Recent Advances in the Estimation of Photosynthetic Stress for Terrestrial Ecosystem Services Related to Carbon Uptake

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3.1 Introduction

Estimation of the carbon uptake of terrestrial vegetation is still a major challenge in evaluating ecosystem services. In general, these services are the direct and indirect contribution of ecosystems to human well-being or, in other terms, the goods and services provided by ecosystems. Because photosynthesis is the key process mediating 90% of carbon and water fluxes (Joiner et al. 2011), it is one of the main drivers of many of the services provided by the ecosystems, such as climate regulation, carbon sequestration, carbon storage, food, or livestock grassland production (Costanza et al. 1997; de Groot et al. 2002; Naidoo et al. 2008). The integrity of ecosystem services is thus fundamental to human well-being. We need to understand the links between these services and the ecosystem processes. Estimating their magnitude at the local, regional, and global scales is crucial for maintaining them over time (Haines-Young and Potschin 2010).

The distribution of photosynthetic tissues changes across spatial and temporal scales and across different land uses (e.g., Paruelo et al. 2004). Traditional remote sensing techniques allow the assessment of green plant biomass and, therefore, plant photosynthetic capacity. However, detecting how much of this capacity is actually realized is a more challenging goal that is necessary to estimate photosynthetic carbon fluxes or the gross primary productivity (GPP), the ecosystem level expression of the photosynthetic carbon uptake. The efficiency involved in the conversion of absorbed light by plant photosynthetic tissues into organic compounds (i.e., light use efficiency [LUE] of terrestrial vegetation) also varies in time and space (Runyon et al. 1994; Gamon et al. 1995; Garbulsky et al. 2010) due to the periodic environmental and physiological limitations of photosynthesis. Contrasting functional types (Gamon et al. 1997; Huemmrich et al. 2010), drought and temperature extremes (Landsberg and Waring 1997; Sims et al. 2006), and nutrient levels (Gamon et al. 1997; Ollinger et al. 2008) are the factors that contribute to this variability.

In various forms, the simple relationships between primary productivity and the product between absorbed radiation by vegetation and the efficiency that plants convert radiation into biomass (Monteith 1977), have been the basis for many evaluations of photosynthesis and primary production from the canopy scale to the global scale (Field et al. 1995; Running et al. 2004). Monteith (1977) originally proposed this relationship for the estimation of the net primary productivity (NPP). However, production efficiency models (PEMs) are based on the theory of LUE for GPP, which states that a relatively constant relationship exists between photosynthetic carbon uptake and radiation absorbed by the canopy. Different approaches for estimating carbon uptake are based on this model of LUE. Many of these approaches have assumed a constant efficiency (Myneni et al. 1995) or derived this term from constant values by biome, cited in the literature (Ruimy et al. 1994). Another approach...
is to downregulate the maximum efficiency by biome using meteorological variables, such as vapor pressure deficit (VPD) and temperature, as surrogates for photosynthetic stresses (Running et al. 2004). Because VPD and temperature alone are not always good surrogates of reduced efficiency (Garbulsky et al. 2010), meteorologically based methods may not always adequately explain efficiency variation. Therefore, other methods of determining photosynthetic stress or LUE for carbon uptake estimations are needed to produce better assessments of the derived ecosystem services. A direct remote estimation of LUE may thus be of great importance and may have multiple applications, such as estimation of productivity (CO₂ fixation) or detection of effects of environmental stress on vegetation carbon uptake, that may precede reduction in leaf area (Garbulsky et al. 2008b).

Since concerns have recently been voiced by the scientific community and the society at large regarding the global effects of the alteration in carbon cycle, important improvements in our capacity to remotely estimate LUE have occurred (Grace et al. 2007). The approaches to remotely estimate LUE are linked to how we can gather a signal of the photosynthetic efficiency from reflected light, heat, or chlorophyll fluorescence (Figure 3.1). Although the theory of developing remotely sensed estimations from these pathways seems clear enough and estimations are made at different scales,

**FIGURE 3.1 (See color insert.)**
The incidental sunlight reaching the leaves and the complementary pathways of absorbed light after the interception by the canopy. Absorbed light by chlorophylls can be used to drive photochemistry, a process that can use up to 80% of the absorbed radiation. Alternatively, it can be lost as fluorescence (between 0.5% and 2% of absorbed radiation) or as heat (18%–98%). Photosynthesis, chlorophyll fluorescence, and heat loss are closely linked and in direct competition; thus, the increase of the rate of one process will unfailingly decrease the rate of the others.
complications still are being resolved as new platforms and sensors become available.

The main challenge related to the remote estimation of carbon uptake and primary productivity is to elucidate how to scale up the signal from leaves to the entire ecosystem and, therefore, how remote sensors can make assessments from foliar to ecosystem functional traits. In particular, the challenge is to estimate the actual photosynthetic performance or leaf photosynthesis stress and to scale up this to the ecosystem level. In this chapter, we review and synthesize recent approaches to remotely estimating LUE (i.e., the photosynthetic efficiency of carbon uptake) using current and future data. We present state-of-the-art methods of estimating LUE and recent advances in available remote sensing technologies and data.

3.2 Alternative Ways to Remotely Estimate Photosynthetic Stress of Terrestrial Vegetation

3.2.1 Leaf Pigments

Leaf pigment variation is a key tool for diagnosing a range of plant physiological properties and processes (Peñuelas and Filella 1998; Blackburn 2007). Different approaches related to contents and cycles of leaf pigments that try to estimate carbon uptake efficiency are based on the relationship with biochemical processes at the leaf level.

3.2.1.1 Chlorophyll Content

This approach is based on the remote estimation of the crop chlorophyll content (Chl) of vegetation as an estimator of GPP. In annual crops, because long- or medium-term changes in canopy Chl are related to crop phenology, canopy stresses, and photosynthetic capacity of the vegetation (e.g., Ustin et al. 1998; Zarco-Tejada et al. 2002), these can also be related to GPP. At the canopy level, Chl may appear to be the community property most relevant for the prediction of productivity (Dawson et al. 2003). Chlorophyll content is not a surrogate of LUE, but it estimates the total photosynthesis capacity. This approach does not precisely depend on LUE estimation, but it assumes that Chl is equivalent to the product of the fraction of absorbed photosynthetically active radiation (fAPAR) × LUE. In principle, it does not depend on the relationship between the widely used Normalized Difference Vegetation Index (NDVI), a spectral index derived from the red and infrared reflectances of the canopy, and fAPAR. In this context, it is proposed that the LUE model can be written as GPP = VI × PAR, where VI is a spectral index proxy of Chl.
The previously mentioned vegetation indices (VIs) are based on reflectance ($\rho$) in two spectral channels: the near-infrared (NIR) and either the green or the red edge. Several VIs, such as the MERIS Terrestrial Chlorophyll Index (MTCI = \([\rho_{\text{NIR}} - \rho_{\text{red edge}}] / [\rho_{\text{red edge}} - \rho_{\text{red}}]\)) and chlorophyll indices (CIgreen = $\rho_{\text{NIR}} / \rho_{\text{green}} - 1$; CIred edge = $\rho_{\text{NIR}} / \rho_{\text{red edge}} - 1$) have been specifically proposed to estimate total Chl content (Gitelson et al. 2003, 2005; Dash and Curran 2004). In annual crops, such as maize, the relationships between total Chl content and VIs showed that some VIs could explain more than 87% of Chl content variation (Peng et al. 2011). The determination coefficient of the relationship between CIgreen or CIred edge and total Chl in maize and soybean exceeded 0.92 (Gitelson et al. 2005). Thus, these chlorophyll- and green Leaf Area Index (LAI)-related VIs can be used as a proxy for Chl in the model GPP = VI \times PAR, specifically for herbaceous annual crops in which water or nutritional stresses will lead to a fast decrease in carbon uptake through total chlorophyll loss. At the ecosystem level, across 15 eddy covariance towers encompassing a wide variation in North American vegetation composition, the relationship between MTCI and tower GPP was stronger than that between either the Moderate Resolution Imaging Spectroradiometer (MODIS) GPP or Enhanced Vegetation Index (EVI) and tower GPP in croplands and deciduous forests, and to a lesser degree in grasslands. However, this was not the case in evergreen forests (Harris and Dash 2010) or in peatlands (Harris and Dash 2011). These analyses suggest that data from the MERIS sensor can be used as an alternative to MODIS for estimating carbon fluxes. Correlations between tower GPP and both vegetation indices (EVI and MTCI) were similar only for deciduous vegetation, indicating that physiologically driven spectral indices, such as the MTCI, may also complement existing structurally based indices in satellite-based carbon flux modeling efforts. The relationship between GPP and any chlorophyll index may thus be highly dependent in its parameters and its strength for different vegetation functional types (Figure 3.2).

The last evaluations of the model that relied on total Chl content and incident PAR showed that it can be applied to accurately estimate GPP in irrigated and rain-fed maize and soybean (Peng and Gitelson 2012). Due to differences in leaf structures and canopy architectures, the algorithms for GPP estimation are species-specific for maize and soybean, especially when using VIs with NIR and either red or green reflectance. However, it is possible to apply a unified algorithm for GPP estimation in both maize and soybean using CIred edge, MTCI, and red edge NDVI with MERIS spectral bands, which are least sensitive to different crop species. CIred edge and red edge NDVI with the red edge band around 720 nm were found to be non-species-specific for maize and soybean and to be very accurate in the estimation of GPP in maize and soybean combined.

This technique can provide accurate estimations of midday GPP in maize and soybean crops, and perhaps other annual crops, under rainfed and irrigated conditions because of a rather constant relationship between LUE
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and chlorophyll content. In contrast, there is little evidence for the utility of this approach in ecosystem types such as evergreen forest or other drought-adapted canopies. Further studies used the green CI (CIgreen)—mainly proposed for the estimation of canopy chlorophyll content (Gitelson et al. 2005)—as an estimator of midday LUE using cloud-free MODIS images (500 m) and flux measurements in maize (Wu et al. 2012). This relationship was then successfully applied for the estimation of midday LUE for coniferous forest and grassland.

3.2.1.2 Leaf Pigment Cycles and the Photochemical Reflectance Index

One proven pathway for detecting the spatial and temporal variations in LUE is the remote sensing of plant pigment cycles. The foundation of this remote sensing approach for estimating LUE is the de-epoxidation state of the xanthophyll cycle, which is linked to heat dissipation of leaves (Demmig-Adams and Adams 1996). This is a decay process of excited chlorophyll that competes with and is complementary to photosynthetic electron transport (Niyogi 1999). Hyperspectral remote sensing has been used to develop technologies and analytical methods for quantifying pigments nondestructively and repeatedly across a range of spatial scales. The recent progress in deriving predictive relationships among various characteristics and transformations of hyperspectral reflectance data related to plant pigments showed an expanding range of applications in the ecophysiological, environmental, agricultural, and forestry sciences (Blackburn 2007; Nichol et al. 2012).

FIGURE 3.2
Schematic relationships between midday gross primary productivity (GPP) and a chlorophyll index in ecosystems with contrasting phenologies and GPP dynamics. Although the relationships for crops and deciduous forests are well supported by the literature, those for grasslands and evergreen forests are not because of the lower strength and high dispersion of the data symbolized by the ellipses.
During the 1990s, a series of studies at the leaf and close canopy levels using close-range remote sensing from the ground or from low platforms were able to assess this efficiency parameter (LUE) based on concurrent xanthophyll pigment changes (Gamon et al. 1990, 1992, 1997; Peñuelas et al. 1994, 1995, 1997, 1998; Filella et al. 1996; Gamon and Surfus 1999). Because reflectance at 531 nm is functionally related to the de-epoxidation state of the xanthophyll cycle (Gamon et al. 1990, 1992; Peñuelas et al. 1995), a photochemical reflectance index (PRI; typically calculated as \([R_{531} - R_{570}] / [R_{531} + R_{570}]\), where \(R\) indicates reflectance and numbers indicate wavelength nanometers at the center of the bands) was developed as a method to remotely assess photosynthetic efficiency using narrow-band reflectance (Gamon et al. 1992; Peñuelas et al. 1995).

PRI measures the relative reflectance on either side of the green reflectance peak (550 nm, Figure 3.3); therefore, it also compares the reflectance in the blue (chlorophyll and carotenoids absorption) region of the spectrum with the reflectance in the red (chlorophyll absorption only) region (Peñuelas et al. 2011). Consequently, it can serve as an index of relative chlorophyll/carotenoid levels, often referred to as bulk pigment ratios. Over longer time scales (weeks–months), changes in bulk pigment content and ratios due to leaf development, aging, or chronic stress have been reported to play a significant role together with the xanthophyll pigment epoxidation in the PRI signal (Peñuelas et al. 1997; Gamon et al. 2001; Stylinski et al. 2002). Thus, PRI is also often related to carotenoid/chlorophyll ratios in

![FIGURE 3.3](image)

The pigments cycle approach to remotely sense gross light use efficiency (LUE) in terrestrial vegetation by means of the photochemical reflectance index (PRI). The remote sensing of the xanthophyll cycle provides a surrogate for the estimation of dissipation of excess radiation not used for photosynthesis from leaf to primary productivity at regional scales. Dark gray for the arrows and reflectance spectrum are indicative of conditions with excess radiation and therefore low LUE while the gray spectrum around 531 nm indicates the conditions with high LUE.
leaves across a large number of species, ages, and conditions (Stylinski et al. 2002; Filella et al. 2009). Therefore, to the extent that photosynthetic activity correlates with changing chlorophyll/carotenoid ratios in response to stress, ontogeny, or senescence, PRI may provide an effective measure of relative photosynthetic rates. Seasonally varying pigment levels also strongly affect PRI. This seasonal variation may actually help explain the good performance of PRI to predict LUE because of the covarying chlorophyll/carotenoid ratios with xanthophyll pigment levels. All the relationships described here show that this approach offers great possibilities for significantly improving the monitoring of CO₂ uptake in terrestrial ecosystems globally as well as regionally.

Although the mechanics of these wavelength selections have been fully explored at the leaf scale (Gamon et al. 1993), there is less support at a canopy or greater scale, where a variety of alternate wavebands have been used that are often based on statistical correlations (Gamon et al. 1992; Inoue et al. 2008) or determined by instrument limitations (Garbulsky et al. 2008b). The lack of a clear consensus in the literature on which PRI wavelengths best estimate LUE has hindered cross-study comparisons. Consequently, it is not entirely clear if the best wavelengths for measuring this feature at the leaf scale (531 and 570 nm) are necessarily the best wavelengths at progressively larger scales, where multiple scattering and other confounding effects may alter the spectral response of the xanthophyll cycle feature, much in the way that pigment absorption peaks can vary depending upon their chemical and scattering medium. More work, therefore, may be needed to determine the ideal PRI algorithm for airborne or spaceborne platforms; these studies have been hampered by the limited availability and high costs of suitable airborne and spaceborne instruments.

Together, these responses to the de-epoxidation state of the xanthophyll cycle and to carotenoid/chlorophyll ratios ensure that PRI scales with photosynthetic efficiency vary across a wide range of conditions, species, and functional types. The available evidence shows that the PRI is a reliable estimator of ecophysiological variables closely related to the photosynthetic efficiency at the leaf and canopy levels over a wide range of species, plant functional types, and temporal scales (see cites herein; Garbulsky et al. 2011).

Since 2000, the availability of global data provided by the MODIS sensor has been the primary tool for testing the utility of PRI at the ecosystem level. The 530-nm (526–536) waveband provided by the satellite-borne MODIS sensor was used as a LUE indicator at the ecosystem scale across different vegetation types with significant success (Rahman et al. 2004; Drolet et al. 2005, 2008; Garbulsky et al. 2008a, 2008b; Goerner et al. 2009). Currently, there are few spaceborne remote sensing instruments of high spectral resolution. (Note that Hyperion and CHRIS/PROBA are exceptions, but these are demonstration instruments with limited accessibility.) But these types of data can now be collected from a range of novel helicopter and aircraft
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instruments (Malenovsky et al. 2009) and from the planned new satellite data. Apart from the sensors already in orbit, there are various others coming up (Table 3.1) that will provide better data for estimating LUE from space based on pigment physiology. The launching of new image spectrometers, such as the HyspIRI by NASA or the EnMAP project led by the German Aerospace Centre (DLR), will allow the calculation of PRI at high spatial resolution, thus offering great new potential for remote sensing of the vegetation pigment cycle.

3.2.1.3 Drawbacks, Caveats, and Cautionary Remarks

There are different problems that still prevent the generalization of PRI use for ecosystem and biospheric scales and its global and operational use as a LUE estimator (Grace et al. 2007). Possible multiple biochemical, ecological, and physical confounding factors operating at several levels of aggregation in the LUE–PRI relationship emerge from the literature review (Garbulsky et al. 2011). At the leaf level, biochemical processes, including photorespiration, PSI cyclic electron transport, and nitrate reduction, can compete with CO₂ fixation for reductant generated by photosynthetic electron transport (Niyogi 1999). This can cause PSII (Photosystem II) efficiency (PRI) and CO₂ assimilation to diverge. There are even other pigment cycles, such as those included in the lutein epoxide cycle of tropical trees (Matsubara et al. 2008; Esteban et al. 2009) that could also produce noise in the PRI signal. Despite these potential complications, it appears that the overall photosynthetic system is often sufficiently regulated to maintain consistent relationships between PSII processes and CO₂ fixation (Gamon et al. 1997; Stylinski et al. 2002). On the other hand, to the extent that pigment ratios are not closely related to LUE, changing pigment ratios would be a confounding variable, as mentioned earlier.

At the canopy level, the problems are related to the structural differences of the canopies, the varying background effects of the satellite data (e.g., soil color, moisture, shadows, or presence of other non-green landscape components), the different reflectance signals derived from illumination and viewing angle variations (Filella et al. 2004; Sims et al. 2006; Hilker et al. 2010), or other physical effects of canopy and stand structure (e.g., LAI changes), such as leaf movement, sun and viewing angles, soil background, and shadows that can significantly influence the PRI signal (Barton and North 2001; Gamon et al. 1995). Different studies showed that PRI reflectance could be affected by sun–target–sensor geometry and by stand structure (Asner 1998; Barton and North 2001; Drolet et al. 2005; Hall et al. 2008; Hilker et al. 2008). Recent advances (from the analysis of multiangular satellite observations from the CHRIS sensor on board the PROBA satellite at 34-m spatial resolution) showed that PRI depends on the canopy shadow fractions for low levels of LUE across evergreen or mixed forest sites. A negative logarithmic relationship was found between the slope of the relationship between
# TABLE 3.1

<table>
<thead>
<tr>
<th>Satellite</th>
<th>Sensor</th>
<th>Launching/Service Period</th>
<th>Reference</th>
<th>Main Features of the Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Earth Observing -1 (EO-1)</td>
<td>Hyperion</td>
<td>November 2000</td>
<td><a href="http://eo1.gsfc.nasa.gov">http://eo1.gsfc.nasa.gov</a></td>
<td>Descending polar orbit with an equatorial crossing time of 10:03. High-resolution hyperspectral imager with 220 spectral bands (from 400 to 2500 nm) at 30-m resolution with a revisit period of 16 days.</td>
</tr>
<tr>
<td>PROBA (Project for On-Board Autonomy)</td>
<td>CHRIS (Compact High Resolution Imaging Spectrometer)</td>
<td>October 22, 2001</td>
<td><a href="https://earth.esa.int/web/guest/missions/esa-operational-eo-missions/proba">https://earth.esa.int/web/guest/missions/esa-operational-eo-missions/proba</a></td>
<td>Sun-synchronous orbit with a revisit of seven days. Depending on the setting mode, spatial resolution is 18 or 34 m at nadir setting. Along track narrow-band spectrometric observations of PRI of up to five angles.</td>
</tr>
<tr>
<td>TERRA–AQUA</td>
<td>MODerate resolution Imaging Spectroradiometer (MODIS)</td>
<td>TERRA: January 2000, AQUA: May 2002</td>
<td><a href="http://modis.gsfc.nasa.gov">http://modis.gsfc.nasa.gov</a></td>
<td>Same sensor on board two satellites. Two revisits a day (morning and afternoon) for 16 spectral bands from 400 to 1000 nm at 250-m, 500-m, and 1000-m spatial resolution and 10-nm bandwidth.</td>
</tr>
<tr>
<td>ADvanced Earth Observing Satellite II (ADEOS-2)</td>
<td>GLocal Imager (GLI)</td>
<td>December 2002–October 2003</td>
<td><a href="http://sharaku.eorc.jaxa.jp/ADEOS2">http://sharaku.eorc.jaxa.jp/ADEOS2</a></td>
<td>Six 250-m resolution channels and 30 other 1-km resolution channels and four-day revisit.</td>
</tr>
<tr>
<td>Environmental Mapping and Analysis Program (EnMAP)</td>
<td>HyperSpectral Imager (HSI)</td>
<td>Planned for 2015</td>
<td><a href="http://www.enmap.org">http://www.enmap.org</a></td>
<td>Sun-synchronous orbit with a revisit of four days and a spatial resolution of 30 m × 30 m; 94 bands between 420 and 1000 nm.</td>
</tr>
<tr>
<td>Hyperspectral Infrared Imager (HyspIRI)</td>
<td>VSWIR</td>
<td>Currently in the study stage</td>
<td><a href="http://hyspiri.jpl.nasa.gov">http://hyspiri.jpl.nasa.gov</a></td>
<td>380 to 2500 nm in 10-nm contiguous bands with a spatial resolution of 60 m at nadir and a revisit of 19 days.</td>
</tr>
</tbody>
</table>
PRI and the canopy shadow fraction with the gross LUE (Hilker et al. 2011). In contrast, other recent analysis showed that MODIS, PRI, and also NDVI, in contrast to EVI, were not affected by view angle across a 10-year period in three forest sites (Sims et al. 2011), results that may be contradictory with other studies. In any case, shadow fraction could be a variable affecting spatial resolution of the data.

The consistency of the relationship between PRI, LUE, and CO₂ uptake that is increasingly found in different studies across ecosystems (Garbulsky et al. 2011; Hilker et al. 2011; Peñuelas et al. 2011) suggests a great degree of functional convergence of biochemical, physiological, and structural components affecting ecosystem C fluxes between ecosystem types (Field 1991). Emergent ecosystem properties may allow exploration of their complex photosynthetic behavior using simple spectral methods such as measurement of the plant pigment cycle through the PRI. Understanding the basis for this convergence (and finding the ecophysiological principles governing these responses) remains a primary goal of current research. Meanwhile, PRI, which is more important for the pragmatic empirical remote sensing of CO₂ uptake, especially from near-nadir satellite observations (Goerner et al. 2010) and with multiangular atmospheric correction (Lyapustin and Wang 2009; Hilker et al. 2010), can become an excellent tool for continuous global monitoring of GPP, which is essential to follow the C sequestration under changing climate.

The use of uniform protocols is needed to generate comparable data and, at the end, a possible general calibration of the PRI–LUE relationship (Peñuelas et al. 2011). Further studies are also needed to disentangle the several drivers of the PRI signal and to resolve the potentially confounding factors to improve the assessment of CO₂ fluxes in many different biomes using hyperspectral or narrow-band remote sensing.

3.2.2 Chlorophyll Fluorescence

Estimating LUE and carbon uptake from chlorophyll fluorescence viewed from space is undoubtedly a field of knowledge where great advancements have taken place in recent years. Remote sensing of terrestrial vegetation fluorescence from space is of great interest because it can provide global information on the functional status of vegetation including LUE and GPP. Global retrieval of solar-induced fluorescence emitted by terrestrial vegetation is beginning to provide an unprecedented measure for photosynthetic efficiency.

3.2.2.1 Basics, Origin, and Characteristics of Fluorescence

Improvements in fluorescence measuring techniques have made the fluorescence method an important tool for basic and applied plant physiology research (Krause and Weis 1991). The fluorescence signal originates in the
core of the photosynthetic apparatus, where absorbed photosynthetically active radiation (APAR) is converted into chemical energy. Fluorescence reflects the competition among several pathways for the excitation captured in the antenna. When photochemistry occurs with maximal efficiency, excitation is passed mainly to the photoreactions. When the photochemical traps are closed, excitation is lost because of a competition between fluorescence and nonradiative dissipative pathways, the latter converting the energy to heat. Because the fluorescence yield varies inversely with the fraction of open reaction centers, it provides a useful tool for investigation of photosynthetic processes. A small part of the light absorbed by chlorophyll in an assimilating leaf can be reemitted as fluorescence by the chlorophyll molecules of the photosystem II, which adds a weak signal to reflected solar radiation. Because these processes occur in competition, by measuring chlorophyll fluorescence we can also know the efficiency of photochemistry and heat dissipation, which is linked to CO₂ assimilation (Baker 2008).

Chlorophyll fluorescence measurements are traditionally made at the leaf level using an external source of light. The fluorescence spectrum peak is of a longer wavelength than the absorbed light; therefore, fluorescence yield can be quantified by exposing a leaf to light of a defined wavelength and measuring the amount of light reemitted at longer wavelengths when the light is turned off. This technique allows the quantifying of different parameters related to the light phase of carbon fixation. Extensive experimental and theoretical studies demonstrate that chlorophyll fluorescence is a proxy to actual photosynthesis and as such directly related to LUE and CO₂ uptake (Seaton and Walker 1990); it also behaves as an indicator of plant vitality and plant stress because fluorescence emission competes with adaptation/protection mechanisms set up by the plant. Hence, measuring fluorescence can provide access to missing information regarding photosynthesis performance variables (Maxwell and Johnson 2000).

This laboratory measurement methodology is far from the requirements necessary to estimate fluorescence of an ecosystem scale; therefore, new methods are needed to measure Chl fluorescence from space. Solar-induced Chl fluorescence (F) can provide an early and direct approach for the evaluation of the actual functional status of vegetation because of the rapid response to perturbations in the environmental conditions such as light and water stress; therefore, F can detect stress conditions before significant reductions in Chl content or LAI have occurred. The fluorescence of green vegetation consists of blue-green fluorescence (maxima at 440 and 520 nm) and of red and far-red chlorophyll fluorescence (maxima at 690 and 740 nm). To monitor vegetation photosynthesis, it is necessary to analyze the red and far-red chlorophyll fluorescence from the photosynthetically active parts of the leaf tissues. The magnitude of the two broad peaks with maxima around 685 and 740 nm can be related to photosynthetic efficiency. Because the magnitude of solar radiation reflected by vegetation and by atmosphere can be 100 to 150 times more intense than F at the top of the atmosphere,
the main challenge in achieving an F estimation from remote sensing passive measurements is to decouple the F signal from the solar radiation (Meroni et al. 2009).

### 3.2.2.2 Recent Advancements

Even though the first attempts to quantify chlorophyll on terrestrial vegetation without an artificial excitation source date back to the 1970s, the remote sensing of chlorophyll fluorescence is still in a developmental stage, but research is advancing. The F signal can be detected passively in narrow absorption lines (≈2–3 nm) of the solar and atmospheric spectrum in which irradiance is strongly reduced (i.e., the Fraunhofer lines). Three main Fraunhofer lines in the visible and NIR have been used for F estimation: Hα due to hydrogen (H) absorption in the solar atmosphere centered at 656.4 nm and two telluric oxygen (O2) absorption bands in the Earth’s atmosphere: O2-B centered at 687.0 nm and O2-A at 760.4 nm. A combination of Fraunhofer lines and O2 lines would make it possible to measure all the main fluorescence bands. The two O2 bands (A and B) and the Hα bands are considered the most useful (Meroni et al. 2009).

Radiance measurements at high spectral resolution exploit the Fraunhofer line to decouple F from the reflected flux. F retrieval in solar Fraunhofer lines is based on the evaluation of the in-filling of the Fraunhofer lines due to F and hereafter. Because the fractional depth of Fraunhofer lines is not affected by atmospheric scattering and by absorption in narrow spectral windows free from telluric absorption features, the atmospheric modeling required is much simpler than with atmospheric bands.

Although there have been many measurements of fluorescence, especially recently, from ground- and airborne-based instruments (Meroni et al. 2009), there has been scant information available from satellites. The first space-based estimation of F (Gunter et al. 2007) was performed using data from the O2-A absorption band provided by the ENVISAT MEdium Resolution Imaging Spectrometer (MERIS). The MERIS-derived fluorescence correlated well (R2 = 0.85) with data acquired by the Compact Airborne Spectrographic Imager (CASI-1500) sensor and ground-based estimates. Recent studies (Joiner et al. 2011; Frankenberg et al. 2011b) presented the first results at the global scale from the use of high spectral resolution data from the Thermal And Near-infrared Sensor for carbon Observation–Fourier Transform Spectrometer (TANSO–FTS/GOSAT). These two studies used different approaches. The method used by Joiner et al. (2011) makes use of one strong Fraunhofer line (K I at 770.1 nm). It employs real solar irradiance measurements from the TANSO–FTS in order to avoid the explicit modeling of the instrument line shape function (ILSF). In turn, the method proposed in Frankenberg et al. (2011a) extends this single-line approach to two broader spectral windows centered at 755 and 770 nm. This retrieval, making use of broader spectral windows containing several Fraunhofer
lines, is expected to be less sensitive to instrumental noise than that based on one single line, whereas retrievals performed for the two separate windows provide more independent measurements to be used to enhance the signal-to-noise ratio of the final F products. At present, data from a 22-month series have shown an accurate comparison of F intensity levels and spatial patterns with physically based Fs retrieval approach. However, there is a need for a biome-dependent scaling from Fs to gross primary production (Gunter et al. 2012).

3.2.2.3 Future of Chlorophyll Fluorescence

Several projects are underway to develop satellite platforms and sensors to remotely determine chlorophyll fluorescence for the estimation of the carbon cycle of terrestrial vegetation (Table 3.2). Because vegetation fluorescence can be converted into an indicator of photosynthetic activity, by using fluorescence data we can achieve a better understanding of how much carbon is being taken up by plants and their role in the carbon and water cycles. In addition to the sensors in orbit at the time of this publication, there are a number of satellite projects related to the measurements of vegetation fluorescence. The availability of fluorescence data at detailed levels from regional to global scales is a great step forward and will represent a huge increase in the capability of PEMs to assess the spatial and temporal variability of carbon uptake by terrestrial vegetation. One of the major and more ambitious satellite projects, scheduled to be in orbit in 2018, is led by the European Space Agency. Called the FLuorescence EXplorer (FLEX), its objective is to observe photosynthesis for a better understanding of the carbon cycle and to provide global maps of vegetation fluorescence. The main instrument is the fluorescence imaging spectrometer (FIS) that covers the O2-A (760 nm) and O2-B (687 nm) absorption lines with a spectral band of 20 nm. The ground spatial resolution at nadir will be 300 m, and the revisiting period will be seven days.

Another important projected satellite is NASA’s Orbiting Carbon Observatory-2 (OCO-2) that will be specifically dedicated to studying atmospheric carbon dioxide from space. Three high-resolution grating spectrometers (Day et al. 2011)—one for each spectral band located at O2 A-Band (757–772 nm), weak CO2 Band (1590–1621 nm), and strong CO2 Band (2041–2082 nm)—will be combined with meteorological observations and ground-based CO2 measurements to characterize CO2 sources and sinks on regional scales at monthly intervals for two years at 1.29 km × 2.25 km spatial resolution.

The Geostationary Carbon Process Mapper (GCPM) has three proposed geostationary platforms. This project aims to measure key atmospheric trace gases and process tracers related to climate change and human activity at high temporal resolution. This understanding comes from contiguous maps of carbon dioxide (CO2), methane (CH4), carbon monoxide (CO),
### TABLE 3.2
Remote Sensing Tools for Chlorophyll Fluorescence Assessment from Space

<table>
<thead>
<tr>
<th>Satellite</th>
<th>Sensor</th>
<th>Launch/in Orbit</th>
<th>Reference</th>
<th>Main Features of the Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>ENVISAT</td>
<td>MeDium Resolution Imaging Spectrometer (MERIS)</td>
<td>From March 2002 to April 2012</td>
<td><a href="http://wdc.dlr.de/sensors/meris">http://wdc.dlr.de/sensors/meris</a></td>
<td>Spatial resolution: 260 m × 300 m. Two channels near the O₂-A-bands centered at 753.8 and 760.6 nm; bandwidths = 7.5 and 3.75 nm, respectively.</td>
</tr>
<tr>
<td>ENVISAT</td>
<td>SCanning Imaging Absorption spectrometer for Atmospheric CHartographY (SCIAMACHY)</td>
<td>From March 2002 to April 2012</td>
<td><a href="http://www.sciamachy.org">http://www.sciamachy.org</a> wdc.dlr.de/sensors/sciamachy</td>
<td>From 0.2 to 0.5 nm, from 240 nm to 1700 nm, and from 2000 to 2400 nm. Limb vertical 3 km × 132 km, Nadir horizontal 32 km × 215 km.</td>
</tr>
<tr>
<td>Earth Explorer 8</td>
<td>Fluorescence EXplorer (FLEX) Fluorescence Imaging Spectrometer (FIS)</td>
<td>2018 or later, now in development</td>
<td><a href="http://esamultimedia.esa.int/docs/SP1313-4_FLEX.pdf">http://esamultimedia.esa.int/docs/SP1313-4_FLEX.pdf</a></td>
<td>Descending sun-synchronous orbit with an equator crossing time 10:00.</td>
</tr>
<tr>
<td>Geostationary Carbon Process Mapper (GCPM)</td>
<td>Geostationary Fourier Transform Spectrometer (GeoFTS)</td>
<td>In project phase</td>
<td>Key et al. 2012</td>
<td>Geostationary: 10 times per day at ~4 km × 4 km.</td>
</tr>
</tbody>
</table>
and F collected up to 10 times per day at relatively high spatial resolution (~4 km × 4 km) from geostationary orbit (GEO). These measurements will capture the spatial and temporal variability of the carbon cycle across diurnal, synoptic, seasonal, and interannual time scales. The combination of high-resolution mapping and high measurement frequency provides quasi-continuous monitoring, effectively eliminating atmospheric transport uncertainties from source/sink inversion modeling. The CO$_2$/CH$_4$/CO/CF measurements could also provide the information needed to disentangle natural and anthropogenic contributions to atmospheric carbon concentrations.

3.2.2.4 Final Comments on Chlorophyll Fluorescence from Space

Currently, there are a number of new, encouraging results and ongoing projects on the estimation of carbon uptake by vegetation from chlorophyll fluorescence from space. The retrieval of chlorophyll fluorescence from space is feasible through the Fraunhofer line retrieval method, which is simple, fast, and robust, and is now verified with real data on the ground. Fluorescence appears to display information that is independent of reflectance data (e.g., fAPAR). Chlorophyll fluorescence retrievals from the GOSAT and the OCO-2, in conjunction with their global atmospheric CO$_2$ measurements, will provide an exceptional combination of a vegetation and atmospheric perspective on the global carbon budget, constraining our model predictions for future atmospheric CO$_2$ abundance. Most importantly, this method is largely unaffected by atmospheric scattering and is even able to sense F through thin clouds.

Although this approach seems promising, different problems also arise from the available data. The strong correlation between F and GPP displayed is not as strong in boreal summers because of the overestimation produced in savannas and croplands and the underestimation produced in boreal needleleaf forests. Therefore, additional research is needed to disentangle the effect of disturbance factors such as illumination, canopy structure, and temporal and spatial resolution of the satellite data on the relationship between sun-induced fluorescence and photosynthesis.

3.3 Final Considerations

Although eddy covariance towers represent the current standard for ecosystem carbon flux estimation of GPP, we must learn to properly calibrate these estimations with the new remote sensing products, if our objective is to develop reliable remote sampling methods for ecosystem carbon flux.
This remains a significant challenge because flux towers sample through time, whereas remotely sensed imagery samples through space (Rahman et al. 2001). To make this calibration, we should blend these sampling domains by applying remote sensing aircraft and satellite measurements at the same temporal and spatial scales as flux tower footprint measurements, which is rarely done. Therefore, coordinated flux and optical data acquisition from different biomes are needed. In addition, standardized ground-based optical sampling programs at flux towers (Gamon et al. 2006) should be expanded. We have to properly calibrate the surrogates for LUE for different ecosystems or vegetation types, and then we will be able to apply remote sensing to extrapolate in time and space from tower sites. Actual widespread location of the towers across vegetation types (the long-term goal of this methodology) and the increasing availability of remote sensing tools at different spatial, temporal, and spectral resolutions are the main advantages and the reasons to conduct further research along this avenue.

The different approaches outlined in this chapter highlight how remote estimation of chlorophyll fluorescence will provide accurate global estimations of LUE in the near future. Although research efforts to generate estimates of chlorophyll fluorescence outweigh all other approaches, chlorophyll fluorescence estimation seems to be less ecosystem dependant than the other approaches. The temporal reaction of each of the remote sensing approaches is one issue to be considered in the estimations of LUE considering the objectives of GPP estimations. Although chlorophyll fluorescence has a very short reaction time (in the order of milliseconds) in relation to the changes in environmental conditions regulating photosynthesis, chlorophyll content change as a response to stress is a process that can take up to three days in herbaceous crops (Houborg et al. 2011). The proposed geostationary constellation of satellite platforms to capture chlorophyll fluorescence (Table 3.2) will provide, in contrast, an extraordinary daily temporal resolution database.

Even though important, specifically designed missions are providing and will provide data on LUE, it is interesting to note that three new satellite missions—Suomi National Polar-orbiting Partnership (NPP), Landsat 8, and Sentinel—will not give much information on LUE spatial and temporal variability. In the case of the Suomi NPP, as the continuity of MODIS missions, it is not designed to provide the bands to calculate PRI. In any case, there is a wide and promising avenue for the estimation of terrestrial vegetation LUE from satellite data.

In this chapter, we presented and analyzed the most recent advances related to the quantification of services related to carbon uptake by terrestrial ecosystems. The cascade effects of GPP, as the main energy input that determines many ecosystem services, warrants accurate estimation of these fluxes in time and space. Remote sensing technologies are providing new methodologies for such estimations.
Acknowledgments

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Recent Advances in the Estimation of Photosynthetic Stress


