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Technical note

# A simple filtered photodiode instrument for continuous measurement of narrowband NDVI and PRI over vegetated canopies

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ABSTRACT

Recent advances in understanding relationships between spectral reflectance of vegetation canopies and the structural and physiological drivers of canopy-atmosphere carbon dioxide exchange highlight the potential for using narrowband spectral vegetation indices to spatially scale $CO_2$ fluxes beyond the area of a tower footprint. However, ground reference observations of narrowband spectral reflectance in support of satellite observations can be challenging to obtain because (1) automated sampling of both upwelling and downwelling radiation is required over extended time periods to characterize diurnal and seasonal variability, (2) hyperspectral spectroradiometer data and hardware can be sensitive to environmental factors such as temperature and moisture, and (3) hyperspectral spectroradiometers are expensive, greatly limiting prospects for widespread automated sampling. We have therefore developed the QuadPod: a simple, lightweight, relatively low cost and low power sensor capable of continuously measuring upwelling and downwelling radiation in 10 nm wavebands centered at 532 nm, 568 nm, 676 nm, and 800 nm. QuadPod measurements can be combined to calculate spectral reflectance indices (e.g., the photochemical reflectance index, PRI; and the normalized difference vegetation index, NDVI) useful for modeling canopy-atmosphere carbon exchange. The basic QuadPod instrument design described here can be implemented using any combination of optical filters in order to calculate other spectral vegetation indices.

## 1. Introduction

Networks of environmental instruments are increasingly used to provide critical information about biosphere–atmosphere interactions, with a major research focus on uncovering mechanisms influencing exchanges of mass and energy between plant canopies and the atmosphere (e.g., Running et al., 1999). Networks of micrometeorological flux towers, such as those represented globally by Fluxnet, are vital for understanding the processes controlling these exchanges of mass and energy (Baldocchi et al., 2001), and provide data necessary for calibrating and validating models designed to scale $CO_2$ fluxes from the footprint of these towers to the global extent (Cohen and Justice, 1999). Central to these scaling efforts are spectral remote sensing measurements collected from satellites (e.g., Running et al., 2004; Hill et al., 2006; Drolet et al., 2008; Sims et al., 2008), aircraft (e.g., Nichol et al., 2000; Fuentes et al., 2006), and increasingly, tower-based instruments (e.g., Leuning et al., 2006; Sims et al., 2006; Hall et al., 2008; Hilker et al., 2007, 2008a,b). While tower-based spectral measurements show great potential for understanding links between canopy-level ecophysiological processes and global-level spectral observations (Gamon et al., 2006a), the number of towers that currently support spectral reflectance measurements is few, in part due to the high cost and complicated long-term operation of hyperspectral spectroradiometers.

### 1.1. Background theory

The primary use of spectral reflectance data in studies of vegetation productivity and $CO_2$ exchange involves the incorporation of spectrally derived vegetation indices into some form of vegetation productivity model. Monteith (1972) proposed a simple model of gross primary productivity (GPP) for crops, which has provided the basis for many models using remote sensing driven estimates of ecosystem productivity (Sims et al., 2006). This model relies on inputs of incident photosynthetically active radiation (PAR), the fraction of incident radiation absorbed by photosynthetic tissue (fPAR), and the efficiency with which absorbed radiation is used to fix carbon by the plant (mol C fixed per mol quanta absorbed), hereafter referred to as light use

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efficiency (LUE; Eq. (1)).

$$\mathrm{GPP} = (\mathrm{PAR} * \mathrm{fPAR}) * \mathrm{LUE} \quad (1)$$

A growing body of work has demonstrated the utility of narrowband (≤10 nm full width half maximum (FWHM) spectral resolution) optical remote sensing to derive both fPAR and LUE estimates that can in turn be used to estimate GPP based on Eq. (1) (Rahman et al., 2001, 2004; Sims et al., 2005, 2006). The specific vegetation indices typically used in these and other studies for estimating fPAR and LUE are the Normalized Difference Vegetation Index (NDVI; Eq. (2)) and the Photochemical Reflectance Index (PRI; Eq. (3)), respectively. Sellers (1987) demonstrated the functional relationship between NDVI and fPAR, while Gamon et al. (1990, 1992) showed that changes in reflectance near 531 nm corresponded with xanthophyll pigment interconversion, which in many plants correlates highly with LUE. These narrowband vegetation indices are calculated as:

$$\mathrm{NDVI} = \frac{\rho 800 - \rho 675}{\rho 800 + \rho 675} \quad (2)$$

and

$$\mathrm{PRI} = \frac{\rho 531 - \rho 570}{\rho 531 + \rho 570} \quad (3)$$

where $\rho$ is the reflectance at the specified wavelength.

To acquire such narrowband optical data, field- and satellite-based hyperspectral instruments that collect tens to hundreds of spectral bands are used. However, it is often a major challenge to adequately match temporal and spatial resolutions between flux source area as measured via tower-based micrometeorological instrumentation and optical signals measured by earth orbiting spectrometers. For example, the MODIS GPP product is produced as an 8-day composite (Running et al., 2004), whereas eddy covariance flux estimates are generally calculated on the half hourly to hourly time scale. To better understand the mechanisms driving the relationships between biosphere–atmosphere fluxes of $CO_2$ and canopy reflectance a growing number of researchers now use dual-channel spectroradiometers mounted on or around flux towers (Gamon et al., 2006a). These 'dual-channel' instruments provide both sky irradiance and canopy radiance measurements to allow continuous calculation of canopy reflectance at spatial and temporal scales much finer than those available via aircraft- or satellite-based instruments and that more closely match the source footprint of flux towers (e.g., Leuning et al., 2006; Sims et al., 2006; Hilker et al., 2007). The potential for using such high frequency diurnal canopy reflectance data was demonstrated by Hilker et al. (2008a,b), who reported the effects of canopy shading on the relationship between the PRI and canopy LUE. Results from these studies have begun to provide significant insight relating to the mechanistic linkages between the spectral and physiological behavior of various vegetative communities, and underscore the need to expand such optical sampling to a larger number of tower locations.

As findings from the aforementioned studies indicate, for many vegetation canopies it may only be necessary to measure a limited number of narrow wavebands to accurately model canopy GPP under a variety of environmental conditions. Consequently, the instruments used to record narrowband reflectance from flux towers can be simplified. For example, it may be more desirable to deploy low-cost and low-maintenance instruments that detect a few narrow wavebands (e.g., the PRI and NDVI bands listed in Eqs. (2) and (3)) rather than use dual-channel hyperspectral spectroradiometers capable of collecting hundreds of contiguous spectral channels. Indeed, photovoltaic semi-conductors (photodiodes) have a well established history in ecophysiological research and represent a potential alternative to spectroradiometers for measuring narrowband radiation required to model canopy-atmosphere $CO_2$ exchange. One of the earliest ecological applications of photodiodes was the use of filtered selenium and silicon photodiodes to measure photosynthetic photon flux density (PPFD) within plant canopies (Federer and Tanner, 1966; Biggs et al., 1971). Unfiltered gallium arsenide phosphide photodiodes have a spectral response function similar to the PAR wavelengths in the range 400–700 nm and therefore have more recently become standard instrumentation for PPFD measurement across a wide range of environments, including crop canopies (e.g., Gutschick et al., 1985), temperate and tropical forest canopies (e.g., Pfitsch and Pearcy, 1992; Vierling and Wessman, 2000), and streambeds (e.g., Melbourne and Daniel, 2003). Currently, photodiodes represent the core sensing apparatus in most commercially available PPFD instruments. While typically used to quantify radiant energy across wide wavebands (e.g., across the full PAR spectrum), these same photodiodes can be used to measure narrowband radiation when used with narrow bandpass filters (after Pontailler and Genty, 1996). Such a filtered narrowband instrument could be configured to continuously collect data to aid in understanding the diurnal and seasonal variability in these wavelengths and their corresponding canopy characteristics (see Gutschick et al., 1985; Vierling et al., 1997 for further discussion). Recent developments in our understanding of canopy physiology, combined with current sensor technology and low cost, low power data logging options now make it practical to develop sensor systems to acquire temporally continuous spectral information above and within vegetation canopies.

Here, we describe a simple 4 band filtered photodiode-based sensor system (hereafter referred to as the QuadPod) for measuring downwelling and upwelling radiation in the NDVI and PRI wavelengths. The QuadPod represents an application of basic 'off-the-shelf' optics, circuit design, and miniaturized data logging technology to address questions that require high spatio-temporal resolution spectral data of vegetation canopies. The design of this instrument and component choices were based on the following criteria:

1. lightweight (~1 kg) to facilitate deployment above and within vegetation canopies and on micrometeorological towers;
2. relatively low cost and low maintenance operation to facilitate simultaneous deployment at many locations to quantify temporal and spatial variability in canopy radiative properties;
3. self-contained, low power, weather resistant, and capable of unattended, automated data collection; and
4. having a spectral resolution ≤10 nm FWHM to allow for the calculation of narrowband spectral vegetation indices, such as the PRI.

## 2. Instrument design and technical specifications

We assembled two types of QuadPod instruments using standard electronics and commercially available parts. One type of QuadPod was designed to measure upwelling radiation (radiance), while the other was designed to measure downwelling radiation (irradiance). The technical details of the components included in each sensor are described below, and a material list is provided in Appendix A.

### 2.1. Photodiodes

We used silicon photodiodes as the primary light detecting component within the QuadPods (S2386-18K; Hamamatsu Corp., Bridgewater, NJ). These photodiodes had a spectral response range