can be measured with cosine corrected foreoptics pointed vertically up, or with a diffuse white reference panel (see Figure 2). Importantly, the materials, calibration status, and method selected to measure irradiance may have an impact on the result. Biggs et al. (1971) highlight the need for a properly designed foreoptic to avoid spectral variations caused by changing sun azimuth and zenith angles. Malthus and Mac Lellan (2010) demonstrated that the material selected for the foreoptic diffuser can significantly affect the spectra with angular/wavelength dependencies and a poor cosine response. Similarly, they reported that the performance of cosine diffusers in the Short Wave Infrared (SWIR) tends to be very poor with high signal attenuation above 1400 nm (Malthus and Mac Lellan, 2010), and suggested that a diffuse reference panel will provide a better cosine response than a cosine-corrected foreoptics. Importantly, because reference panels present spectral and angular-dependent time degradation at such wavelenghts, especially when used in the field (e.g. Anderson et al., 2002; Georgiev and Butler, 2007) (Fig. 3), recalibration and regular maintenance is essential. Recalibration requires a dedicated laboratory facility as demonstrated by Georgiev et al. (2011) for the SWIR region of the solar spectrum. In turn, Labsphere, the manufacturers of Spectralon®, provide guidance on how to clean reference panels. Consequent care, careful cleaning and recalibration of reference panels are essential to minimise error propagation and uncertainties when conducting spectral measurements.

Selection of reference panel material is also very important. Manufacturers of reference panels for spectroscopy such as LabSphere (Spectralon ®) or SphereOptics (Zenith polymer ®) use a sintered fluoropolymer manufactured to have a very high reflectance, possibly in excess of 96% and approximate a Lambertian reflectance across the 400 nm to 2,500 nm spectral region. Alternatively, low cost PTFE sheets (i.e. Teflon) can be purchased at lower cost. However, PTFE sheets have lower reflectance, approximately 80%, and have higher specular reflection. Also, because PTFE sheets are not manufactured to be used as 'references' there may be variability between individual sheets and wavelength dependent reflectances may be unknown. Overall, PTFE sheets are not recommended as field spectroscopy reference standards.

Similarly, the material and design of cosine receptors affect the estimation of hemispherical reference factors (Malthus and MacLellan, 2010) and consequently, the indices derived from them. Therefore, significant and unquantified uncertainties will be introduced when comparing data from sites that used different cosine receptors or sites characterized by a different range of Solar Zenith Angles (SZA). For example, for SZA greater than 60° variation in reflectance factors obtained with different cosine receptors can exceed 20%. This effect is reduced when considering normalized VIs, and it depends on the spectral distance between bands selected for the VI calculation (Julitta, 2015).

Again, characterization of the properties of cosine diffusers and regular maintenance/replacement should be included inside the measurement routine.

### 3.2.3 The fields-of-view of field spectrometers and multispectral sensors~~Field-of-view heterogeneity~~

Field spectroscopists normally assume that the Earth surface sampled by a non-imaging spectrometer with a limited FOV foreoptic is spatially delimited by the solid angle specified by the manufacturer and that the response across the surface delimited by the FOV ~~that area~~ is the same for all points inside the given FOV~~at all points~~ (Castro-Esau et al., 2006; Ferrier et al., 2009; Murphy et al., 2005; Nichol and Grace, 2010). In practice, the spectral response within FOV of a field spectrometer ~~sensor~~ is not constant (i.e. certain areas within the FOV contribute more to the signal than others) (MacArthur et al., 2012, Eklundh et al. 2011), this can be ~~.~~determined by the viewing angle and the instrument's Directional Response Function (DRF) (CEI 1987) which can be characterized. The DRF will be affected by both the internal design of the spectrometer (e.g. open path or fiber optic transfer to individual detectors) and the foreoptics used. When measurements of heterogeneous surfaces were simulated using the measured ~~directional response functions (~~DRFs~~)~~, significant differences were found between simulated reflectance factors and those expected from the manufacturers' specifications (Mac Arthur et al., 2012). Even when less optically complex spectrometers, measuring only across the VNIR region are considered,~~,~~ ~~measuring only across the VNIR region are considered,~~ the Earth surface sampled is not necessarily that inferred from the manufacturers' specified FOV included solid angle (Caras et al., 2011). The manufacturers of some spectrometers now offer optical elements within their foreoptic mounts to defocus the foreoptics and thereby homogenize the light received (e.g. the ASD FS pistol grip "scrambler"), or have improved the optical components used to minimize 'chromatic aberrations' and heterogeneities and again, homogenize the light received prior to it being distributed to the detectors (e.g. SVC HR-2014i spectrometers). Therefore, the spectrometers' response should be more closely represented by a Gaussian or Cauchy response, albeit centre-weighted, with all areas within the FOV represented in the integrated measurement. These limitations affect the estimation of reflectance factors measured from heterogeneous Earth surfaces (Mac Arthur et al. 2013) because the sample area is ill defined and unknown but systematic sampling errors appear. In contrast, multispectral field sensors normally comprise of individual foreoptics/detector assemblies for each spectral band and subsequently have less complex optical paths than their hyperspectral counterparts, and each sensor can be more reasonably assumed to have a center-weighted and Cauchy response, though this response is also affected by the viewing angle of the instrument (Eklundh et al., 2011). For a more detailed discussion of the FOV and DRF of field spectrometers and multispectral sensors we refer readers to Mac Arthur et al. (2012) and Eklundh et al. (2011), respectively.

#### 3.2.4 Temporal stability of measurements and calibrations

The temporal stability of the measurements and the calibrations are essential factors to be considered when conducting long-term *in situ* spectral measurements. Factors such as diurnal or seasonal fluctuations in temperature, gradual particle deposition onto optical parts (e.g cosine diffusers or reference panels), or any other processes causing a temporal drift in the functioning of will interact with the measured signals and calibrations. In turn, the impact of these factors will depend on the signals we are measuring and the instrumentation we use. For example, because the impact of these factors may be wavelength-dependent it may interfere with the estimation of reflectance indices. Similarly, in DFOV systems constructed around two sensors, the differential impact of these factors in each sensor may also introduce significant errors. Unfortunately, the quantitative characterization of these sources of variability, and the establishment of a set of recommendations, remains a key question after EUROSPEC and clearly requires further attention. We briefly introduce the topic and present some indicative data that we hope will help the reader to understand the importance of temporal stability.

Stability issues can be grouped around two points: The temporal stability of the calibration or cross calibration of a sensor pair; and thermal stability of the measurements.

1) Temporal stability of the calibration/cross calibration. Sensor calibration against a source of known spectral and radiometric properties is needed to derive radiometric units and control for spectral shifts in sensor response. Similarly, cross calibration of two sensors (e.g. Gamon et al. 2015, Jin and Eklundh 2015) is essential for deriving reflectance factors using two different sensors (e.g. DFOV systems) and to control for between-sensor variability. Importantly, particle deposition, component aging, or partial damage of sensor components such as optical fibers, may cause a change in these calibrations which we need to detect, quantify and correct for. For example, the temporal degradation of the white reference panel becomes a critical issue in systems such as the ASD-WhiteRef (See Section 3.3), which thanks to the system design was found to be insignificant (maximum of 2% differences at 400nm) over the measuring period (Sakowska et al. 2015). In the absence of additional information, the general recommendation is to start with an intensive calibration/cross-calibration scheme and adjust the frequency later on when the stability of the calibrations for the specific field conditions is known. Key questions that the user should consider are: what is the temporal drift in calibration for the specific sensors and measuring conditions? what

is the impact of this drift on the resulting signal/indices? and what is the optimal calibration/cross calibration frequency?

2) Thermal stability. Changes in temperature may have an impact on both the intensity and the spectral information of the measured signal. Accordingly, characterizing the temperature stability of a spectral system and its impact on the signal we seek to measure, is a critical step when designing and deploying *in situ* spectral measurements. For example, the radiometric response to temperature in silicon diodes is more pronounced in the NIR compared to the visible. Saber et al. (2011) characterized the percentage change in the response a spectrometer relative to its response at the calibration temperature (20 °C) and found a variation of -0.13 % / ºC at 30 ºC that was constant between 400 and 700 nm but increased to +0.2 % / ºC at 30 ºC at 1050 nm. Similarly, Pacheco-Labrador et al. (2014) characterized the effect of temperature on the signal and the spectral calibration of two sensors in a DFOV system based on a pair of Unispec DC spectroradiometers, for the range of temperatures between 13.9 ºC and 46.1 ºC, finding higher variation in the NIR, between -10 % to 21% (relative to 30 ºC) compared to variations between -1 % to + 4 % below 750 nm. Clearly, the spectral component of this temperature dependencies do not only affect the quantification of radiometric quantities, but also the comparison of the quantities measured at different wavelengths. This is especially critical when estimating VIs or solar-induced chlorophyll fluorescence where two or more spectral bands are combined. In these cases, seasonal changes in temperature could, if not properly addressed and corrected, mask the physiological component of the signal or even generate spurious dynamics (e.g. Pacheco-Labrador et al. 2014). Key questions that the user should consider are: How do changes in temperature affect sensor/spectrometer output? what is the impact on the resulting signal/indices? What are the wavelenght/sensor dependent thermal responses? If needed, how to control and correct for thermal stability for the selected application?

### 3.3. Development of instrumentation for continuous field measurements

Conducting *in situ* long-term spectral measurements in the field is not straightforward. In addition to a number of logistic and infrastructural requirements, long-term field measurements require instrumentation specially designed and conceived for the task. One of the goals of EUROSPEC was to identify the main requirements of such sensors and to promote the development of new dedicated instrumentation. As part of these activities we organized a Science-Industry Interaction Meeting where EUROSPEC scientists got together with representatives of the “spectrometry” industry sector. A number of general requirements for field optical sensors were identified and are summarized in Box 1. In addition, industry representatives raised the issue of how to cover the non-recurring engineering costs associated with instrument development. The possibility of establishing partnerships and seeking funding for joint collaborative projects between science and industry was suggested, particularly to produce prototypes for new instruments.

Four different hyperspectral systems were identified during EUROSPEC for continuous proximal sensing from EC towers in Europe (Fig. 4): 1) A temperature-controlled spectrometer system for continuous and unattended measurements of canopy spectral radiance and reflectance (UNIEDI System) developed by the University of Edinburgh (Drolet et al., 2014) that has been operating at the FluxNet Hyytiälä site (http://fluxnet.ornl.gov/site/447) in Southern Finland since March 2010. 2)The Multiplexer Radiometer Irradiometer (MRI) developed by the Remote Sensing of Environmental Dynamics Laboratory, Dipartimento di Scienze dell’Ambiente e del Territorio e di Scienze della Terra, Università degli Studi Milano- Bicocca (Italy) and deployed for relatively short periods (weeks to months) in the context of different projects (Bresciani et al., 2013; Cogliati et al., 2015); 3) the HyperSpectral Irradiometer (HSI) also developed by the previous group which has operated in the field from 2009 to 2011 (Meroni et al., 2011; Rossini et al., 2012, 2014); and 4) the AMSPEC-MED system, a version of the automated, multiangular spectroradiometer system AMSPEC II (Hilker et al., 2010) modified by the Environmental Remote Sensing and Spectroscopy Laboratory (SpecLab), Spanish National Remote Sensing (CSIC) and the Centro de Estudios Ambientales del Mediterráneo (CEAM) in Spain. The system has been operating at Las Majadas Fluxnet site in Spain (http://fluxnet.ornl.gov/site/440) since August 2013 (Pacheco-Labrador and Martín, 2015).

**Box 1. General Requirements for *in situ* long-term optical sensors**

- Waterproof (should withstand direct rain)
- Robust design: e~~E~~xternal parts withstanding tension
- Avoidance of holes and cavities (perfect place for birds and insect nests)
- Attachments for easy field installation
- Minimum payload (threshold depending on application)
- Minimum size (threshold depending on application)
- Low power consumption (threshold depending on site infrastructure)
- Maximize long-term stability of optical parts (i.e. filters, diffusers, etc.) to minimize recalibration frequency
- For global networks: Operating temperature range matching the wide thermal distribution of terrestrial plant species, from -50ºC to 50ºC. For local measurements: temperature range matching local variation.
- ~~Low temperature-sensitivity~~High thermal stability
- Linear sensor response
- H~~h~~igh signal~~-~~to-~~-~~noise ratio
- ~~Ideal~~ Optimal cosine directional response function
- Logic user interface and easy to program systems

The first three systems are based on commercially available spectrometers from Ocean Optics, relatively low cost and compact optical benches housed in temperature controlled environments and operated by dedicated software. The main difference between each of these systems lies in their design.

The UNIEDI system (Fig. 4A) has a hemispherical-conical configuration, and is a DFOV system that uses a pair of spectrometers (Ocean Optics, USB2000+) with one spectrometer measuring up-welling radiance through a FOV limited foreoptic (24.8 deg) and the other spectrometer measuring down-welling irradiance using a cosine corrected diffuser. One limitation of this system is that, despite that both spectrometers are kept at constant temperature using a temperature control system (Drolet et al., 2014), regular intercalibration of the two spectrometers is essential to account for sensor-specific time- and temperature-dependent drift in their radiometric capabilities. Intercalibration can be done using a calibration lamp and a dark setting either *in situ* or in the laboratory. In fact, Anderson et al (2006) showed that for calibrating field-based spectra collected with a DFOV spectrometer, a field-derived intercalibration function provides the most accurate results.

The MRI system has also a hemispherical-conical configuration, but it is a SFOV system with a single spectrometer. A commercially available optical multiplexer is used to switch the input to the spectrometer from down-welling to up-welling radiant flux. Irradiance can be measured through a fibre connected to either a cosine corrected diffuser or an up-looking integrating sphere foreoptic. Up-welling radiance is measured through a bare optical fibre with a FOV of 25 deg. The S-FLUOR

has been more recently developed in collaboration with the Forschungszentrum Jülich GmbH based on the MRI design (see Fig 45B). The major technical improvements are an overall compact design and the integration of the cooling system within the instrument box (Cogliati et al., 2015). The S-FLUOR has been used in the years from 2012 to 2014 as reference instrument for the HyPlant (Specim, Finland) airborne fluorescence imager (Rossini et al., 2015). The HSI system (Fig. 4C) has a bi-hemispherical configuration and a SFOV and uses of a rotating optic with a cosine response to measure the down-welling and the up-welling radiant flux. Because both the MRI and HSI are SFOV they present a time delay (at best multiple seconds) between the down-welling and the up-welling measurement. These delays may add some measurement uncertainties due to changes in sky conditions between the individual measurements, particularly under cloudy or overcast conditions.
The AMSPEC-MED system is based on a commercial Unispec dual channel VIS-NIR spectroradiometer (PP-Systems, Amesbury, MA, USA) equipped with a motor driven pan-tilt unit that allows measuring up-welling radiance in a range of zenithal and azimuthal angles. Similar to the UNIEDI, the system is a DFOV system and, therefore, cross calibration between spectrometers is performed regularly using a Spectralon® panel. Because the system is operated with solar panels, temperature control is not possible due to power restrictions. Instead, temperature sensitivity of each of the spectrometers and its impact on the resulting hemispherical-conical reflectance factors was characterized in the laboratory and used in signal post-processing (Pacheco-Labrador and Martín, 2015). Note that power constraints are not system dependent but rather site specific, depending on power availability and site temperature range.

In an attempt to address some of the limitation of the systems reviewed above and based on discussions between groups during EUROSPEC, three new approaches were developed (Fig. 5):

1) The Piccolo system, developed by the UK Natural Environment Research Council (NERC) Field Spectroscopy Facility (FSF) Geoscience, University of Edinburgh, is based on a DFOV hemispherical-conical configuration with a cosine corrected foreoptic to capture down-welling radiant flux and a configurable up-welling channel to capture up-welling radiant flux. The up-welling foreoptic can either be fitted with a view angle limited foreoptic or with another cosine corrected receptor to enable a bi-hemispherical measurement approach to be adopted (Fig.ure 21). The novelty of this system is the use of low weight components for decreased weight, and the use of bifurcated fibre optic with electronic shutters for decreased time delay between up and down-welling measurements (Mac Arthur et al., 2014). In addition, as both light inputs can be closed at the same time, the systems' dark current (inherent electrical noise) can be recorded and used in post processing. The Piccolo system is currently undergoing service life cycle testing and will be field

trialled in a number of flux towers in the near future. In addition, the low weight and DFOV mode of this system makes it compatible with unmanned aerial vehicles (UAV) applications, opening a new range of research possibilities. 2) A similar configuration has been adopted in the SIF-Sys (Burkart et al., 2015) developed by the Forschungszentrum Jülich GmbH. The system hosts a low cost and small size spectrometer (STS-VIS, Ocean Optics, Inc., Dunedin, US) and uses also a bifurcated optical fibre with optical shutters to split the optical signal between two channels: one channel pointing to a white reference panel to measure the down-welling radiant flux and the down-looking channel measuring the radiant flux up-welling from the vegetation. SIF-Sys is specifically intended to measure SIF and, for this reason, it is equipped with a LED emitting at the wavelength of SIF (at 760 nm). The LED is placed in the instrument down-looking FOV and it is used as a reference to assess the uncertainty of passive SIF retrieval in field conditions. SIF-Sys has been tested in dedicated field experiments and will be installed at flux towers for long term and unattended data collection in the near future. 3) The ASD-White Ref system (Sakowska et al., 2015) is an automated system designed for continuous acquisition of measurements using an ASD FieldSpec spectroradiometer. The WhiteRef system was developed by the Forests and Biogeochemical Cycles Research Group, Sustainable Agro-Ecosystems and Bioresources Department, Research and Innovation Centre—Fondazione Edmund Mach, San Michele all'Adige, together with the Institute of Biometeorology—National Research Council, Firenze in Italy, and the contribution of NERC Field Spectroscopy Facility, School of Geosciences, University of Edinburgh, and has been deployed in a grassland site in the Viote del Monte Bondone in Northern Italy. The main advantage of this system is the possibility to scan in the VNIR and SWIR regions (350 nm to 2,500 nm) using a popular and commercially available spectrometer. The system is SFOV and measures in a hemispherical-conical configuration with a FOV of 25 deg. A novelty of the WhiteRef system is that both, reference and vegetation target radiances, are measured by automatically sliding a white reference panel under the fibre optic. To protect the WR panel from light, dust, rain, insects and adverse weather conditions, the WR is kept inside a waterproof box and ejected only during the measurements. Each acquisition is preceded by a reading of a dedicated wetness sensor signal, and in case of rainfall or dew the reference measurements are not conducted. In addition, to remove eventual dust/insects from the measurement surface, the WR panel is sprayed with compressed air during each ejection and insertion phase.

### 3.4. Upscaling optical data and fluxes from the footprint to the landscape level

*In situ* spectral measurements are essential for the successful upscaling of optical and flux data across space and time. In particular, the temporal match between *in situ* spectral measurements and flux data facilitates the characterization, modelling and validation of their linkage. Spatial and temporal scales are tightly connected with each other and neither temporal or spatial upscaling can be fully accomplished without giving attention to the other. Considering that the temporal link between optical and flux data can be covered with *in situ* spectral measurements the main question is probably that of upscaling these signals across space from the footprint to the landscape level (Figure 6).

In the process of integrating remote sensing data with flux measurements an assumption is commonly made: the match between flux footprint and image pixel (e.g. Beer et al. 2010, Tramontana et al 2015). The same assumption can be used between flux data and *in situ* spectral measurements. In order to upscale flux data from the footprint to the landscape level using optical data we need first to establish a good quantitative understanding between flux and optical data at the footprint level. However, a number of factors related to footprint variability, pixel heterogeneity, the BRDF properties of the surface, and the geometry of the measurements can momentarily or systematically decouple optical and flux data adding noise or bias to their relationship at this scale.

-Despite of efforts to orientate the FOV of *in situ* spectral measurements to cover the dominant footprint of EC measurements (e.g. using footprint modelling techniques), the flux footprint of EC measurements will still differ from that of optical measurements most of the time due to footprint variability. Most flux sites are located in places with homogeneous vegetation where footprint variability is not expected to decouple flux and optical data. For example, accurate modelling of the flux footprint did not improve the predictive power of optical data to estimate GPP in a Mediterranean savanna (Pacheco-Labrador et al. 2015) or in a subalpine grassland (Vescovo et al. 2015). However, the mismatch can be relevant in sites with heterogeneous vegetation like agricultural lands, ecotones or sites with adjacent patches of vegetation. In these sites, a detailed characterization of the area of interest and footprint modelling will be critical for the successful implementation of data driven models, e.g. the light use efficiency model introduced in Eqn. 1. For example, when estimating GPP in an agricultural area using MODIS data and a footprint model, Gelybó et al (2013) were able to reduce the RMS error by 28% compared to non-footprint weighted values. This is particularly problematic when vegetation around the EC tower is not homogeneous so that optical and flux data may be sampling different types of plant communities. This mismatch will clearly interfere with the implementation of data driven models, e.g. the light use efficiency model introduced in Eqn 1.

Dealing with the effect of optical vs flux footprint mismatch is challenging from a point of view of tower based measurements. One of the conclusions from EUROSPEC was that new tools are needed to characterize these scale issues more precisely. One of them is the use of small and relatively affordable remotely piloted aircraft (RPAs) or UAVs on which light weight spectrometers, both multi and hyperspectral, and cameras can be deployed. Hyperspectral imaging systems onboard of aircraft or unmanned aerial vehicles (UAV) can for example provide high spatial resolution imagery enabling the identification of pure species pixels within the flux footprint (Zarco-Tejada et al., 2013a). The flexibility, maneuverability, and capacity to view the same target from different heights allows to study the impact of footprint variability and to bridge *in situ* spectral measurements with coarser satellite or airborne data, facilitating their interpretation and un-mixing (Fig. 6). For example, the availability of pure pixels can be used to investigate the effect of aggregating different species or land-cover classes on the resulting hyperspectral signal (Zarco-tejada et al., 2013b). As reported in Gamon et al (2015) or Whitehead K. et al. (2014), the cost effectiveness of UAV platforms make them a valid solution to address footprint variability. Two UAV-based statistical sampling approaches are possible to systematically address footprint variability: i) with no previous knowledge a regular grid might be recommended, whereas ii) if the spatial patterns of vegetation are already known, a stratified sampling for different vegetation types might be more efficient. Overall, the systematic optical sampling of the footprint/pixel area can serve to characterize the different sources of error when upscaling from *in situ* spectral measurements to the satellite pixel level. These topics have just started to be addressed as low cost UAVs and proper instrumentation are becoming available. The technology is relatively under-explored in the context of flux scaling studies, but there are a growing number of papers that comment on the utility of UAVs for fine-scale sensing of landscape ecology and vegetation parameters (e.g. Dandois and Ellis, 2013).

~~In addition, d~~Data from *in situ* and remote sensing ~~spectral~~ measurements are also affected by the structure of the canopy and the geometry of the observation and illumination *per se* (Jones and Vaughan, 2010). The reason is that photons hitting a surface are preferentially scattered (or reflected) in given directions depending on the properties of the surface. This can be characterized by the BRDF of the surface (Nicodemus et al., 1977; Roberts, 2001). In other words, if we would measure an ideal plant canopy with constant fAPAR and LUE, our sensors would still register diurnal and seasonal variations in vegetation parameters due to variations in solar elevation and azimuth. ~~Accordingly, we need to know the BRDF of a surface to correct for measurement geometry effects.~~ This is particularly relevant when comparing seasonal time series of optical data which may have been acquired with significantly different sun elevations (e.g. in boreal latitudes). Accordingly, knowledge on the ~~we need to know the~~ BRDF properties of the surface under examination becomes essential to ~~of a surface to~~ correct for these ~~measurement~~ geometry effects.

The BRDF can be quantified and investigated by mounting sensors on pan-tilt heads (e.g. Huber et al., 2014), by deploying a number of (low-cost) sensors with different fixed off-nadir positions, or by using the UAV systems discussed above. Hilker et al. (2007, 2010), presented a hyperspectral system capable of quantifying and measuring these effects, the AMSPEC and AMSPEC II systems (Automated Multiangular Spectro-radiometer for Estimation of Canopy reflectance). The AMSPEC system (see previous chapter) is a DFOV system that samples hemispherical-conical reflectance factors at different observation angles from the canopy surrounding the tower. Multiangular measurements are used to retrieve the BRDF and can be used to normalize observations to the same viewing and illumination conditions. Data acquired by AMSPEC system over forest stands in North America showed how optical indices, such as the PRI, can be influenced by view angle and shadow fractions (Hilker et al., 2008b). Moreover, retrieved BRDF estimates allows mimicking off-nadir observations of remote sensors and provides a top-of-canopy reference for atmospheric corrections (Hilker et al., 2009). ~~Similarly, low-cost multispectral sensors can be mounted in several fixed off-nadir positions to investigate seasonal variation in BRDFs.~~

~~Dealing with the effect of spectral vs flux footprints inconsistencies is more challenging from a point of view of tower based measurements. One of the conclusions from EUROSPEC was that new tools are needed to characterize these scale issues more precisely. One of them is the use of small and relatively affordable remotely piloted aircraft (RPAs) or UAVs on which light weight spectrometers, both multi and hyperspectral, and cameras can be deployed. Hyperspectral imaging systems onboard of aircraft or unmanned aerial vehicles (UAV) can for example provide high spatial resolution imagery enabling the identification of pure species pixels within the flux footprint (Zarco-Tejada et al., 2013a) The flexibility, maneuverability, and capacity to view the same target from different heights allows to study the impact of footprint variability and to bridge *in situ* spectral measurements with coarser satellite or airborne data, facilitating their interpretation and un-mixing. For example, the availability of pure pixels can be used to investigate the effect of aggregating different species or land-cover classes on the resulting hyperspectral signal (Zarco-tejada et al., 2013b). These topics have just started to be addressed as low cost UAVs and proper instrumentation are becoming available. The technology is relatively under-explored in the context~~

~~of flux scaling studies, but there are a growing number of papers that comment on the utility of UAVs for fine-scale sensing of landscape ecology and vegetation parameters (e.g. Dandois and Ellis, 2013).~~

## 4. Future challenges and opportunities

Quantifying and modelling the spatiotemporal dynamics of the carbon cycle remains a key goal in climate change and global biogeochemistry research. Global questions call for global initiatives to provide sensible data at the global scale. Flux tower networks such as FluxNet (http://fluxnet.ornl.gov/) and other long-term monitoring infrastructures such as ICOS (https://www.icos-ri.eu/~~http://www.icos-infrastructure.eu/~~) or NEON (http://www.neoninc.org/) are responding to these needs by ensuring a long-term and an increasing flow of global carbon flux and ecological data. Simultaneously, the increasing number of current and planned satellite missions warranties an equally increasing flow of remotely sensed data (e.g. Venμs, Sentinel-2 and 3; OCO-2, FLEX), offering improved geographical coverage, as well as temporal, spatial, and spectral resolutions. However, our capacity to capitalize on these space developments depends very much on how well we can relate the resulting satellite data to ground observations of ecosystem processes, such as photosynthetic carbon assimilation.

EC measurements provide good temporal resolution of carbon fluxes at the ecosystem level but they are limited by spatial resolution and coverage. In contrast, remote sensing data provides good to moderate spatial resolution and coverage but are limited by temporal resolution. The complementarity and synergy between these two sources of data is clear but their integration remains a challenge due to scale mismatch. We need a Rosetta stone to help us translate and link the information from these two sources of data: something that can be done only via *in situ* spectral measurements. On one hand, *in situ* spectral measurements can provide the same optical indices than satellites, serving as a landmark to interpret, calibrate and validate remotely sensed data products (i.e. we can establish a link between satellite data and ground optical data). On the other hand, because data from *in situ* spectral measurements has comparable temporal resolution and relatively similar biological footprint to that of EC measurements, they can be used to develop quantitative models that associate the two signals.

Overall, there is a clear need to establish a global n~~N~~etwork of sites with standardized and coordinated *in situ* spectral measurements to facilitate the integration of remotely sensed data and EC data towards improving the global monitoring of the carbon cycle. In addition, such network is also needed to calibrate and validate satellite data products, and to resolve and avoid problems that appear when inferring ecosystem properties directly from satellite data, such as the "spurious amazon green-up" (Morton et al., 2014; Soudani et al., 2014); or the controversy around the remote sensing of foliar-nitrogen (Knyazikhin et al., 2013; Townsend et al., 2013).

The EUROSPEC Cost Action was a starting point for the organization of the European community of scientists working with *in situ* spectral measurements. We identified many areas that still need further work and perhaps the main conclusion of EUROSPEC was to realize that we need more projects such as EUROSPEC. As a continuation, a new COST Action (ES1309) "Innovative optical t~~T~~ools for proximal sensing of ecophysiological processes (OPTIMISE) (http://optimise.dcs.aber.ac.uk/) was recently begun that expands the work of EUROSPEC to include UAVs, "smart" spectral data storage systems and to go in-depth into the measurement and interpretation of multi-scale chlorophyll fluorescence data.

Despite that regional level networking projects such as the EUROSPEC and OPTIMISE COST Actions, AusCover (http://www.auscover.org.au/), or EcoSIS (http://labs.russell.wisc.edu/townsend/tag/ecosis/) are important, we need also activities and n~~N~~etworking at the global level. SpecNet is an excellent platform that could be used to accomplish this coordination goal and liaise with national and regional projects. SpecNet could be also used to share information, know-how, data, general guidelines on measurement and calibration protocols, and challenges between scientists, but also including industry stakeholders. This is perhaps the fastest and most effective way, in terms of costs and results, to promote standardization. As long as the information remains disperse and the global network links remain weak, independent groups will continue to adopt different solutions for *in situ* spectral measurements without following a set of general guidelines. This is perhaps the main risk behind *in situ* spectral measurements in the near future.

The following challenges and opportunities were identified during EUROSPEC:

1) Need to compile information on best-practices for *in situ* spectral measurements. Information on what to purchase, how to install, maintain, calibrate, analyze, and store the data from *in situ* spectral measurements is to some extent available from a number of studies conducted as part of EUROSPEC or by other groups (see e.g. Anderson et al., 2011; Balzarolo et al., 2011; Gamon et al., 2015; Harris et al., 2014; Jin and Eklundh, 2015). These types of studies will most likely continue to appear in the near-future. However, a major up-to-date synthesis effort is urgently needed to provide a comprehensive treatise on such measurements. This would facilitate the different phases

of decision-making by site PIs and promote standardization within relevant networks such as ICOS and FLUXNET.

2) Quantifying and dealing with uncertainty. Measurement uncertainty is instrument- and environment-specific. Accordingly, characterization of sensor performance and quantification of measurement uncertainty is crucial to produce accurate data (Anderson et al., 2011; Castro-Esau et al., 2006; Jung et al., 2012). Anderson et al (2011) haves demonstrated that laboratory-derived measurement uncertainties do not present a useful means of quantifying all uncertainties in field spectroscopy. Laboratory measurements can serve to define features such as signal-to-noise ratio, noise equivalent radiance and linearity, but these uncertainties are added to by complexities of the hemispherical illumination environment experienced in the field. Clearly, the optimal way to characterize measurement uncertainty is to do so in the conditions that typify the measurement scenario. Protocols for systematic measurement uncertainty characterizations in the field should be adopted in the future.

3) Need for characterization and calibration. Networks of research sites engaged in optical sampling should follow an instrument characterisation and calibration scheme to ensure direct result inter-comparison (Anderson et al., 2013; Balzarolo et al., 2011). Optical sensors could for instance be characterized and calibrated against a common standard in a central laboratory prior to field deployment then tested annually to monitor change or degradation. In addition, portable calibration/verification standards could be rotated periodically around sites to conduct validation measurements across space and time. Cross calibration of sensors in DFOV systems is also critical and should be accomplished regularly. Calibration frequency will depend on signal drift rate which may be instrument- and climate-dependent. Accordingly, it would seem logical to characterize and adjust calibration demands to each site and instrument, for example by calibrating at high frequencies during the first measuring season and adjusting later on depending on signal drift rate.

4) Need for a ‘smart’ data repository and information access portal. Spectral data are time intensive to collect but their analysis is even more time consuming. In turn, most spectral data collections remain poorly documented which greatly reduces their use for data sharing, if not nullifying it. There is an urgent need for a spectral information system that: (a) establishes a data pool that can hold spectral data collected from various instruments, providing them in an easily accessible and generic form, and (b) includes metadata that is standardised to a degree that allows data selections to answer new science questions. Such databases have been developed (Bojinski et al., 2003; Ferwerda, 2006; Hueni and Tuohy, 2006), but their adoption by the spectroscopy community has

been slow. Currently, there are only a few available and persisting spectral information systems, the most prominent one being the open source SPECCHIO (Hueni et al., 2009). SPECCHIO has seen many upgrades over time with a large contribution by the Australian National Data Service (Hueni et al., 2012) and support from EUROSPEC. The challenges for the future are numerous, but most pressing appears the issue of automated data quality and metadata standards. SPECCHIO is currently being further developed under the new COST Action OPTIMISE ~~(http://optimise.dcs.aber.ac.uk)~~.

5) Upscaling issues: BRDF and footprint analysis. Scaling up *in situ* spectral measurements to those acquired from airborne and satellite platforms and linking this optical data to that of EC measurements remains an issue (Ju et al., 2005; Simic et al., 2004; Wu and Li, 2009). BRDF effects, footprint variability, and scale mismatch are factors that ~~impair~~ constrain our capacity to link and upscale remotely sensed and EC data. The rapid advances in UAV technology have opened new opportunities to deal with these challenges. Micro-hyperspectral field spectrometers and imaging sensors can now be mounted on UAVs. These measurements can serve to retrieve the BRDF of challenging Earth surfaces, such as forest canopies, to measure footprint optical variability, or to sample the same target at different heights facilitating the treatment of the scale issue. Deployment of specialized instruments on board ~~drones~~ UAVs with a view to collecting narrowband multispectral or hyperspectral data will constitute a step-change in scientific understanding of the connection between spectral data and multiple ecosystem processes. Investigating this potential is again one of the goals of the new COST Action OPTIMISE.

6) Permanent platform for communication and information dissemination. The need for and the potential of a permanent channel for cross-talk between research communit<u>ies</u>~~y~~ as well as between scientists and industry stakeholders was identified. Such a channel could be for example a moderated mailing list (e.g. Fluxnet type) or making use of other social media. This platform would provide the opportunity to share known-how and best-practices between users helping to promote standardization. In addition, it would also promote collaboration between research groups as well as between scientists and industry stakeholders, which in turn might foster the development of new instruments.

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## References

Alton, P. B.: From site-level to global simulation: Reconciling carbon, water and energy fluxes over different spatial scales using a process-based ecophysiological land-surface model, Agric. For. Meteorol., 176, 111–124, doi:10.1016/j.agrformet.2013.03.010, 2013.

Anderson, K., Milton, E. J. and Rollin, E. M.: Calibration of dual-beam spectroradiometric data, Int. J. Remote Sens., 27(5), 975–986, doi:10.1080/01431160500213375, 2006.

Anderson, K., Dungan, J. L. and MacArthur, A.: On the reproducibility of field-measured reflectance factors in the context of vegetation studies, Remote Sens. Environ., 115(8), 1893–1905, doi:http://dx.doi.org/10.1016/j.rse.2011.03.012, 2011.

Anderson, K., Rossini, M., Pacheco-Labrador, J., Balzarolo, M., Mac Arthur, A., Fava, F., Julitta, T. and Vescovo, L.: Inter-comparison of hemispherical conical reflectance factors (HCRF) measured with four fibre-based spectrometers, Opt. Express, 21(1), 605–617, doi:10.1364/oe.21.000605, 2013.

Anderson, N., Biggar, S.F., Burkhart, C.J., Kurtis, J.T. and Mavko, M.: Bi-directional calibration results for the cleaning of Spectralon™ reference panels, in: Proceedings of SPIE - The International Society for Optical Engineering, vol. 4814, Earth Observing Systems VII, Seattle, WA, 25 September 2002, pp. 201-210, 2002.

Aubinet, M., Grelle, A., Ibrom, A., Rannik, U., Moncrieff, J., Foken, T., Kowalski, A. S., Martin, P. H., Berbigier, P., Bernhofer, C., Clement, R., Elbers, J., Granier, A., Grunwald, T., Morgenstern, K., Pilegaard, K., Rebmann, C., Snijders, W., Valentini, R. and Vesala, T.: Estimates of the annual net carbon and water exchange of forests: The EUROFLUX methodology, Adv. Ecol. Res., 30, 113–175, 2000.

Baldocchi, D.: Breathing of the terrestrial biosphere: lessons learned from a global network of carbon dioxide flux measurement systems, Aust. J. Bot., 56(1), 1–26, doi:10.1071/bt07151, 2008.

Balzarolo, M., Anderson, K., Nichol, C., Rossini, M., Vescovo, L., Arriga, N., Wohlfahrt, G., Calvet, J.-C. C., Carrara, A., Cerasoli, S., Cogliati, S., Daumard, F., Eklundh, L., Elbers, J. A., Evrendilek, F., Handcock, R. N., Kaduk, J., Klumpp, K., Longdoz, B., Matteucci, G., Meroni, M., Montagnani, L., Ourcival, J.-M. M., Sánchez-Cañete, E. P., Pontailler, J.-Y. Y., Juszczak, R., Scholes, B., Martín, M. P., Pilar Martín, M. and Martín, M. P.: Ground-based optical measurements at european flux sites: A review of methods, instruments and current controversies, Sensors, 11(8), 7954–7981, 2011.

Balzarolo, M., Boussetta, S., Balsamo, G., Beljaars, A., Maignan, F., Calvet, J. C., Lafont, S., Barbu, A., Poulter, B., Chevallier, F., Szczypta, C. and Papale, D.: Evaluating the potential of large-scale simulations to predict carbon fluxes of terrestrial ecosystems over a European Eddy Covariance network, Biogeosciences, 11(10), 2661–2678, doi:10.5194/bg-11-2661-2014, 2014.

Balzarolo, M., Vescovo, L., Hammerle, A., Gianelle, D., Papale, D., Tomelleri, E. and Wohlfahrt, G.: On the relationship between ecosystem-scale hyperspectral reflectance and $CO_2$ exchange in European mountain grasslands, Biogeosciences, 12(10), 3089–3108, doi:10.5194/bg-12-3089-2015, 2015.

Beer, C., Reichstein, M., Tomelleri, E., Ciais, P., Jung, M., Carvalhais, N., Rodenbeck, C., Arain, M. A., Baldocchi, D., Bonan, G. B., Bondeau, A., Cescatti, A., Lasslop, G., Lindroth, A., Lomas, M., Luyssaert, S., Margolis, H., Oleson, K. W., Roupsard, O., Veenendaal, E., Viovy, N., Williams, C., Woodward, F. I. and Papale, D.: Terrestrial gross carbon dioxide uptake: Global distribution and covariation with climate, Science, 329(5993), 834–838, doi:10.1126/science.1184984, 2010.

Biggs, W. W., Edison, A. R., Eastin, J. D., Brown, K. W., Maranville, J. W. and Clegg, M. D.: Photosynthesis light sensor and meter, Ecology, 52(1), 125–131, doi:10.2307/1934743, 1971.

Bojinski, S., Schaepman, M., Schläpfer, D. and Itten, K.: SPECCHIO: A spectrum database for remote sensing applications, Comput. Geosci., 29(1), 27–38, doi:10.1016/S0098-3004(02)00107-3, 2003.

Bresciani, M., Rossini, M., Morabito, G., Matta, E., Pinardi, M., Cogliati, S., Julitta, T., Colombo, R., Braga, F. and Giardino, C.: Analysis of within- and between-day chlorophyll-a dynamics in Mantua Superior Lake, with a continuous spectroradiometric measurement, Mar. Freshw. Res., 64(4), 303–316, doi:10.1071/mf12229, 2013.

Brook, A. and Ben-Dor, E.: Supervised Vicarious Calibration (SVC) of multi-source hyperspectral remote-sensing data, Remote Sens., 7(5), 6196–6223, doi:10.3390/rs70506196, 2015.

Burkart, A., Schickling, A., Pilar Cendrero Mateo, M., Wrobel, T., Rossini, M., Cogliati, S., Julitta, T. and Rascher, U.: A Method for uncertainty assessment of passive sun-induced chlorophyll fluorescence retrieval by using an infrared reference light, IEEE Sens. J., PP(99), doi:10.1109/JSEN.2015.2422894, 2015.

Caras, T., Karnieli, A. and Hedley, J.: Exploring field-of-view non-uniformities produced by a hand-held spectroradiometer, J. Spectr. Imaging, ~~1(a3)~~2, 1-11, doi:10.1255/jsi.~~2010~~2011.~~a3~~a1, 2011.

Castro-Esau, K. L., Sánchez-Azofeifa, G. A. and Rivard, B.: Comparison of spectral indices obtained using multiple spectroradiometers, Remote Sens. Environ., 103(3), 276–288, doi:http://dx.doi.org/10.1016/j.rse.2005.01.019, 2006.

Chen, B., Coops, N. C., Fu, D., Margolis, H. A., Amiro, B. D., Black, T. A., Arain, M. A., Barr, A. G., Bourque, C. P. A, Flanagan, L. B., Lafleur, P. M., McCaughey, J. H. and Wofsy, S. C.: Characterizing spatial representativeness of flux tower eddy-covariance measurements across the Canadian Carbon Program Network using remote sensing and footprint analysis, Remote Sens. Environ., 124, 742–755, doi:10.1016/j.rse.2012.06.007, 2012.

Cheng, Y., Gamon, J. A., Fuentes, D. A., Mao, Z., Sims, D. A., Qiu, H., Claudio, H., Huete, A. and Rahman, A. F.: A multi-scale analysis of dynamic optical signals in a Southern California chaparral ecosystem: A comparison of field, AVIRIS and MODIS data, Remote Sens. Environ., 103(3), 369–378, doi:http://dx.doi.org/10.1016/j.rse.2005.06.013, 2006.

Ciais, P., Dolman, A. J., Bombelli, A., Duren, R., Peregon, A., Rayner, P. J., Miller, C., Gobron, N., Kinderman, G., Marland, G., Gruber, N., Chevallier, F., Andres, R. J., Balsamo, G., Bopp, L., Bréon, F. M., Broquet, G., Dargaville, R., Battin, T. J., Borges, A., Bovensmann, H., Buchwitz, M., Butler, J., Canadell, J. G., Cook, R. B., Defries, R., Engelen, R., Gurney, K. R., Heinze, C., Heimann, M., Held, A., Henry, M., Law, B., Luyssaert, S., Miller, J., Moriyama, T., Moulin, C., Myneni, R. B., Nussli, C., Obersteiner, M., Ojima, D., Pan, Y., Paris, J. D., Piao, S. L., Poulter, B., Plummer, S., Quegan, S., Raymond, P., Reichstein, M., Rivier, L., Sabine, C., Schimel, D., Tarasova, O., Valentini, R., Wang, R., Van Der Werf, G., Wickland, D., Williams, M. and Zehner, C.: Current systematic carbon-cycle observations and the need for implementing a policy-relevant carbon observing system, Biogeosciences, 11(13), 3547–3602, doi:10.5194/bg-11-3547-2014, 2014.

CIE (1987) “Methods of characterizing illuminance meters and luminance meters,” Comm. Int. L’Eclairage, Vienna, Austria, Tech. Rep. 69. (FORMAT)

Clevers, J. G. P. W. and Gitelson, A. A.: Remote estimation of crop and grass chlorophyll and nitrogen content using red-edge bands on Sentinel-2 and -3, Remote Sens. Environ., 23, 344-351, doi:10.1016/j.jag.2012.10.008, 2013.

Clement, R. J., Jarvis, P. G. and Moncrieff, J. B.: Carbon dioxide exchange of a Sitka spruce plantation in Scotland over five years, Agric. For. Meteorol., 153, 106–123, doi:10.1016/j.agrformet.2011.07.012, 2012.

Cogliati, S., Rossini, M., Julitta, T., Meroni, M., Schickling, A., Burkart, A., Pinto, F., Rascher, U. and Colombo, R.: Continuous and long-term measurements of reflectance and sun-induced chlorophyll fluorescence by using novel automated field spectroscopy systems, Remote Sens. Environ., 164, 270-281, doi:10.1016/j.rse.2015.03.027, 2015.

Czapla-Myers, J., McCorkel, J., Anderson, N., Thome, K., Biggar, S., Helder, D., Aaron, D., Leigh, L. and Mishra, N.: The ground-based absolute radiometric calibration of Landsat 8 OLI, Remote Sens., 7(1), 600–626, 2015.

Dandois, J. P. and Ellis, E. C.: High spatial resolution three-dimensional mapping of vegetation spectral dynamics using computer vision, Remote Sens. Environ., 136, 259–276, doi:10.1016/j.rse.2013.04.005, 2013.

Drolet, G. G., Huemmrich, K. F., Hall, F. G., Middleton, E. M., Black, T. A., Barr, A. G. and Margolis, H. a.: A MODIS-derived photochemical reflectance index to detect inter-annual variations in the photosynthetic light-use efficiency of a boreal deciduous forest, Remote Sens. Environ., 98(2–3), 212–224, doi:http://dx.doi.org/10.1016/j.rse.2005.07.006, 2005.

Drolet, G., Wade, T., Nichol, C. J., MacLellan, C., Levula, J., Porcar-Castell, A., Nikinmaa, E. and Vesala, T.: A temperature-controlled spectrometer system for continuous and unattended measurements of canopy spectral radiance and reflectance, Int. J. Remote Sens., 35(5), 1769–1785, doi:10.1080/01431161.2014.882035, 2014.

Eklundh, L., Jin, H., Schubert, P., Guzinski, R. and Heliasz, M.: An optical sensor network for vegetation phenology monitoring and satellite data calibration, Sensors, 11(8), 7678–709, doi:10.3390/s110807678, 2011.

Enting, I. G., Rayner, P. J. and Ciais, P.: Carbon cycle uncertainty in regional carbon cycle assessment and processes (RECCAP), Biogeosciences, 9(8), 2889–2904, doi:10.5194/bg-9-2889-2012, 2012.

Ferrero, A., Campos, J. and Pons, A.: Apparent violation of the radiant exposure reciprocity law in interline CCDs., Appl. Opt., 45(17), 3991–3997, doi:10.1364/AO.45.003991, 2006.

Ferrier, G., Hudson-Edwards, K. A. and Pope, R. J.: Characterisation of the environmental impact of the Rodalquilar mine, Spain by ground-based reflectance spectroscopy, J. Geochemical Explor., 100(1), 11–19, doi:http://dx.doi.org/10.1016/j.gexplo.2008.03.001, 2009.

Ferwerda, J. G.: A free online reference library for hyperspectral reflectance signatures, SPIE Newsroom, 1–2, doi:10.1117/2.1200612.0551, 2006.

Frankenberg, C., Fisher, J. B., Worden, J., Badgley, G., Saatchi, S. S., Lee, J.-E., Toon, G. C., Butz, A., Jung, M., Kuze, A. and Yokota, T.: New global observations of the terrestrial carbon cycle from GOSAT: Patterns of plant fluorescence with gross primary productivity, Geophys. Res. Lett., 38(17),~~ n/a–n/a~~L17706, doi:10.1029/2011GL048738, 2011.

Frankenberg, C., O'Dell, C., Berry, J., Guanter, L., Joiner, J., Köhler, P., Pollock, R. and Taylor, T. E.: Prospects for chlorophyll fluorescence remote sensing from the Orbiting Carbon Observatory-2, Remote Sens. Environ., 147, 1–12, doi:10.1016/j.rse.2014.02.007, 2014.

Gamon, J. A., Penuelas, J. and Field, C. B.: A narrow-wave band spectral index that tracks diurnal changes in photosynthetic efficiency, Remote Sens. Environ., 41(1), 35–44, 1992.

Gamon, J. A., Rahman, A. F., Dungan, J. L., Schildhauer, M., and Huemmrich, K. F.: Spectral Network (SpecNet) – what is it and why do we need it?, Remote Sens. Environ., 103, 227–235, doi:10.1016/j.rse.2006.04.003, 2006.

Gamon, J. A., Coburn, C., Flanagan, L. B., Huemmrich, K. F., Kiddle, C., Sanchez-Azofeifa, G. A., Thayer, D. R., Vescovo, L., Gianelle, D., Sims, D. A., Rahman, A. F. and Pastorello, G. Z.: SpecNet revisited: bridging flux and remote sensing communities, Can. J. Remote Sens., 36, S376–S390, 2010.

Gamon, J. A., Kovalchuk, O., Wong, C. Y. S., Harris, A. and Garrity, S. R.: Monitoring seasonal and diurnal changes in photosynthetic pigments with automated PRI and NDVI sensors, Biogeosciences~~ Discuss.~~, 12~~(3)~~, ~~2947–2978~~4149-4159, doi:10.5194/bg~~d~~-12-~~2947~~4149-2015, 2015.

Garbulsky, M. F., Penuelas, J., Papale, D. and Filella, I.: Remote estimation of carbon dioxide uptake by a Mediterranean forest, Glob. Chang. Biol., 14(12), 2860–2867, doi:10.1111/j.1365-2486.2008.01684.x, 2008.

Gelybó, G., Barcza, Z., Kern, A. and Kljun, N.: Effect of spatial heterogeneity on the validation of remote sensing based GPP estimations, Agric. For. Meteorol.,174-175, 43-53, doi:10.1016/j.agrformet.2013.02.003, 2013.

Georgiev, G. T. and Butler, J. J.: Long-term calibration monitoring of Spectralon diffusers BRDF in the air-ultraviolet, Appl. Opt., 46(32), 7892–7899, doi:10.1364/ao.46.007892, 2007.

Georgiev, G. T., Butler, J. J., Cooksey, C., Ding, L. and Thome, K. J.: SWIR calibration of spectralon reflectance factor, in: Sensors, Systems, and Next-Generation Satellites XV, vol. 8176, edited by: ~~R.~~ Meynart, R; ~~S. P.~~ Neeck, S. P.; and ~~H.~~ Shimoda, H., Proceedings of SPIE ~~p. 81760W–81760W–11~~, Prague, Czech Republic, p. 81760W–81760W–11 2011.

Gitelson, A. A., Viña, A., Verma, S. B., Rundquist, D. C., Arkebauer, T. J., Keydan, G., Leavitt, B., Ciganda, V., Burba, G. G. and Suyker, A. E.: Relationship between gross primary production and chlorophyll content in crops: Implications for the synoptic monitoring of vegetation productivity, J. Geophys. Res. Atmos., 111(8), D08S11, doi:10.1029/2005jd006017, 2006.

Gitelson, A. A., Viña, A., Masek, J. G., Verma, S. B., Suyker, A. E., Viña, A., Masek, J. G., Verma, S. B. and Suyker, A. E.: Synoptic monitoring of gross primary productivity of maize using Landsat data, Ieee Geosci. Remote Sens. Lett., 5(2), 133–137, doi:10.1109/lgrs.2008.915598, 2008.

Gitelson, A. A., Peng, Y., Masek, J. G., Rundquist, D. C., Verma, S., Suyker, A., Baker, J. M., Hatfield, J. L. and Meyers, T.: Remote estimation of crop gross primary production with Landsat data, Remote Sens. Environ., 121, 404–414, doi:10.1016/j.rse.2012.02.017, 2012.

Göckede, M., Foken, T., Aubinet, M., Aurela, M., Banza, J., Bernhofer, C., Bonnefond, J. M., Brunet, Y., Carrara, A., Clement, R., Dellwik, E., Elbers, J., Eugster, W., Fuhrer, J., Granier, A., Grünwald, T., Heinesch, B., Janssens, I. A., Knohl, A., Koeble, R., Laurila, T., Longdoz, B., Manca, G., Marek, M., Markkanen, T., Mateus, J., Matteucci, G., Mauder, M., Migliavacca, M., Minerbi, S., Moncrieff, J., Montagnani, L., Moors, E., Ourcival, J. M., Papale, D., Pereira, J., Pilegaard, K., Pita, G., Rambal, S., Rebmann, C., Rodrigues, a, Rotenberg, E., Sanz, M. J., Sedlak, P., Seufert, G., Siebicke, L., Soussana, J. F., Valentini, R., Vesala, T., Verbeeck, H. and Yakir, D.: Quality control of CarboEurope flux data - Part 1: Coupling footprint analyses with flux data quality assessment to evaluate sites in forest ecosystems, Biogeosciences, 5(2), 433–450, doi:10.5194/bg-5-433-2008, 2008.

Goulden, M. L.: Carbon assimilation and water-use efficiency by neighboring Mediterranean-climate oaks that differ in water access, Tree Physiol., 16, 417–424, 1996.

Grace, J., San Jose, J., Meir, P., Miranda, H. S., Montes, R. A., José, J. S., Meir, P., Miranda, H. S. and Montes, R. a.: Productivity and carbon fluxes of tropical savannas, J. Biogeogr., 33(3), 387–400, doi:10.1111/j.1365-2699.2005.01448.x, 2006.

Guan, K., Pan, M., Li, H., Wolf, A., Wu, J., Medvigy, D., Caylor, K. K., Sheffield, J., Wood, E. F., Malhi, Y., Liang, M., Kimball, J. S., Saleska, S. R., Berry, J., Joiner, J. and Lyapustin, A. I.: Photosynthetic seasonality of global tropical forests constrained by hydroclimate, Nat. Geosci, 8(4), 284–289, doi:10.1038/ngeo2382, 2015.

Guanter, L., Alonso, L., Gómez-Chova, L., Amorós-López, J., Vila, J. and Moreno, J.: Estimation of solar-induced vegetation fluorescence from space measurements, Geophys. Res. Lett., 34(8), L08401, doi:10.1029/2007GL029289, 2007.

Guanter, L., Aben, I., Tol, P., Krijger, J. M., Hollstein, A., Köhler, P., Damm, A., Joiner, J., Frankenberg, C. and Landgraf, J.: Potential of the TROPOspheric Monitoring Instrument

(TROPOMI) onboard the Sentinel-5 Precursor for the monitoring of terrestrial chlorophyll fluorescence, Atmos. Meas. Tech., 8(3), 1337–1352, doi:10.5194/amt-8-1337-2015, 2015.

Harris, A. and Dash, J.: The potential of the MERIS terrestrial chlorophyll index for carbon flux estimation, Remote Sens. Environ., 114(8), 1856–1862, doi:10.1016/j.rse.2010.03.010, 2010.

Harris, A., Gamon, J. A., Pastorello, G. Z. and Wong, C. Y. S.: Retrieval of the photochemical reflectance index for assessing xanthophyll cycle activity: a comparison of near-surface optical sensors, Biogeosciences, 11(22), 6277–6292, doi:10.5194/bg-11-6277-2014, 2014.

Heiskanen, J., Rautiainen, M., Stenberg, P., Mõttus, M. and Vesanto, V.-H.: Sensitivity of narrowband vegetation indices to boreal forest LAI, reflectance seasonality and species composition, ISPRS J. Photogramm. Remote Sens., 78(0), 1–14, doi:http://dx.doi.org/10.1016/j.isprsjprs.2013.01.001, 2013.

Hilker, T., Coops, N. C., Nesic, Z., Wulder, M. A. and Black, A. T.: Instrumentation and approach for unattended year round tower based measurements of spectral reflectance, Comput. Electron. Agric., 56(1), 72–84, doi:10.1016/j.compag.2007.01.003, 2007.

Hilker, T., Coops, N. C., Wulder, M. A., Black, T. A. and Guy, R. D.: The use of remote sensing in light use efficiency based models of gross primary production: A review of current status and future requirements, Sci. Total Environ., 404(2-3), 411–423, doi:10.1016/j.scitotenv.2007.11.007, 2008a.

Hilker, T., Coops, N. C., Hall, F. G., Black, T. A., Wulder, M. A., Nesic, Z. and Krishnan, P.: Separating physiologically and directionally induced changes in PRI using BRDF models, Remote Sens. Environ., 112, 2777-2788, doi:10.1016/j.rse.2008.01.011, 2008b.

Hilker, T., Lyapustin, A., Hall, F. G., Wang, Y., Coops, N. C., Drolet, G. and Black, T. A.: An assessment of photosynthetic light use efficiency from space: Modeling the atmospheric and directional impacts on PRI reflectance, Remote Sens. Environ., 113(11), 2463–2475, doi:10.1016/j.rse.2009.07.012, 2009.

Hilker, T., Nesic, Z., Coops, N. C. and Lessard, D.: A new, automated, multiangular radiometer instrument for tower-based observations of canopy reflectance (Amspec II), Instrum. Sci. Technol., 38, 319–340, doi:10.1080/10739149.2010.508357, 2010.

Huber, S., Tagesson, T. and Fensholt, R.: An automated field spectrometer system for studying VIS, NIR and SWIR anisotropy for semi-arid savanna, Remote Sens. Environ., 152, 547–556, doi:10.1016/j.rse.2014.06.007, 2014.

Hueni, A. and Tuohy, M.: Spectroradiometer data structuring, pre-processing and analysis – an IT based approach, J. Spat. Sci., 51(2), 93–102, doi:10.1080/14498596.2006.9635084, 2006.

Hueni, A., Nieke, J., Schopfer, J., Kneubühler, M., Itten, K.: The spectral database SPECCHIO for improved long term usability and data sharing. Computers & Geosciences, 35(3), 557-565, 2009.

Hueni, A., Chisholm, L., Suarez, L., Ong, C. and Wyatt, M.: Spectral information system development for Australia, in: Proceedings of the 2nd Geospatial Science Research Symposium, Melbourne, Australia, December, 2012.

Huete, A., Didan, K., Miura, T., Rodriguez, E. P., Gao, X. and Ferreira, L. G.: Overview of the radiometric and biophysical performance of the MODIS vegetation indices, Remote Sens. Environ., 83, 195–213, doi:10.1016/S0034-4257(02)00096-2, 2002.

Inoue, Y., Peñuelas, J., Miyata, A. and Mano, M.: Normalized difference spectral indices for estimating photosynthetic efficiency and capacity at a canopy scale derived from hyperspectral and $CO_2$ flux measurements in rice, Remote Sens. Environ., 112(1), 156–172, doi:10.1016/j.rse.2007.04.011, 2008.

Jin, H. and Eklundh, L.: A physically based vegetation index for improved monitoring of plant phenology, Remote Sens. Environ., 152, 512–525, doi:10.1016/j.rse.2014.07.010, 2014.

Jin, H. and Eklundh, L.: In situ calibration of light sensors for long-term monitoring of vegetation, 53(6), 3405–3416, 2015.

Joiner, J., Yoshida, Y., Vasilkov, A. P., Corp, L. A., Middleton, E. M., Yoshida, Y., Corp, L. A. and Middleton, E. M.: First observations of global and seasonal terrestrial chlorophyll fluorescence from space, Biogeosciences, 8(3), 637–651, doi:10.5194/bg-8-637-2011, 2011.

Jones, H.G. and Vaughan, R.A.: Remote sensing of vegetation: Principles, techniques, and applications, Oxford University Press, Oxford, pp. 353, 2010.

Joos, F., Prentice, I. C., Sitch, S., Meyer, R., Hooss, G., Plattner, G.-K., Gerber, S. and Hasselmann, K.: Global warming feedbacks on terrestrial carbon uptake under the Intergovernmental Panel on Climate Change (IPCC) emission scenarios, Global Biogeochem. Cycles, 15(4), 891–907, doi:10.1029/2000gb001375, 2001.

Ju, J., Gopal, S. and Kolaczyk, E. D.: On the choice of spatial and categorical scale in remote sensing land cover classification, Remote Sens. Environ., 96(1), 62–77, doi:10.1016/j.rse.2005.01.016, 2005.

Julitta, T.: Optical proximal sensing for vegetation monitoring, Phd thesis , Faculty of Mathematical, Physical and Natural Sciences, Department of Environmental and Earth Sciences, University of Milano-Bicocca, Milan, Italy, 136 pp., 2015.

Jung, A., Götze, C., Glässer, C, Halle (Saale): Overview of experimental setups in spectroscopic laboratory measurements – the SpecTour Project, ~~PFG~~ Photogramm. Fernerkun~~dung, Geoinf~~., 4, 0433–0442, doi:10.1127/1432-8364/20/0129, 2012.

Jung, M., Reichstein, M., Margolis, H. A., Cescatti, A., Richardson, A. D., Arain, M. A., Arneth, A., Bernhofer, C., Bonal, D., Chen, J., Gianelle, D., Gobron, N., Kiely, G., Kutsch, W., Lasslop, G., Law, B. E., Lindroth, A., Merbold, L., Montagnani, L., Moors, E. J., Papale, D., Sottocornola, M., Vaccari, F. and Williams, C.: Global patterns of land-atmosphere fluxes of carbon dioxide, latent heat, and sensible heat derived from eddy covariance, satellite, and meteorological observations, J. Geophys. Res. Biogeosciences, 116, G00J07, doi:10.1029/2010jg001566, 2011.

Karpouzli, E., Malthus, T., Place, C., Mitchell, C.A., Garcia, M.I. and Mair, J.D.: Underwater light characterisation for correction of remotely sensed images, Int. J. Remote Sens., 24, 2683–2702, 2003.

Keenan, T. F., Davidson, E., Moffat, A. M., Munger, W. and Richardson, A. D.: Using model-data fusion to interpret past trends, and quantify uncertainties in future projections, of terrestrial ecosystem carbon cycling, Glob. Chang. Biol., 18(8), 2555–2569, doi:10.1111/j.1365-2486.2012.02684.x, 2012.

Knyazikhin, Y., Schull, M. A., Stenberg, P., Mõttus, M., Rautiainen, M., Yang, Y., Marshak, A., Latorre Carmona, P., Kaufmann, R. K., Lewis, P., Disney, M. I., Vanderbilt, V., Davis, A. B., Baret, F., Jacquemoud, S., Lyapustin, A. and Myneni, R. B.: Hyperspectral remote sensing of foliar nitrogen content, Proc. Natl. Acad. Sci., 110(3), E185–E192, doi:10.1073/pnas.1210196109, 2013.

Kormann, R. and Meixner, F. X.: An analytical footprint model for non-neutral stratification, Boundary-Layer Meteorol., 99(2), 207–224, doi:10.1023/a:1018991015119, 2001.

Lagergren, F., Eklundh, L., Grelle, A., Lundblad, M., Molder, M., Lankreijer, H. and Lindroth, A.: Net primary production and light use efficiency in a mixed coniferous forest in Sweden, Plant, Cell Environ., 28(3), 412–423, doi:10.1111/j.1365-3040.2004.01280.x, 2005.

Le Maire, G., François, C., Soudani, K., Berveiller, D., Pontailler, J. Y., Bréda, N., Genet, H., Davi, H. and Dufrêne, E.: Calibration and validation of hyperspectral indices for the estimation of broadleaved forest leaf chlorophyll content, leaf mass per area, leaf area index and leaf canopy biomass, Remote Sens. Environ., 112(10), 3846–3864, doi:10.1016/j.rse.2008.06.005, 2008.

Mac Arthur, A., MacLellan, C.J. and Malthus, T.: The fields of view and directional response functions of two field spectroradiometers, IEEE Trans. Geosci. Remote Sens., 50(10), 3892–3907, 2012.

Mac Arthur, A., Alonso, L., Malthus, T. and Moreno, J.: Spectroscopy field strategies and their effect on measurements of heterogeneous and homogeneous earth surfaces, in: Proceedings of the 2013 Living Planet Symposium, 9–13 September, Edinburgh, UK, 2013.

Mac Arthur, A., Robinson, I., Rossini, M., Davis, N. and MacDonald, K.: A dual-field-of-view spectrometer system for reflectance and fluorescence measurements (Piccolo Doppio) and correction of etaloning, in: Proceedings of the Fifth International Workshop on Remote Sensing of Vegetation Fluorescence, 22-24 April, edited by E. S. Agency, Paris, France, 2014.

Malthus, T. J. and MacLellan, C. J.: High performance fore optic accessories and tools for reflectance and radiometric measurements with the ASD FieldSpec 3 Spectroradiometer, in: Art, Science and Applications of Reflectance Spectroscopy Scientific Symposium, Boulder, Colorado, 23-25th February 2010, pp. 1–5, 2010.

Meroni, M., Rossini, M., Guanter, L., Alonso, L., Rascher, U., Colombo, R. and Moreno, J.: Remote sensing of solar-induced chlorophyll fluorescence: Review of methods and applications, Remote Sens. Environ., 113(10), 2037–2051, doi:http://dx.doi.org/10.1016/j.rse.2009.05.003, 2009.

Meroni, M., Barducci, A., Cogliati, S., Castagnoli, F., Rossini, M., Busetto, L., Migliavacca, M., Cremonese, E., Galvagno, M., Colombo, R. and Di Cella, U. M.: The hyperspectral irradiometer, a new instrument for long-term and unattended field spectroscopy measurements, Rev. Sci. Instrum., 82(4), 43106, doi:doi:http://dx.doi.org/10.1063/1.3574360, 2011.

Milton, E. J., Schaepman, M. E., Anderson, K., Kneubühler, M. and Fox, N.: Progress in field spectroscopy, Remote Sens. Environ., 113, Suppl(0), S92–S109, doi:http://dx.doi.org/10.1016/j.rse.2007.08.001, 2009.

Monteith, J. L.: Solar radiation and productivity in tropical ecosystems, J. Appl. Ecol., 9(3), 747–766, doi:10.2307/2401901, 1972.

Morton, D. C., Nagol, J., Carabajal, C. C., Rosette, J., Palace, M., Cook, B. D., Vermote, E. F., Harding, D. J. and North, P. R. J.: Amazon forests maintain consistent canopy structure and greenness during the dry season, Nature, 506, 221–224, doi:10.1038/nature13006, 2014.

Murphy, R. J., Tolhurst, T. J., Chapman, M. G. and Underwood, A. J.: Estimation of surface chlorophyll- a on an emersed mudflat using field spectrometry: accuracy of ratios and derivative-based approaches, Int. J. Remote Sens., 26, 1835–1859, doi:10.1080/01431160512331326530, 2005.

Myneni, R. B. and Williams, D. L.: On the relationship between FAPAR and NDVI, Remote Sens. Environ., 49(3), 200–211, 1994.

Nichol, C. J. and Grace, J.: Determination of leaf pigment content in Calluna vulgaris shoots from spectral reflectance, Int. J. Remote Sens., 31(20), 5409–5422, doi:10.1080/01431160903302957, 2010.

Nichol, C. J., Lloyd, J. O. N., Shibistova, O., Arneth, A., Röser, C., Knohl, A., Matsubara, S. and Grace, J.: Remote sensing of photosynthetic-light-use efficiency of a Siberian boreal forest, Tellus B, 54(5), 677–687, doi:10.1034/j.1600-0889.2002.01347.x, 2002.

Nicodemus, F., Richmond, J. and Hsia, J.: Geometrical considerations and nomenclature for reflectance, Sci. Technol., 60, 1–52, doi:10.1109/LPT.2009.2020494, 1977.

Norton, P.: Photodetectors, in Handbook of Optics, volume II, edited by M. Bass, V. Mahajan, and E. Stryland, The McGraw-Hill Companies, New York, 2010.

Olofsson, P. and Eklundh, L.: Estimation of absorbed PAR across Scandinavia from satellite measurements. Part II: Modeling and evaluating the fractional absorption, Remote Sens. Environ., 110, 240–251, doi:10.1016/j.rse.2007.02.020, 2007.

Olsson, A. D., van Leeuwen, W. J. D. D. and Marsh, S. E.: Feasibility of invasive grass detection in a desertscrub community using hyperspectral field measurements and Landsat TM imagery, Remote Sens., 3, 2283–2304, doi:10.3390/rs3102283, 2011.

Oren, R. A. M., Hsieh, C.-I., Stoy, P., Albertson, J., McCarthy, H. R., Harrell, P. and Katul, G. G.: Estimating the uncertainty in annual net ecosystem carbon exchange: spatial variation in turbulent fluxes and sampling errors in eddy-covariance measurements, Glob. Chang. Biol., 12(5), 883–896, doi:10.1111/j.1365-2486.2006.01131.x, 2006.

Pacheco-Labrador, J. and Martin, M. P.: Nonlinear response in a field portable spectroradiometer: Characterization and effects on output reflectance, Geosci. Remote Sensing, IEEE Trans., 52(2), 920–928, doi:10.1109/tgrs.2013.2245671, 2014.

Pacheco-Labrador, J. and Martín, M. P.: Characterization of a field spectroradiometer for unattended vegetation monitoring. Key sensor models and impacts on reflectance, Sensors, 15, 4154–4175, doi:10.3390/s150204154, 2015.

Pacheco-Labrador, J., Ferrero, A. and Martín, M. P.: Characterizing integration time and gray-level-related nonlinearities in a NMOS sensor, Appl. Opt., 53(32), 7778–7786, doi:10.1364/ao.53.007778, 2014.

Pacheco-Labrador, J., Martín, M.P., Rossini, M., de Miguel, E. and Zarco-Tejada, P.: Relaciones espacio-temporales entre los datos ópticos adquiridos por el sensor hiperespectral CASI y flujos de carbono en un ecosistema de dehesa (in Spanish). XVI Congreso de la Asociación Española de Teledetección, 21-23 Octubre 2015.

Peng, Y. and Gitelson, A. A.: Remote estimation of gross primary productivity in soybean and maize based on total crop chlorophyll content, Remote Sens. Environ., 117, 440–448, doi:10.1016/j.rse.2011.10.021, 2012.

Pfitzner, K., Bartolo, R., Carr, G., Esparon, A. and Bollhöfer, A.: Standards for reflectance spectral measurement of temporal vegetation plots, in Supervising Scientist Report 195, pp. 1325–1554, Supervising Scientist, Darwin NT, Australia., 2011.

Piao, S. L., Sitch, S., Ciais, P., Friedlingstein, P., Peylin, P., Wang, X. H., Ahlstrom, A., Anav, A., Canadell, J. G., Cong, N., Huntingford, C., Jung, M., Levis, S., Levy, P. E., Li, J. S., Lin, X., Lomas, M. R., Lu, M., Luo, Y. Q., Ma, Y. C., Myneni, R. B., Poulter, B., Sun, Z. Z., Wang, T., Viovy, N., Zaehle, S. and Zeng, N.: Evaluation of terrestrial carbon cycle models for their response to climate variability and to $CO_2$ trends, Glob. Chang. Biol., 19(7), 2117–2132, doi:10.1111/gcb.12187, 2013.

Porcar-Castell, A., Garcia-Plazaola, J. I., Nichol, C. J., Kolari, P., Olascoaga, B., Kuusinen, N., Fernandez-Marin, B., Pulkkinen, M., Juurola, E. and Nikinmaa, E.: Physiology of the seasonal relationship between the photochemical reflectance index and photosynthetic light use efficiency, Oecologia, 170(2), 313–323, doi:10.1007/s00442-012-2317-9, 2012.

Porcar-Castell, A., Tyystjärvi, E., Atherton, J., van der Tol, C., Flexas, J., Pfündel, E. E., Moreno, J., Frankenberg, C. and Berry, J. A.: Linking chlorophyll a fluorescence to photosynthesis for remote sensing applications: mechanisms and challenges, J. Exp. Bot., 65(15), 4065–4095, doi:10.1093/jxb/eru191, 2014.

Reichstein, M., Bahn, M., Mahecha, M. D., Kattge, J. and Baldocchi, D. D.: Linking plant and ecosystem functional biogeography, Proc. Natl. Acad. Sci., 111, 13697–13702, doi:10.1073/pnas.1216065111, 2014.

Richter, R., Wang, X., Bachmann, M. and Schläpfer, D.: Correction of cirrus effects in Sentinel-2 type of imagery, Int. J. Remote Sens., 32, 2931-2941, 2011.

Roberts, G.: A review of the application of BRDF models to infer land cover parameters at regional and global scales, Progress in Physical Geography, 25, 483-511, 2001.

Rossini, M., Meroni, M., Migliavacca, M., Manca, G., Cogliati, S., Busetto, L., Picchi, V., Cescatti, A., Seufert, G. and Colombo, R.: High resolution field spectroscopy measurements for estimating gross ecosystem production in a rice field, Agric. For. Meteorol., 150(9), 1283–1296, doi:10.1016/j.agrformet.2010.05.011, 2010.

Rossini, M., Cogliati, S., Meroni, M., Migliavacca, M., Galvagno, M., Busetto, L., Cremonese, E., Julitta, T., Siniscalco, C., Morra di Cella, U. and Colombo, R.: Remote sensing-based estimation of gross primary production in a subalpine grassland, Biogeosciences, 9(7), 2565–2584, doi:10.5194/bg-9-2565-2012, 2012.

Rossini, M., Migliavacca, M., Galvagno, M., Meroni, M., Cogliati, S., Cremonese, E., Fava, F., Gitelson, A., Julitta, T., Morra di Cella, U., Siniscalco, C. and Colombo, R.: Remote estimation of grassland gross primary production during extreme meteorological seasons, Int. J. Appl. Earth Obs. Geoinf., 29, 1–10, doi:10.1016/j.jag.2013.12.008, 2014.

Rossini, M., Nedbal, L., Guanter, L., Ač, A., Alonso, L., Burkart, A., Cogliati, S., Colombo, R., Damm, A., Drusch, M., Hanus, J., Janoutova, R., Julitta, T., Kokkalis, P., Moreno, J., Novotny, J., Panigada, C., Pinto, F., Schickling, A., Schüttemeyer, D., Zemek, F. and Rascher, U.: Red and far red Sun-induced chlorophyll fluorescence as a measure of plant photosynthesis, Geophys. Res. Lett., 42, 1632-1639, doi:10.1002/2014gl062943, 2015.

Rouse, J. W., Haas, R. H., Schell, J. A. and Deering, D. W.: Monitoring the vernal advancement and retrogradation (green wave effect) of natural vegetation, Progress Report, Goddard Space Flight Center, Greenbelt, Maryland, pp. 112, 1973.

Ruimy, A., Saugier, B. and Dedieu, G.: Methodology for the estimation of terrestrial net primary production from remotely sensed data, J. Geophys. Res. Atmos., 99(D3), 5263–5283, 1994.

Running, S. W., Nemani, R. R., Heinsch, F. A., Zhao, M. S., Reeves, M. and Hashimoto, H.: A continuous satellite-derived measure of global terrestrial primary production, Bioscience, 54(6), 547–560, doi:10.1641/0006-3568(2004)054[0547:acsmog]2.0.co;2, 2004.

Ryu, Y., Baldocchi, D. D., Verfaillie, J., Ma, S., Falk, M., Ruiz-Mercado, I., Hehn, T. and Sonnentag, O.: Testing the performance of a novel spectral reflectance sensor, built with light emitting diodes (LEDs), to monitor ecosystem metabolism, structure and function, Agric. For. Meteorol., 150(12), 1597–1606, 2010.

Saber, S. G. R., Fox, N. P., Theocharous, E., Sun, T. and Grattan, K. T. V: Temperature and nonlinearity corrections for a photodiode array spectrometer used in the field, Appl. Opt., 50(6), 866–875, doi:10.1364/ao.50.000866, 2011.

Sakowska, K., Vescovo, L., Marcolla, B., Juszczak, R., Olejnik, J. and Gianelle, D.: Monitoring of carbon dioxide fluxes in a subalpine grassland ecosystem of the Italian Alps using a multispectral sensor, Biogeosciences, 11, 4695–4712, doi:10.5194/bg-11-4695-2014, 2014.

Sakowska, K., Gianelle, D., Zaldei, A., Macarthur, A., Carotenuto, F., Miglietta, F., Zampedri, R., Cavagna, M. and Vescovo, L.: WhiteRef: A new tower-based hyperspectral system for continuous reflectance measurements, Sensors, 15, 1088–1105, doi:10.3390/s150101088, 2015.

Schaepman-Strub, G., Schaepman, M. E. E., Painter, T. H. H., Dangel, S. and Martonchik, J. V. V: Reflectance quantities in optical remote sensing—definitions and case studies, Remote Sens. Environ., 103(1), 27–42, doi:http://dx.doi.org/10.1016/j.rse.2006.03.002, 2006.

Schimel, D., Pavlick, R., Fisher, J. B., Asner, G. P., Saatchi, S., Townsend, P., Miller, C., Frankenberg, C., Hibbard, K. and Cox, P.: Observing terrestrial ecosystems and the carbon cycle from space, Glob. Chang. Biol., 21(5), 1762–1776, doi:10.1111/gcb.12822, 2015.

Schmid, H. P.: Footprint modeling for vegetation atmosphere exchange studies: a review and perspective, Agric. For. Meteorol., 113(1–4), 159–183, doi:http://dx.doi.org/10.1016/S0168-1923(02)00107-7, 2002.

Schubert, P., Eklundh, L., Lund, M. and Nilsson, M.: Estimating northern peatland $CO_2$ exchange from MODIS time series data, Remote Sens. Environ., 114, 1178–1189, doi:10.1016/j.rse.2010.01.005, 2010.

Schubert, P., Lagergren, F., Aurela, M., Christensen, T., Grelle, A., Heliasz, M., Klemedtsson, L., Lindroth, A., Pilegaard, K., Vesala, T. and Eklundh, L.: Modeling GPP in the Nordic forest landscape with MODIS time series data-Comparison with the MODIS GPP product, Remote Sens. Environ., 126, 136–147, doi:10.1016/j.rse.2012.08.005, 2012.

Simic, A., Chen, J. M., Liu, J. and Csillag, F.: Spatial scaling of net primary productivity using subpixel information, Remote Sens. Environ., 93(1-2), 246–258, doi:10.1016/j.rse.2004.07.008, 2004.

Sims, D. A., Luo, H., Hastings, S., Oechel, W. C., Rahman, A. F. and Gamon, J. A.: Parallel adjustments in vegetation greenness and ecosystem $CO_2$ exchange in response to drought in a Southern California chaparral ecosystem, Remote Sens. Environ., 103(3), 289–303, 2006.

Sjöström, M., Ardö, J., Arneth, A., Boulain, N., Cappelaere, B., Eklundh, L., de Grandcourt, A., Kutsch, W. L., Merbold, L. and Nouvellon, Y.: Exploring the potential of MODIS EVI for modeling gross primary production across African ecosystems, Remote Sens. Environ., 115, 1081–1089, doi:10.1016/j.rse.2010.12.013, 2011.

Soudani, K. and François, C.: Remote sensing: A green illusion, Nature, 506, 165–166, doi:10.1038/nature13052, 2014.

Tagesson, T., Fensholt, R., Guiro, I., Rasmussen, M. O., Huber, S., Mbow, C., Garcia, M., Horion, S., Sandholt, I., Holm-Rasmussen, B., Göttsche, F. M., Ridler, M.-E., Olén, N., Lundegard Olsen, J., Ehammer, A., Madsen, M., Olesen, F. S. and Ardö, J.: Ecosystem properties of semiarid savanna grassland in West Africa and its relationship with environmental variability, Glob. Chang. Biol., 21(1), 250–264, doi:10.1111/gcb.12734, 2015.

Tan, B., Woodcock, C. E. E., Hu, J., Zhang, P., Ozdogan, M., Huang, D., Yang, W., Knyazikhin, Y. and Myneni, R. B. B.: The impact of gridding artifacts on the local spatial properties of MODIS data: Implications for validation, compositing, and band-to-band registration across resolutions, Remote Sens. Environ., 105, 98–114, doi:10.1016/j.rse.2006.06.008, 2006.

Thenkabail, P. S., Smith, R. B., Pauw, E. De and De Pauw, E.: Evaluation of Narrowband and Broadband Vegetation Indices for Determining Optimal Hyperspectral Wavebands for Agricultural Crop Characterization, Photogramm. Eng. Remote Sensing, 68(6), 607–621, 2002.

Townsend, P. A, Serbin, S. P., Kruger, E. L. and Gamon, J. A.: Disentangling the contribution of biological and physical properties of leaves and canopies in imaging spectroscopy data, Proc. Natl. Acad. Sci. U. S. A., 110(12), E1074–E1074, doi:10.1073/pnas.1300952110, 2013.

Tramontana ,G., Ichii, K., Camps-Valls, G., Tomelleri, E. and Papale, D.: Uncertainty analysis of gross primary production upscaling using random forests, remote sensing and eddy covariance data. Remote Sens. Environ., 168, 360-373, 2015.

Tucker, C. J.: Red and photographic infrared linear combinations for monitoring vegetation, Remote Sens. Environ., 8, 127–150, 1979.

Vesala, T., Kljun, N., Rannik, Ü., Rinne, J., Sogachev, A., Markkanen, T., Sabelfeld, K., Foken, T. and Leclerc, M. Y.: Flux and concentration footprint modelling: State of the art, Environ. Pollut., 152(3), 653–666, doi:http://dx.doi.org/10.1016/j.envpol.2007.06.070, 2008.

Vescovo, L. and Sakowska, K.: Modelling the spatial distribution of $CO_2$ fluxes in a subalpine grassland plateau of the italian Alps using multiple airborne AISA eagle hyperspectral sensor observations and Sentinel-2 simulated data. AGU Fall Meeting, 14-18 December 2015, Abstract Number 79938, 2015

Wang, Q., Li, P., Pu, Z. and Chen, X.: Calibration and validation of salt-resistant hyperspectral indices for estimating soil moisture in arid land, J. Hydrol., 408(3-4), 276–285, doi:10.1016/j.jhydrol.2011.08.012, 2011.

Wong, C. Y. S. and Gamon, J. A.: The photochemical reflectance index provides an optical indicator of spring photosynthetic activation in evergreen conifers, New Phytol., 206(1), 196–208, doi:10.1111/nph.13251, 2015.

Wu, H. and Li, Z.-L.: Scale issues in remote sensing: a review on analysis, processing and modeling., Sensors, 9(3), 1768–1793, doi:10.3390/s90301768, 2009.

Xiao, J., Zhuang, Q., Law, B. E., Chen, J., Baldocchi, D. D., Cook, D. R., Oren, R., Richardson, A. D., Wharton, S., Ma, S., Timothy, A. M., Shashi, B. V., Suyjer, A. E., Scott, R. L., Monson, R. K., Litvak, M., Hollinger, David, Y., Sun, G., Davis, K. J., Bolstad, P. V., Burns, S. P., Curtis, P. S., Drake, B. G., Falk, M., Fischer, M. L., Foster, D. R., Gu, L., Hadley, J. L., Katul, G. G., Matamala, R., McNulty, S., Meyers, T. P., Munger, J. W., Noormets, A., Oechel, W. C., Paw U, K. T., Schmid, H. P., Starr, G., Torn, M. S. and Wofsy, S. C.: A continuous measure of gross primary production for the conterminous United States derived from MODIS and AmeriFlux data, Remote Sens. Environ., 114, 576–591, doi:10.1016/j.rse.2009.10.013, 2010.

Xiao, X., Hollinger, D., Aber, J., Goltz, M., Davidson, E. A., Zhang, Q. and Moore Iii, B.: Satellite-based modeling of gross primary production in an evergreen needleleaf forest, Remote Sens. Environ., 89(4), 519–534, doi:http://dx.doi.org/10.1016/j.rse.2003.11.008, 2004a.

Xiao, X., Zhang, Q., Braswell, B., Urbanski, S., Boles, S., Wofsy, S., Moore Iii, B. and Ojima, D.: Modeling gross primary production of temperate deciduous broadleaf forest using satellite images and climate data, Remote Sens. Environ., 91(2), 256–270, doi:http://dx.doi.org/10.1016/j.rse.2004.03.010, 2004b.

Yao, X., Zhu, Y., Tian, Y., Feng, W. and Cao, W.: Exploring hyperspectral bands and estimation indices for leaf nitrogen accumulation in wheat, Int. J. Appl. Earth Obs. Geoinf., 12, 89–100, doi:10.1016/j.jag.2009.11.008, 2010.

Zanotelli, D., Montagnani, L., Manca, G., Scandellari, F. and Tagliavini, M.: Net ecosystem carbon balance of an apple orchard, Eur. J. Agron., 63, 97–104, doi:10.1016/j.eja.2014.12.002, 2015.

Zarco-Tejada, P.J., Morales, A., Testi, L., Villalobos, F.J.: Spatio-temporal patterns of chlorophyll fluorescence and physiological and structural indices acquired from hyperspectral imagery as compared with carbon fluxes measured with eddy covariance, Remote Sens. Environ., 133, 102–115, 2013a.

Zarco-Tejada, P.J., Suárez, L., González-Dugo, V.: Spatial resolution effects on chlorophyll fluorescence retrievals in a heterogeneous canopy using hyperspectral imagery and radiative transfer simulation, IEEE Geosci. Remote Sens. Lett., 10(4), 937-941, 2013b.

Zhao, M. S., Heinsch, F. A., Nemani, R. R. and Running, S. W.: Improvements of the MODIS terrestrial gross and net primary production global data set, Remote Sens. Environ., 95(2), 164–176, doi:10.1016/j.rse.2004.12.011, 2005.

**Table 1.** Advantages and disadvantages of different approaches and configurations for *in situ* spectral measurements.

| | **Advantages** | **Disadvantages** |
|---|---|---|
| **Method of data acquisition** | | |
| SFOV | • Only one instrument, lower cost<br>• No need for intercalibration | • Non-simultaneous up-welling/down-welling measurements.<br>• Need to automate the system for target and reference measurements.<br>• Either temperature control or characterization of the temperature sensitivity of the instrument and post-processing, are needed to acquire consistent time series of radiometric |

| | | |
|---|---|---|
| | | measurementsNeed for temperature control to derive radiometric quantities in absolute units |
| DFOV | • Quasi-simultaneous up-welling/down-welling measurements<br>• No need to automate for target and reference measurements. | • Typically two instruments, higher cost (but see Piccolo and SIF-Sys)<br>• Need for regular intercalibration<br>• Either temperature control or characterization of the temperature sensitivity of each of the instruments and post-processing, are needed both for derivation of reflectance factors or to acquire consistent time series of radiometric measurementsNeed to temperature control to derive both radiometric quantities in absolute units and reflectance ratios<br>• More sensitive to component degradation effects (each unit degrading at different rate) |
| **Spectral Resolution** | | |
| Multispectral | • Low cost<br>• Low weight and power consumption | • Fixed wavelengths/ no post-purchase flexibility<br>• Spectral calibration is difficult |
| Hyperspectral | • High versatility<br>• Possibility to estimate several indices (including future indices) and resample to specific spectral bands.<br>• Increased range of possibilities for the inversion of radiative transfer modelsOption to process the data with radiative transfer models | • Higher cost<br>• More sensible to spectral shifts and miscalibration<br>• Higher power consumption (either due to automation or temperature control units) |
| **Configuration** | | |
| Hemispherical-conical | • Easier comparison with airborne or satellite measurements<br>• Small Sampling sampling area | • Small sampling area (depending on FOV), requires taller towers for increased sampling area. |

| | | |
|---|---|---|
| | (allows studying smaller units: shoots, single canopies) | • Poor cosine response of cosine receptor and Spectralon in the SWIR<br>• If using Spectralon (SFOV): more expensive and delicate than cosine receptor. |
| Bi-hemispherical | • Wider sampling area | • More prone to BRDF effects of vegetation<br>• Difficult for comparison with airborne or satellite measurements if sun zenith angle is large<br>• Reflectance measurements not comparable with nadir observations<br>• Poor cosine response of the receptors in the SWIR |

## Figure Legends

Fig. 1. Main instrument configurations adopted for *in situ* spectral measurements.

Fig. 2. Different sampling strategies: discrete vs continuous. Spectral resolution denoted by bandwidth and sampling intervals. The narrower the bandwidth and the shorter the interval between bands the higher will be the resolution at which spectral features can be resolved. Note that sensor responses are here represented as Gaussian just for simplicity reasons but typical sensor responses may present different shapes.

Fig. 3. Spectralon® panel refectance before (dotted line) and after cleaning (solid line). The panel had been 'lightly' and carefully used in the field for one season. Data provided by C. MacLellan, NERC/NCEO Field Spectroscopy Facility, GeoScience, U. of Edinburgh.

Fig. 4. Hyperspectral systems in use before and during EUROSPEC. The UNIEDI System (A), the S-FLUOR/MRI System (B), the HSI System in which both the up- and down-welling measurements are hemispherical (C) and the AMSPEC-MED System where the spectrometer measuring up-welling radiance can measure at multiple zenithal and azimuthal angles (D). Down-welling hemispherical foreoptics (1), Up-welling conical-FOV foreoptics (2) and the box housing the spectrometers box (3) are marked in the respective panels.

Fig. 5. Hyperspectral systems developed during EUROSPEC. The Piccolo system (A) and the SIF-Sys (B) use a single spectrometer to measure two fields of view by means of a bifurcated fibre optics. The White-Ref system (C) uses a sliding white reference panel to measure irradiance. See further details in the text.

Fig. 6. Upscaling of optical and flux data across space and time. While long-term *in situ* spectral measurements help us establish a link between optical and flux data across time, new tools like UAVs are still needed to facilitate the spatial upscaling from the footprint to the landscape level.

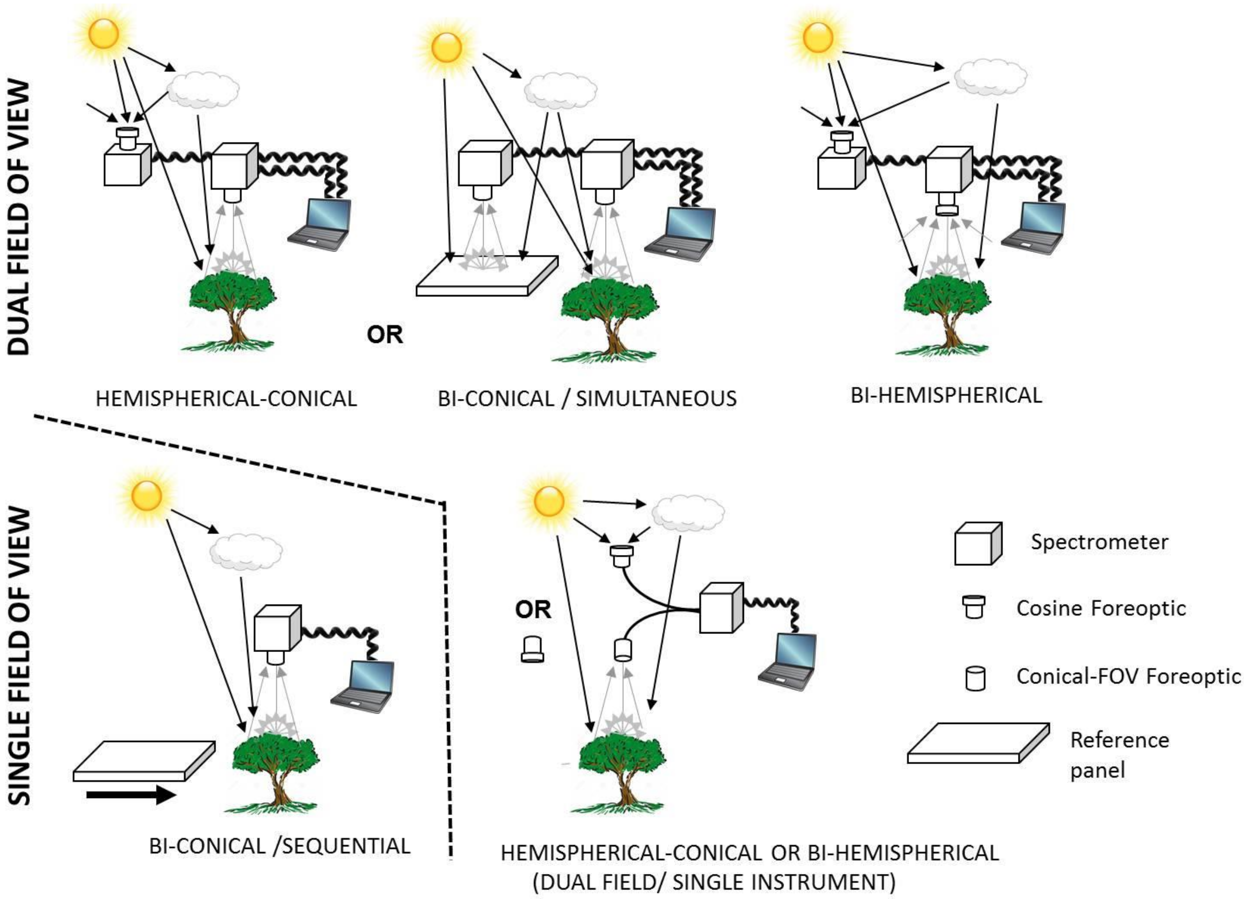
DUAL FIELD OF VIEW
OR
HEMISPHERICAL-CONICAL
BI-CONICAL / SIMULTANEOUS
BI-HEMISPHERICAL
SINGLE FIELD OF VIEW
BI-CONICAL /SEQUENTIAL
OR
HEMISPHERICAL-CONICAL OR BI-HEMISPHERICAL
(DUAL FIELD/ SINGLE INSTRUMENT)
Spectrometer
Cosine Foreoptic
Conical-FOV Foreoptic
Reference
panel

Figure 1.

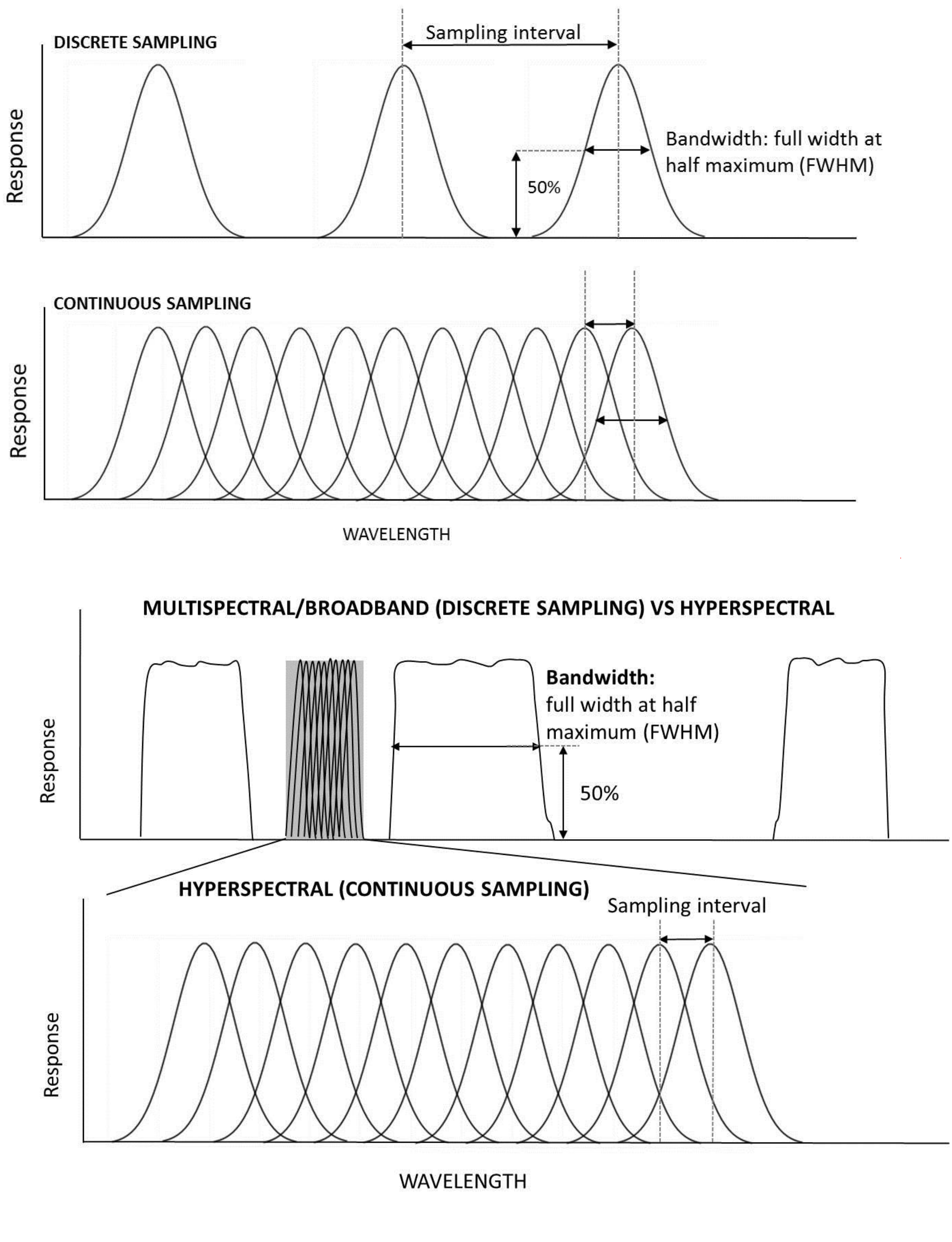
DISCRETE SAMPLING
Sampling interval
Response
Bandwidth: full width at half maximum (FWHM)
50%
CONTINUOUS SAMPLING
Response
WAVELENGTH
MULTISPECTRAL/BROADBAND (DISCRETE SAMPLING) VS HYPERSPECTRAL
Response
Bandwidth:
full width at half maximum (FWHM)
50%
HYPERSPECTRAL (CONTINUOUS SAMPLING)
Sampling interval
Response
WAVELENGTH

Figure 2.

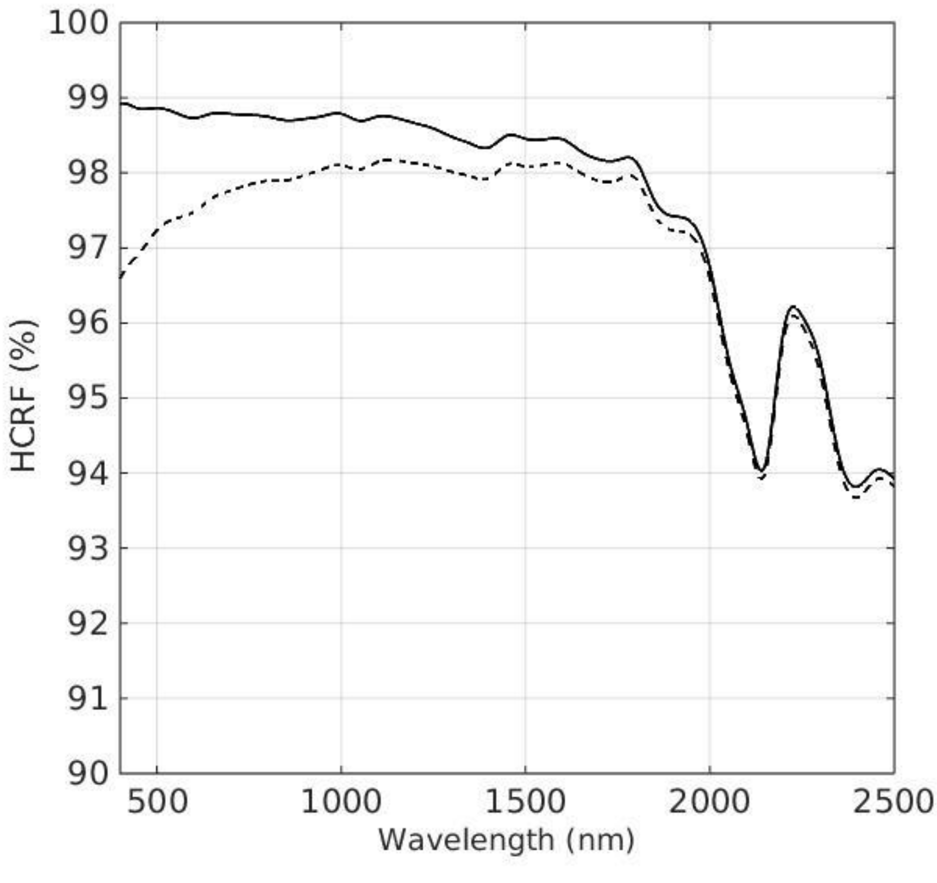
100
99
98
97
96
95
94
93
92
91
90
HCRF (%)
500
1000
1500
2000
2500
Wavelength (nm)

Figure 3.

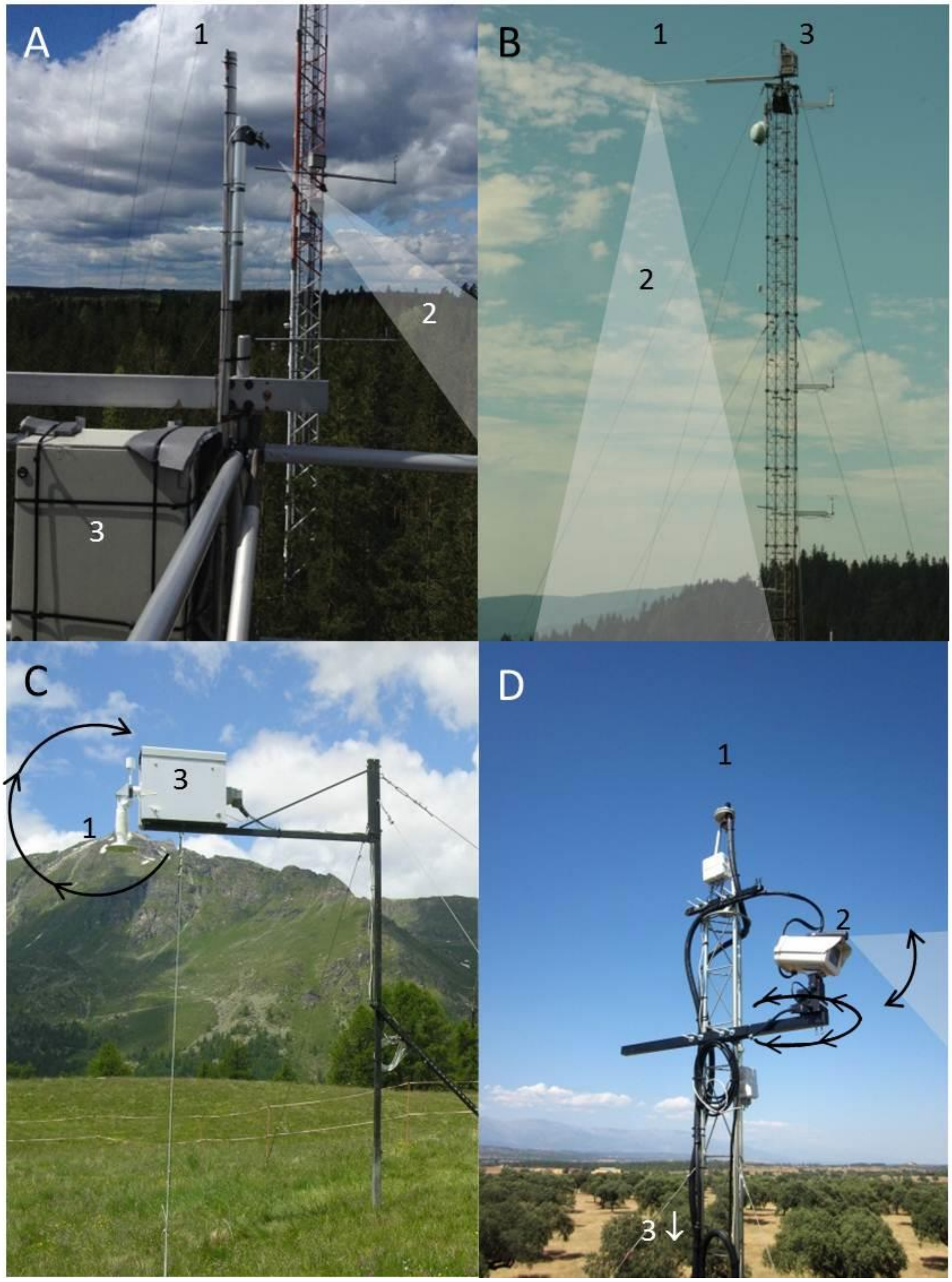


Figure 4.

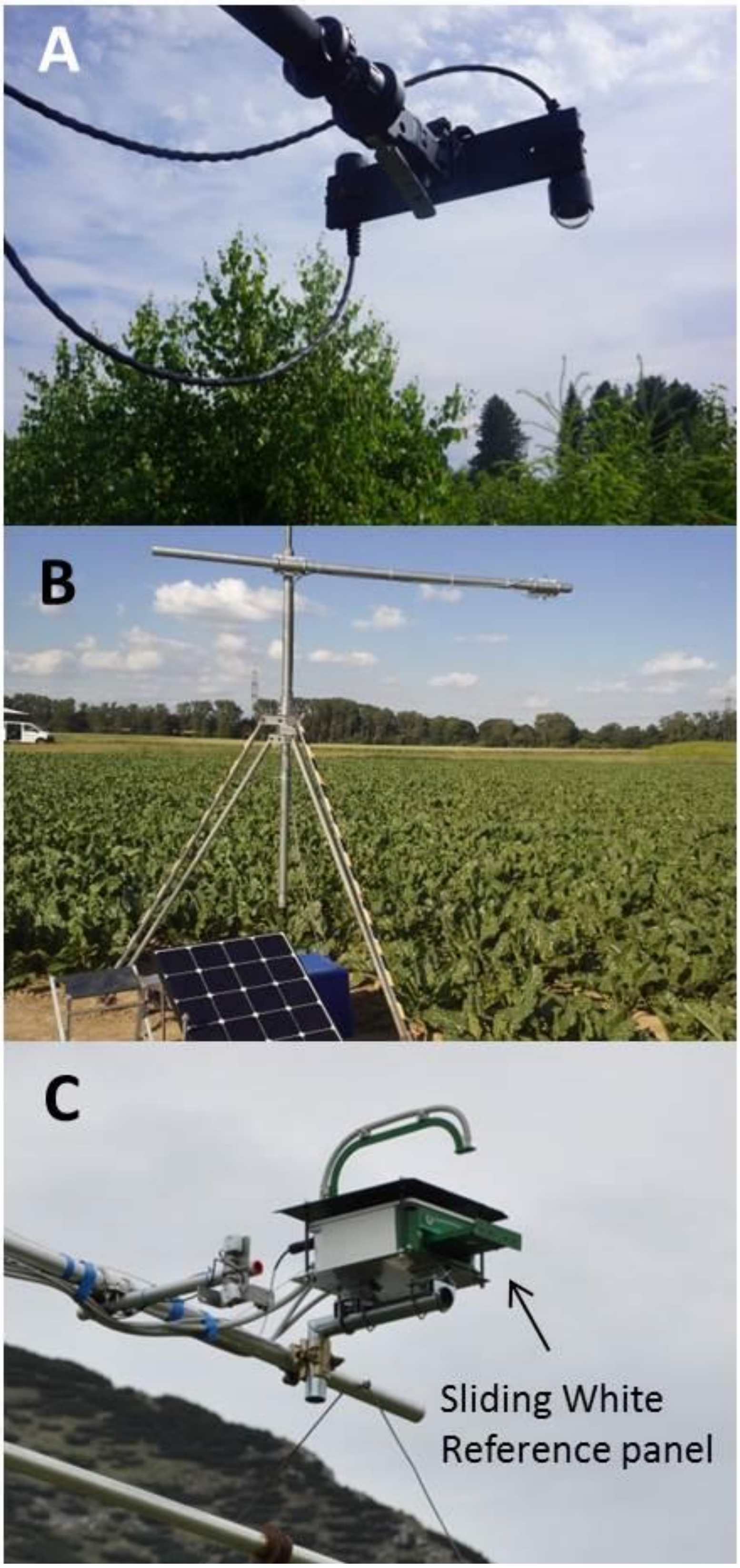


Figure 5.

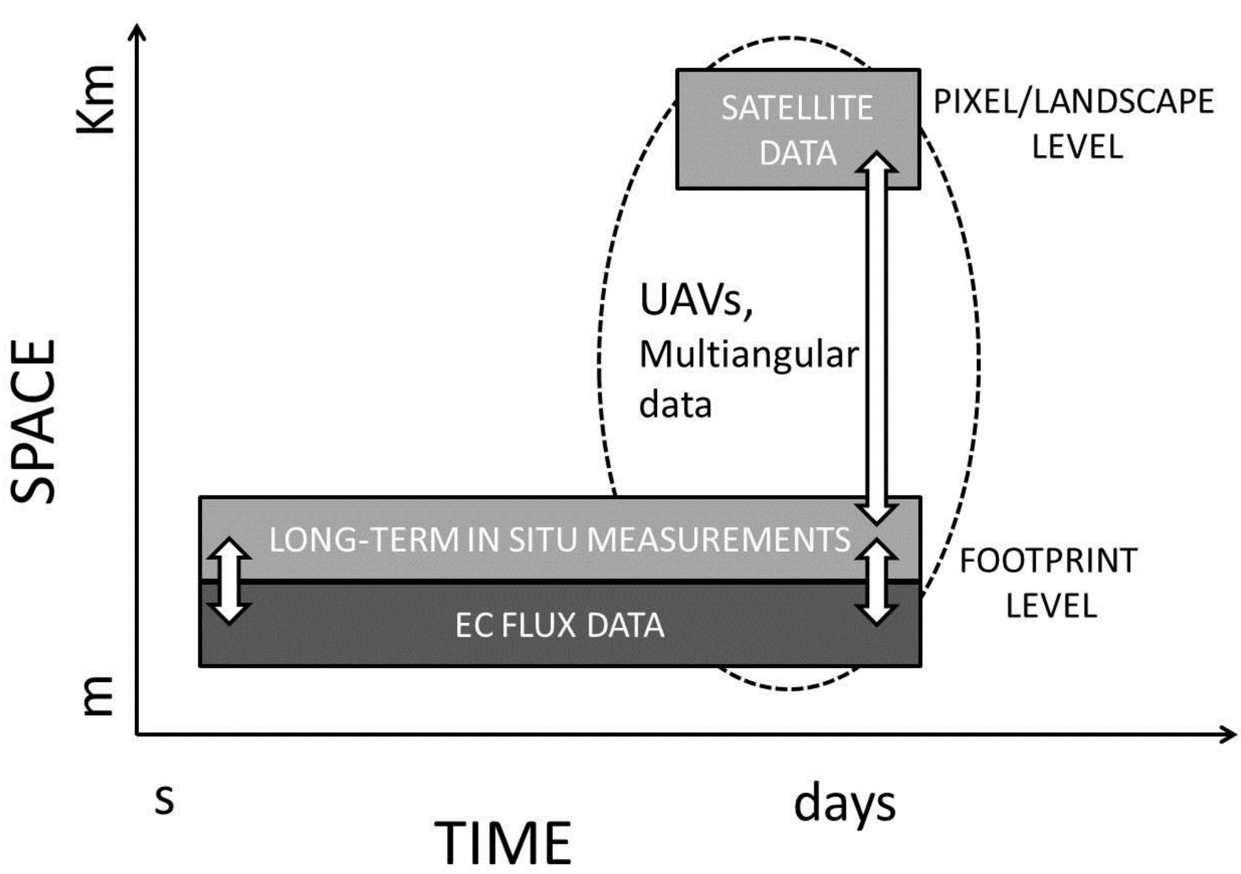
SATELLITE DATA
PIXEL/LANDSCAPE LEVEL
UAVs, Multiangular data
LONG-TERM IN SITU MEASUREMENTS
EC FLUX DATA
FOOTPRINT LEVEL
SPACE
Km
m
s
days
TIME

Figure 6