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# Including the lateral redistribution of soil moisture in a supra regional water balance model to better identify suitable areas for tree species

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ABSTRACT

To assess suitable areas for species, plant ecologists need accurate spatial information about available water for plants. Despite the recognized importance of topography in controlling soil moisture patterns, existing maps do not account for the redistribution of water through lateral fluxes. We included lateral fluxes in a GIS-based soil water balance model with the aim of evaluating the influence of lateral fluxes on soil moisture patterns and their importance to explain tree species distribution at regional scale. We used hydrological knowledge about lateral fluxes to map the distribution of monthly average soil moisture over the 1961–1990 period, for a 43,000-$km^2$ area in northeastern France. We then compared the ability of soil water estimated with or without lateral fluxes to explain the distribution of 19 common tree species. Spatial patterns significantly change when lateral fluxes are included in the model, with both large-scale effects due to variations in climate and soil properties, and local effects due to topography. The lateral redistribution given by the model revealed from 5% to 25% less water on the crests compared to in the valleys for metamorphic, sand and sedimentary bedrocks. Most of the tree species distributions studied were better explained when lateral fluxes were taken into account. Estimating soil moisture dynamics improves the ability to determine suitable areas for species at the landscape scale. It has major implications in the current climate change context owing to the potential to delineate topographic refugia or areas where species could colonize.

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## 1. Introduction

Soil moisture is both recognized as one of the major determinants for plant composition and ecological processes, and one of the most difficult to estimate due to its high variability in space and time (Porporato et al., 2004). The evaluation of the fine-scale spatial variability of available water for plants over large geographic areas and for long periods of time is crucial for plant ecologists in order to improve their understanding of species ecology and to adapt vegetation management to local conditions (Barbour and Billings, 2000; Botkin and Keller, 1995; Chabot and Mooney, 1985). This knowledge is particularly important in the current climate change context, with an expected decrease in water availability in large parts of the world (Bates et al., 2008). The important spatial variability of soil moisture and the difficulties to obtain relevant datasets at the landscape scale make its estimation particularly difficult. It is often evaluated using the soil water balance (SWB, see Table 1 for abbreviations), which estimates the amount of plant available water (PAW) for a defined period. Its calculation, based on the principle of the conservation of water contained in a volume of soil (Choisnel, 1992), states that the amount of water entering is equal to the amount of water leaving, plus the change in the amount of water stored.

The variables involved are related to climate, soils and vegetation (Dyck, 1985; Saxton, 1985). Climate includes both precipitation (P) and potential evapotranspiration (PET), defined as the water demand of the atmosphere that would be possible under ideal conditions of moisture supply (Thornthwaite, 1948). The soil-related components are linked to soil water holding capacity (SWHC), actual evapotranspiration (AET), and soil water runoff processes. The SWHC represents the maximum amount of water that plants can extract from the soil (Granier et al., 1999), corresponding to the difference between the water contents at field capacity ($\Theta fc$) and the permanent wilting point ($\Theta pwp$). It depends on soil physical properties such as soil depth, texture, density and organic matter content, and the prospectable soil volume (Bruand et al., 2003). AET represents the amount of soil water delivered to the atmosphere both by evaporation and transpiration. Soil water runoff processes concern the surface runoff (water that flows at the ground surface), subsurface lateral fluxes (soil water that moves laterally) and percolation (soil water that flows downwards). Vegetation plays a significant role in the processes of interception and influences evapotranspiration through the transpiration of plants and the evaporation of soil and foliage (Thornthwaite, 1948).

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**Table 1**
List of abbreviations.

| Abbreviation | Description | Units |
|---|---|---|
| SWB | Soil water balance | mm |
| P | Precipitation | mm |
| PET | Potential evapotranspiration | mm |
| AET | Actual evapotranspiration | mm |
| DE | Deficit of evapotranspiration | mm |
| RAW | Runoff available soil water | mm |
| PAW | Plant available water | mm |
| D | Soil thickness | m |
| SWDC | Soil water draining capacity $(\Theta_{sat} - \Theta_{fc}) * D$ | mm |
| SWHC | Soil water holding capacity $(\Theta_{fc} - \Theta_{pwp}) * D$ | mm |
| SWC | Soil water content (PAW + RAW) | mm |
| Volumetric SWC | Volumetric SWC (SWC/D) | $cm^3/cm^3$ |
| FC | Soil water content at field capacity | mm |
| SAT | Soil water content at saturation | mm |
| $K_{sat}$ | Hydraulic conductivity at saturation | $m \cdot d^{-1}$ |
| $\Theta$ | Volumetric soil water content | $cm^3/cm^3$ |
| $\Theta_{pwp}$ | Volumetric water contents at permanent wilting point | $cm^3/cm^3$ |
| $\Theta_{fc}$ | Volumetric water contents at field capacity | $cm^3/cm^3$ |
| $\Theta_{sat}$ | Volumetric water content at saturation | $cm^3/cm^3$ |
| $Q_{surf}$ | Surface runoff | mm |
| $Q_{sub}$ | Lateral subsurface runoff | mm |
| $I_a$ | Initial abstraction | mm |
| S | Potential retention | mm |
| $S_{max}$ | Maximum potential retention | mm |
| CN | Curve number | – |
| V | Flow velocity $(0.02\ m \cdot s^{-1} < V < 2\ m \cdot s^{-1})$ | $m \cdot s^{-1}$ |
| $Q_{out,surf}$ | Surface runoff discharge | $m^3 \cdot s^{-1}$ or mm |
| *n* | Manning's roughness coefficient | $s \cdot m^{-1/3}$ |
| *R* | Hydraulic radius at cell i | m |
| *Slope* | Slope at ground surface | $m \cdot m^{-1}$ |
| B | Flow width (cell width) | m |
| $A_i$ | Upstream drainage area at cell i | $m^2$ |
| a | Network constant $(2.4\ 10^{-4})$ | – |
| b | Geometric scaling exponent (0.5) | – |
| $D_s$ | Saturated depth area | m |
| w | Flow width (dimension of the cell) | m |
| $\tan \beta$ | Land slope | m/m |
| $d_i$ | Fraction of the discharge from a particular cell | – |
| $L_i$ | Effective contour length of cell i: 0.5 and 0.354 for downslope cells in cardinal directions and diagonal directions, respectively | |
| e | Maximum downslope gradient | |
| DTW | Depth-to-water index | m |
| $\Sigma$ (dz/dx) | The cumulative slope (sum of slope values) along the least cost path connecting any point of the landscape to a watercourse | m |
| a | a is a multiplier equal to 1 when the path is in the cardinal direction, and 1.414214 when it is diagonal | – |
| $w_c$ | Grid cell size | m |

Numerous water balance models have been developed at various time scales (e.g., hourly, daily, monthly and yearly) and to varying degrees of complexity (Xu and Singh, 1998; Schwärzel et al., 2011). Most existing PAW maps available over broad areas have been comprised using simplified equations (Van der Schrier et al., 2006; Zierl, 2001). They are often based on models at the monthly scale pioneered in the middle of the last century by Thornthwaite and Palmer (Palmer, 1965; Thornthwaite and Mather, 1955). They do not take hydrological fluxes into account, despite their importance in influencing soil moisture patterns at the toposcale. Indeed, many hydrological studies showed a redistribution of the soil moisture gradient along the hillslope gradient (Brocca et al., 2007; Ticehurst et al., 2003), with large variations depending on the season and precipitation (Weyman, 1973). The effect of topographical position has also been observed on vegetation. Several studies attributed changes in species composition (Deblauwe et al., 2008; Johnson et al., 2007) and productivity (Berges et al., 2005; Curt et al., 1996; Kobal et al., 2015) along the topographical gradient to variations in soil moisture, suggesting that lateral fluxes could be an important consideration in the study of plant ecology.

Lateral fluxes can be estimated by hydrological models such as TOPMODEL (Beven and Kirkby, 1979), TOPOG (Oloughlin, 1981), WET (Moore et al., 1993) or SMR (Frankenberger et al., 1999), using soil hydraulic conductivity at saturation ($K_{sat}$: maximum rate at which a soil can transmit water) and the shape of the surface topography as data inputs. Most of them aim to determine where the runoff takes place in the catchment to reproduce river discharge at the basin outlet (Beven, 1991; Xu and Singh, 1998). They are not suitable to study plant distribution over large areas for different reasons:

- they do not describe PAW spatial variation. Moreover, many of them are semi-distributed, which means that hydrologically similar portions of the watershed are lumped together and are characterized by averaged ecological conditions, which do not provide precise estimation of soil moisture;

- they are based on fine time step calculations, estimating PAW for long periods of time and over broad areas can be too time-consuming and data is not always available;

- some parameters should be calibrated at the catchment scale and cannot be extrapolated.

The aim of this study was to include lateral fluxes in a simple GIS-based soil water balance model at regional scale, to improve the estimation of available water for trees and evaluate the importance of lateral fluxes to explain tree species distribution. By building a program that could easily use available input data and that does not need calibration, we estimated the monthly time step average soil moisture for the 1961–1990 reference period, accounting or not for the lateral fluxes, in a 43,000-$km^2$ area in northeastern France. We used the model outputs to evaluate the influence of lateral fluxes in SWB, and determined their ability to explain the distribution of the most common tree species present in the study area.

## 2. Materials and methods

To estimate available water for plants, we developed a fully-distributed water balance model coupled with a Geographic Information System (GIS) that requires easily available variables. To account for runoff that usually occurs at daily or shorter time scales, the model uses a daily subroutine whose soil water balance components are aggregated on a monthly basis to provide average monthly values of PAW that are representative of a long period of time in order to be related to tree species distribution. The routine was implemented and launched from R statistics software and executed in the environment of GRASS GIS through the R interface library for GRASS 6.4 spgrass6.

### *2.1. Input data*

#### *2.1.1. Climatic data*

The study area (43,000 $km^2$) covers a large climatic gradient in northeastern France, with altitudes ranging between 140 and 1424 m (Fig. 1), and mean annual temperature and precipitation ranging between 6 to 10.5° and 400 to 2400 mm, respectively. Average PAW values are required over long periods of time to understand plant distribution patterns, whereas runoff estimation requires data on a daily or shorter time scale. Since accounting for runoff at a daily time step for many decades is too time-consuming, we used P and PET daily values for a year that were representative of the 1961–1990 period. Because averaging P over this time period will result in an unrealistic sequence, we disaggregated monthly average P for the 1961–1990 period into the most likely sequence of daily rainfall events (Supporting information S1). Daily PET were obtained using the Turc formula (Turc, 1961). This requires solar radiation obtained by dividing monthly 1961–1990 values by the number of days in the month, and temperature obtained by averaging daily values over the 1961–1990 period for each Julian day of the year.

Mean temperatures were extracted from the SAFRAN model (Quintana-Seguí et al., 2008; Vidal et al., 2010) and solar radiation from the Helios model (Piedallu and Gégout, 2007). For P, we extracted

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