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Evaluation of a simple approach for crop evapotranspiration partitioning and analysis of the water budget distribution for several crop species

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ABSTRACT

Climate variability and climate change induce important intra- and inter-annual variability of precipitation that significantly alters the hydrologic cycle. The surface water budgets and the plant or ecosystem water use efficiency (WUE) are in turn modified. Obtaining greater insight into how climatic variability and agricultural practices affect water budgets and regarding their components in croplands is, thus, important for adapting crop management and limiting water losses. Therefore, the principal objectives of this study are:

(1) to assess the contribution of different components to the agro-ecosystem water budget and
(2) to evaluate how agricultural practices and climate modify the components of the surface water budget.

To achieve these goals, we tested a new method for partitioning evapotranspiration (ETR), measured by means of an eddy-covariance method, into soil evaporation (E) and plant transpiration (TR) based on marginal distribution sampling (MDS). The partitioning method proposed requires continuous flux recording and measurements of soil temperature and humidity close to the surface, global radiation above the canopy and assessment of leaf area index dynamics. This method is well suited for crops because it requires a dataset including long bare-soil periods alternating with vegetated periods for accurate partitioning estimation.

We compared these estimations with calibrated simulations of the ICARE-SVAT double source mechanistic model. The results showed good agreement between the two partitioning methods, demonstrating that MDS is a convenient, simple and robust tool for estimating E with reasonable associated uncertainties. During the growing season, the proportion of E in ETR was approximately one-third and varied mainly with crop leaf area. When calculated on an annual time scale, the proportion of E in ETR reached more than 50%, depending on the crop leaf area and on the duration and distribution of bare soil within the year.

1. Introduction

Agricultural water resource limitations have become a major issue as the Earth's population has drastically increased, leading to a corresponding increase in food demand. Furthermore, global climate change will locally impact the mean and variance of temperature as well as the amount and distribution of precipitation and atmospheric CO_2 concentrations (IPCC, 2007). Agriculture will be strongly impacted by these changes (Brouder and Volenec, 2008). In this context, quantifying and understanding the drivers of the water cycle components, such as climate variability, climate change and crop rotations, are essential for facing both agro-economic and environmental challenges.

Allen (2008) documented methods related to the calculation of evapotranspiration (ETR), from experimental and modeling methods using different time and space scales. For all of these methods, which spatial scales ranged from local soil water sampling, lysimeters and eddy covariance (EC) to scintillometry, the reality that an improperly designed experiment or measurement can lead to highly erroneous water use estimates is evident. For ETR partitioning between evaporation (E) and transpiration (TR), sapflow measurements (Granier et al., 1996; Roupsard et al., 2006; Steppe

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et al., 2010) and isotope techniques (Williams et al., 2004) combined with EC measurements over forests have been used to estimate *E* and TR at the canopy scale. In other studies, two levels of EC measurements have been used to infer the TR and WUE of the forest canopy itself (Jarosz et al., 2008; Lamaud et al., 1996; Roupsard et al., 2006), as fluxes from the soil and understory can constitute a significant portion of the total ecosystem flux. Over croplands, gas exchange measurements at the leaf scale (Medrano et al., 2009; Steduto and Albrizio, 2005; Steduto et al., 1997) and lysimeter measurements (Qiu et al., 2008; Steiner and Hatfield, 2008) have also been used to analyze the different components of ETR at the plant or canopy scale.

Empirical modeling approaches based on energy balance formulations have been used to estimate TR (Li et al., 2008; Ritchie, 1972), but large differences compared to TR estimation using sapflow measurements have been observed (Sauer et al., 2007). When using mechanistic modeling to infer TR, one-source (vegetation plus soil as a whole) (Chen et al., 1996; Koren et al., 1999; Noilhan and Mahfouf, 1996; Noilhan and Planton, 1989), two-source (soil plus vegetation, separately) (Gentine et al., 2007; Hu et al., 2009; Sellers et al., 1996; Shuttleworth and Wallace, 1985), three-source (bare soil, shaded soil and vegetation) (Boulet et al., 1999), or multiple-source (Ogée et al., 2003) soil vegetation atmosphere transfer (SVAT) models can be used. The use of two (or more) sources in models allows for a more realistic representation of the energy budget and can describe the respective contributions of the soil and vegetation to ETR. However, although more complex SVATs may be more mechanistic, they require more input parameters, which involve complicated calibrations and often the solution might be ill-defined (Beven, 2006). If the complex model is calibrated over a short period and with too few observed variables, a correct ETR can be obtained with incorrect *E*–TR partitioning. The right answer is obtained yet for the wrong reason. All of these TR estimation methods raise questions regarding their spatial representativeness, the generalization of their applicability, and the complexity of the modeling tools used.

In the present study, the main objectives are (1) to assess the different components of the annual crop water budget and (2) to evaluate a simple and generic method for partitioning ETR into soil and vegetation components. The advantage of such simple method is that it can be easily used in other regions with minimum calibration effort. The obtained result is thus more robust than more complex models, which would require recalibration.

EC measurements of water fluxes were performed continuously over a period of 2 years above winter and summer crops in the southwest of France to highlight the contribution of each component to the agro-ecosystem water budget and the impact of different crop species in relation to climatic conditions on each of them. From these measurements, we developed a new methodology based on marginal distribution sampling (MDS) to infer the partitioning of ETR between *E* and TR during each crop growing season. We evaluated this methodology against actual data during bare soil periods for *E* and against a site-calibrated mechanistic modeling approach using the ICARE-SVAT model (Gentine et al., 2007) for both bare soil and vegetated periods.

2. Materials and methods

2.1. Site and measurement descriptions

Since March 2005, micrometeorological, meteorological and vegetation dynamic measurements have been performed at two cultivated plots located 12 km apart near Toulouse in the southwestern part of France located at Auradé (43°54′97″ N, 01°10′61″ E) and Lamasquère (43°49′65″ N, 01°23′79″ E). Both sites are part of the CarboEurope-IP Regional Experiment (Dolman et al., 2006) and the CarboEurope-IP Ecosystem Component. They have been cultivated for more than 30 years, and they experience similar meteorological conditions but are subjected to different management practices and exhibit different soil properties and topography. The crop rotations on both sites are representative of the main regional crop rotations. Crops from the 2005 to 2006 and 2006 to 2007 growing seasons were analyzed in this study. Each crop year was studied on the basis of the hydrologic year, i.e., from the 1st of October, after the summer crop harvest and before the beginning of winter crop sowing at the end of November. The Auradé plot was cultivated with winter wheat (*Triticum aestivum* L.) from 27 October 2005 to 29 June 2006 followed by sunflower (*Helianthus annuus* L.) from 11 April 2007 to 20 September 2007. The Lamasquère plot was cultivated with maize (*Zea mays* L.) used for silaging from the 1st of May 2006 to 31 August 2006 followed by winter wheat from 18 October 2006 to 15 July 2007. The Lamasquère site was irrigated in 2006 when maize was cultivated.

Turbulent fluxes of water vapor (ETR and latent heat, LE), sensible heat (H) and momentum (τ) were measured continuously by the EC method (Aubinet et al., 2000; Baldocchi, 2003; Grelle and Lindroth, 1996; Moncrieff et al., 1997). EC devices were mounted at heights of 2.8 m at Auradé and 3.65 m at Lamasquère. The instrument heights were chosen to be at least 1 m higher than the crops at the time of their maximum development. The EC system consists of a three-dimensional sonic anemometer (CSAT 3, Campbell Scientific Inc., Logan, UT, USA) and an open-path infrared gas analyzer (LI7500, LiCor, Lincoln, NE, USA). EdiRe software (Robert Clement, © 1999, University of Edinburgh, UK) was used to calculate fluxes following CarboEurope-IP recommendations. A 2D rotation was applied to align the stream-wise wind velocity component with the direction of the mean velocity vector. Fluxes were corrected for spectral frequency loss (Moore, 1986). Water fluxes were corrected for air density variations (Webb et al., 1980). Flux filtering, quality controls and gap filling were performed following CarboEurope-IP recommendations.

Standard meteorological variables in the air and in the soil were recorded at each site to analyze and correct turbulent fluxes. Destructive vegetation measurements were performed regularly to follow biomass and surface vegetation area dynamics. A complete description of the site characteristics, management practices, biomass inventories, vegetation area measurements, instrumentation setups, flux filtering, quality controls and gap filling procedures is available in Béziat et al. (2009).

2.2. Evapotranspiration partitioning between soil evaporation and vegetation transpiration

A statistical methodology based on marginal distribution sampling (MDS) (Reichstein et al., 2005) has been designed to partition ETR between *E* and TR using meteorological variables. The general principle of MDS consists of estimating flux data using the mean of the fluxes under similar meteorological conditions by construction of a look-up table.

To access the partition of ETR during the vegetation period, we first construct an MDS dataset linking measured ETR values with meteorological variables during bare soil periods (when ETR is reduced to its *E* component). Note that, for building the look-up table, we did not use a time moving window as in Reichstein et al. (2005) but the maximum of available data during the bare soil periods before or after the vegetated period. As a result, we estimated *E* during the period with vegetation using MDS (E_{MDS}) with a similar range of driving variables. Bare soil periods were defined as the period between tillage and sowing. Periods immediately following harvesting, when stubble was still on the ground or when regrowth events occurred, were discarded from the MDS