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Comparing methods for partitioning a decade of carbon dioxide and water vapor fluxes in a temperate forest

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ABSTRACT

The eddy covariance (EC) method is routinely used to measure net ecosystem fluxes of carbon dioxide (CO_2) and evapotranspiration (ET) in terrestrial ecosystems. It is often desirable to partition CO_2 flux into gross primary production (GPP) and ecosystem respiration (RE), and to partition ET into evaporation and transpiration. We applied multiple partitioning methods, including the recently-developed flux variance similarity (FVS) partitioning method, to a ten-year record of ET and CO_2 fluxes measured using EC at Morgan Monroe State Forest, a temperate, deciduous forest located in south-central Indiana, USA. While the FVS method has previously been demonstrated in croplands and grasslands, this is the first evaluation of the method in a forest. CO_2 fluxes were partitioned using nonlinear regressions, FVS, and sub-canopy EC measurements. ET was partitioned using FVS and sub-canopy EC measurements, and sub-canopy potential evapotranspiration was calculated as an additional constraint on forest floor evaporation. Leaf gas exchange measurements were used to parameterize a model of water use efficiency (WUE) necessary for the FVS method. Scaled leaf gas exchange measurements also provided additional independent estimates of GPP and transpiration. There was good agreement among partitioning methods for transpiration and GPP, which also agreed well with scaled leaf gas exchange measurements. There was higher variability among methods for RE and evaporation. The sub-canopy flux method yielded lower estimates of evaporation and RE than FVS and lower estimates of RE than the nonlinear regression method, likely due to the exclusion of flux sources within the canopy but above the top of the sub-canopy tower for the sub-canopy flux method. Based on a sensitivity test, FVS flux partitioning was moderately sensitive to errors in WUE values, and underestimates of WUE significantly reduced the rate at which the algorithm was able to produce a physically valid solution. FVS partitioning has unique potential for retroactive ET partitioning at EC sites, because it relies on the same continuous measurements as EC and does not require additional specialized equipment. FVS also has advantages for partitioning CO_2 fluxes, since it does not rely on the mechanistic assumptions necessary for the commonly used nonlinear regression technique.

1. Introduction

Eddy covariance (EC) instrumentation (Baldocchi et al., 1988) measures ecosystem-scale net turbulent fluxes of carbon dioxide and water vapor between the land surface and the atmosphere. It is often desirable to decompose these net fluxes into ecologically relevant components. Net ecosystem exchange (NEE) of carbon dioxide (CO_2) measured by EC instrumentation can be decomposed into gross primary production (GPP) and ecosystem respiration (RE). In this paper, we define NEE = RE − GPP, so that NEE is negative when photosynthesis exceeds respiration, while GPP and RE are always considered to be positive quantities. The most common method for CO_2 flux partitioning uses nonlinear regressions based on quasi-empirical models describing the relationship between these fluxes and meteorological drivers (Lasslop et al., 2009; Reichstein et al., 2005; Stoy et al., 2006). Because photosynthesis does not occur in

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darkness, nighttime NEE is often used to parameterize a simple model of RE that depends on soil temperature. The observed NEE is then subtracted from the modeled daytime RE in order to determine GPP (Reichstein et al., 2005). An alternative method fits NEE to a light response curve, determining RE using the intercept of the curve as incoming shortwave radiation approaches zero (Lasslop et al., 2009). A more recently developed alternative to the nonlinear regression methods uses measurements of carbonyl sulfide (COS), which is taken up by leaves through a similar pathway to CO_2 but is not emitted by respiration-like processes in significant amounts in terrestrial ecosystems (Blonquist et al., 2011). The COS technique is a promising approach for estimating GPP that does not depend on assumed relationships between NEE and its meteorological drivers. However, it is sensitive to assumptions about the rate of COS uptake by soil and the ratio of CO_2 to COS assimilation at the leaf scale (Asaf et al., 2013).

In the case of water vapor, EC measures evapotranspiration (ET), the combination of evaporation and transpiration. These two components are controlled by different processes and are likely to have different responses to environmental drivers such as temperature, humidity, and soil water content (Kool et al., 2014; Wang et al., 2014). Transpiration results from the movement of water through leaf stomata and is controlled by transport of water through plant tissues and by plant physiological control of leaf stomata. Because it is physiologically controlled and tightly coupled with plant tissue properties, transpiration contains important information about plant physiology and responses to environmental drivers such as drought (Chaves et al., 2003; Matheny et al., 2014; Sperry and Love, 2015). Evaporation, in contrast, is not directly limited by biological processes but rather results from the diffusion of water through the soil matrix and evaporation at the soil surface, as well as evaporation from intercepted precipitation in the canopy (Baldocchi and Meyers, 1991; Wilson et al., 2000). Because evaporation is typically smaller than transpiration as a component of the total flux in closed canopy, forested ecosystems, total ET is often used as a proxy for transpiration in studies of forest water use efficiency and ecosystem-scale transpiration (e.g. Keenan et al., 2013; Law et al., 2002; Novick et al., 2015). However, controls on forest floor evaporation rates are poorly characterized and could contribute error to similar analyses if the ratio of evaporation to transpiration varied over time or in response to drivers such as vapor pressure deficit (VPD). This makes ET partitioning a valuable complement to ecosystem-scale studies of forest water use, water use efficiency, and responses to drought.

Partitioning ET into its components requires a different approach from partitioning NEE, because the components of ET are both positive fluxes to the atmosphere that are large during the day, small at night, and sensitive to the same meteorological drivers. Several ET partitioning methods have been developed (Kool et al., 2014; Schlesinger and Jasechko, 2014; Williams et al., 2004). These include the use of oxygen and hydrogen isotope signatures (Wang et al., 2010; Wang and Yakir, 2000), modeling of canopy and sub-canopy fluxes driven by energy balance measurements from different heights (Shuttleworth and Wallace, 1985), eddy covariance measurements of above-canopy and below-canopy fluxes (e.g. Baldocchi and Ryu, 2011), up-scaling of sap-flow and leaf gas exchange measurements (Oren et al., 1998), and flux-variance similarity (FVS) partitioning (Scanlon and Kustas, 2010).

Recently, a new technique – the FVS method – has emerged that is capable of simultaneously partitioning both ET and NEE into their primary components. The technique uses continuous, high-frequency measurements of boundary layer water vapor and carbon dioxide concentrations along with an estimate of mean leaf-scale water use efficiency (WUE) to simultaneously partition ET and NEE into their respective components. Because these gas concentrations are already measured at high frequencies as part of the EC measurement technique, the FVS method can be easily applied to existing EC data records. FVS is uniquely suited for retroactive partitioning of ET at EC flux sites, because it does not require additional measurement equipment. Furthermore, it provides alternative estimates of GPP and RE that are not dependent on the model assumptions inherent to commonly used nonlinear regression partitioning methods, and does not require additional specialized measurement equipment such as that necessary for the carbonyl sulfide and isotope methods. The method has been applied and evaluated in agricultural systems (Scanlon and Kustas, 2010) and grass fields (Good et al., 2014). To our knowledge, this study represents the first effort to evaluate the FVS approach in a forest ecosystem or over decadal time scales. We applied the FVS method to a ten year record of carbon dioxide and water vapor fluxes from the Morgan Monroe State Forest (MMSF; south-central Indiana, USA) flux tower site, leveraging an extensive set of canopy leaf gas exchange measurements collected over three recent growing seasons (2011–2013, Roman et al., 2015) at the site to produce the WUE estimates required for the method. We used the FVS partitioning method along with leaf gas exchange measurements, sub-canopy flux measurements, and nonlinear-regression-based CO_2 flux partitioning in order to accomplish the following objectives:

1 Parameterize a site-specific model of WUE using leaf-level measurements for use with the FVS method
2 Evaluate the sensitivity of the FVS partitioning algorithm to errors in estimated WUE
3 Characterize agreement or disagreement between FVS flux partitioning and alternative partitioning methods

Ecosystem flux partitioning has important applications in the areas of biogeochemistry, plant physiology, and ecohydrology, and the development of partitioning techniques is an important component of advancing these fields. This evaluation of the recently developed FVS flux partitioning method in forests provides a foundation for future applications of the technique in applied studies relating to flux components and WUE.

2. Methods

2.1. Site description

Measurements were conducted at the MMSF Ameriflux site located in south-central Indiana, USA. The site is located in a deciduous broadleaf forest with a mean canopy height of approximately 27 m and a stand age of 80–90 years. The dominant tree species in the forest are sugar maple (*Acer saccharum*), tulip poplar (*Liriodendron tulipifera*), sassafras (*Sassafras albidum*), white oak (*Quercus alba*), black oak (*Quercus velutina*), and red oak (*Quercus rubra*). The forest species composition is typical of other hardwood forests in the region. The site topography is characterized by a ridge-ravine pattern. For additional details about the site, see Schmid et al. (2000).

2.2. Data collection and processing

Ecosystem-atmosphere fluxes of heat, water vapor, and CO_2 have been measured using the EC method at the MMSF site since 1998 at heights of 46 m, 34 m, and 2 m. The 2 m sub-canopy flux measurement station is located approximately 14 m from the main tower. Each of the three flux measurement stations includes a sonic anemometer (CSAT3; Campbell Scientific, Logan, UT, USA) and a connection to a closed-path infrared gas analyzer (IRGA; LI-7000, Li-Cor, Lincoln, NE, USA) at the base of the tower. The IRGAs are calibrated weekly. Measurements of wind speed, CO_2 concentration,