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# Local soil type variability controls the water budget and stand productivity in a beech forest

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ABSTRACT

Climate change and particularly increasing frequency of drought events during the vegetation period may threaten tree vitality and forest biomass productivity in many temperate regions in the future. In that context, the identification of critical environmental factors and a better understanding of their impact on forests are decisive. The water balance is recognized as one of the most important soil factors for stand productivity in temperate forests. Hence, the consequences of short or long term climate change might vary considerably spatially in function of soil type within a given forest. Our study objective was to assess the impact of contrasting soil types on the water balance and stand growth of a beech (*Fagus sylvatica*) forest ecosystem of similar age and management during four climatically contrasting years. The experimental forest site of Montiers presents different soils with contrasting physicochemical properties (Dystric Cambisol, Eutric Cambisol and Rendzic Leptosol) monitored to quantify water fluxes and stand biomass increment. Using data collected over the period 2012–2015, including a particularly dry year (−24% precipitations in 2015), we also quantified the impact of water shortage on stand productivity at the annual scale as a function of soil type. We evidenced important differences in soil water holding capacities (SWHC) along the studied soil sequence, ranging between 57 mm for the Rendzic Leptosol downhill over limestone and 205 mm for the Dystric Cambisol uphill over detrital sediments. The results show that the canopy intercepted the same amount of incident rainfall in the three plots and that there were no significant differences in annual soil moisture dynamics among the studied soils. We evidenced different rooting patterns depending on soil type. Under a same climate and with stand, site exposition and solar radiation equivalency, trees transpiration was the evident primary driver of the stand potential to produce aboveground biomass. Soil water holding capacity, annual trees transpiration and aboveground biomass production increased in that order: Rendzic Leptosol < Eutric Cambisol < Dystric Cambisol. During the drier year 2015, the decrease in aboveground biomass productivity was of similar amplitude on the three soil types.



## 1. Introduction

The regulation of the water cycle plays a major role in the functioning of forest ecosystems, especially as it controls the circulation of nutrients between the atmosphere, the soil and the plants. Incident precipitation is partly intercepted and retained by the forest canopy, then partly or fully evaporated. Water passing through the canopy reaches the forest floor as throughfall or as stemflow (Aussenac, 1970; Bellot et al., 1999) and replenishes the soil water reservoir, where it can be taken up by the root system, carry nutrients for biomass production and return to the atmosphere via trees transpiration. Thus forest productivity is a composite resultant of climate conditions, water availability and soil nutrients.

However, research on climate change predicts rising air temperature and altered precipitation patterns, resulting in increasing frequency and intensity of summer drought in parts of Central Europe during the upcoming decades (Schar et al., 2004; Rowell and Jones, 2006). The Intergovernmental Panel on Climate Change reports that these changes will have a significant impact on terrestrial ecosystems and natural resources (IPCC, 2014). In particular, global

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warming leading to evapotranspiration increase and rainfall decreases may threaten tree vitality and forest biomass productivity in many temperate regions in the future (Bréda et al., 2006; Allen et al., 2010; Lindner et al., 2010; Medlyn et al., 2011; Hlásny et al., 2014). Climate change will affect the terrestrial biosphere primarily through changes in the regional energy balance and associated changes in the water balance. Soil water shortage impacts several steps of water transfer along the soil-tree-atmosphere continuum (Bréda et al., 2006). As a consequence, forest ecologists and managers are debating on the future of European forests and the right choice of tree species for forestry under a drier and warmer climate (Bolte et al., 2009). Some authors discussed the fate of beech forests in Europe (Geβler et al., 2006; Kramer et al., 2010), which play a central role in forest transition strategies (Tarp et al., 2000) as beech (*Fagus sylvatica*) is one of the most representative deciduous tree species in the Northern hemisphere (Fang and Lechowicz, 2006; Bolte et al., 2007).

In 2003, Europe was affected by a particularly intense heat wave associated with extreme drought and a reduction in primary productivity in several forest types in large parts of the continent, including European beech ecosystems (Ciais et al., 2005; Granier et al., 2007; Hentschel et al., 2015). Such severe regional heatwaves may become more frequent in a changing climate (Meehl and Tebaldi, 2004). In that context, the identification of critical factors and a better understanding of their effect on forest ecosystems are decisive. Currently, the response of plant species to environmental factors is increasingly studied and concerns many applications such as modelling ecological niches, mapping distribution ranges and evaluating species abundance, diversity or productivity (Piedallu et al., 2011; Cheaib et al., 2012). For these studies, the availability of accurate environmental descriptors is of major importance.

The distribution and abundance of forest resources are controlled to a large extent by the quantity and seasonality of available moisture (Neilson et al., 1992). Indeed the soil water holding capacity regulates the water supply of soils with normal vertical infiltration and is a key driver in determining the response and resilience of forested areas to extreme climate events. The soil water balance is recognized as one of the most important soil factors for stand productivity in temperate forests, influencing carbon allocation, microbial activity, nutrient cycling, canopy transpiration and carbon assimilation (Bréda et al., 2006; Lebourgeois et al., 2006). The importance of water availability and water deficit on primary production and growth decline has been discussed by many authors (Mun, 1988; Sala et al., 1988; Sampson and Allen, 1999; Granier et al., 2007; Goisser et al., 2013; Huang et al., 2013; Knutzen et al., 2015). Hence, for a given forest, the consequences of both inter-annual variability and long-term changes of climate conditions might vary considerably in function of soil type. As shown on pedological maps of France (Jamagne, 2011), soil types are widely contrasted at a regional scale. It is a challenge for forest managers to consider this spatial variability of soil properties and to adapt forestry practices to the mosaic of soils. However, relevant soil properties such as thickness of the solum, soil texture and stone content are missing on existing forest site maps and are rarely considered to assess the soil water availability (Schwärzel et al., 2009a).

From this angle, our objective was to test two ecological factors that might control the water balance and stand productivity in a homogeneous beech forest ecosystem (same species, tree age and management practices) developed on much contrasting soils:

- soil type: we compared water fluxes and stand growth on three soil types with different physical properties and soil water holding capacities, ranging from a deep and acidic soil to a superficial calcic soil;
- the inter-annual variability of precipitation amount: by using data collected over four years (2012–2015), including the particularly dry year of 2015 (−24% precipitations in 2015), we aimed to determine the impact of water shortage at the annual scale.

## 2. Methods

### 2.1. Study site descriptions

The study was carried out in the Montiers beech forest experimental site, which is managed since 2011 jointly by ANDRA (French National Radioactive Waste Management Agency) and INRA-BEF (French National Institute for Agricultural Research). It was designed to test the effect of soil type on biogeochemical cycling (water and elements) in forest ecosystems. The Montiers site is located in northeastern France in the Meuse department (48° 31′ 54″ N, 5° 16′ 08″ E) where the climate is semi-continental. The annual mean precipitation is 1100 mm and the average temperature over the last ten years was 12.6 °C (Météo-France). The state forest of Montiers was initially chosen because it presents, on a restricted surface area, a diversity of soils representative of the region, from acidic and deep soils to calcic and superficial soils, on which grows a mature and homogeneous beech forest stand (same age, species and forest management). The site covers a soil sequence of approximately 73 ha stretched between 340 and 386 m in altitude in the middle of the forested area. The study area has an overall mean slope of 4.25% with southwest exposure.

The geology of the Montiers site consists of two overlapping soil parent materials, an underlying Tithonian limestone surmounted by acidic Valanginian detrital sediments. The calcareous bedrock contains mainly calcium carbonate and a small amount of clay minerals (∼3.4%). The calcareous stones in the regolith are surrounded by a weathered layer rich in clays due to decarbonation. The surmounting detrital sediments are complex (silt, clay, coarse sand and iron oxide nodules) as they result from various depositions and cross-stratifications. The soil properties vary along the soil sequence in relation with the thickness of the sediment layer. According to the World Reference Base for Soil Resources (FAO, 2016), the soil types range from Rendzic Leptosol and Eutric Cambisol on the lower part to Dystric Cambisol at the top of the hillslope (Fig. 1). Table 1 presents some physicochemical properties of the three soils. The Dystric Cambisol (soil 1; S1) formed on the Valanginian sediment layer to a depth of 2 m on average and is slightly acidic ($pH_w < 5$ in the upper soil layers). The cationic exchange capacity (CEC) is <6.7 cmolc $kg^{-1}$ in the first 60 cm of the profile and the effective base saturation ranges between 26 and 64% with $Ca^{2+}$ and $Al^{3+}$ being the dominant cations. Due to the complex sedimentary source material, the resulting soil is characterized by some textural and structural heterogeneity with sandy and clayey passages in the lower soil layers. The Eutric Cambisol (soil 2; S2) formed on a shallower sediment layer. The soil water pH is constant in the soil profile ($5.2 \leqslant pH_w \leqslant 5.4$) and the CEC varies between 7.7 and 17.8 cmolc $kg^{-1}$; the effective base saturation ranges between 59 and 83% with $Ca^{2+}$ being the dominant cation throughout the profile. The general observation of the soil profile indicated some variability in the depth to the calcareous bedrock. The Rendzic Leptosol (soil 3; S3) lies directly on top of the Portlandian limestone. The soil water pH increases with depth from 5.7 to 6 and the CEC ranges between 20 and 25 cmolc $kg^{-1}$; the effective base saturation is >94% with $Ca^{2+}$ representing almost all of the exchangeable pool. The carbon-to-nitrogen ratio ranged between 9.7 and 16.2 in function of soil depth in the three soils (Table 1). H*umus* type was eutrophic *mull for the Rendzic Leptosol and acid mull for the Dystric Cambisol.*