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Distributed modeling of ecohydrological processes at high spatial resolution over a landscape having patches of managed forest stands and crop fields in SW Europe

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ABSTRACT

We simulated the ecohydrological processes of a forest-dominated landscape that comprises of managed maritime pine stands and crops in the Landes de Gascogne region of South West France. We used an improved model called STEPS that describes ecophysiological, biogeochemical and hydrological processes in a tightly coupled and spatially distributed manner, applicable to both pristine and managed ecosystems. Simulated gross primary productivity (GPP) and evapotranspiration (ET) showed large spatial variability over this landscape owing to the heterogeneities inherent in land cover, soil texture, topography and soil hydrology. Croplands (mainly maize) exhibited higher variability GPP (200–2500 gC m^{-2} yr^{-1}) and ET fluxes (150–800 mm yr^{-1}) relative to other land cover types, primarily due to the presence of fallow versus cultivated lands. The pine stands also showed considerable spatial variability in GPP (426–1320 gC m^{-2} yr^{-1}) and ET (234–570 mm yr^{-1}) but this occurred mainly as a function of stand age and the understory species compositions. Comparison of simulated values with measurements taken at the LeBray stand revealed reasonable model performance for both GPP (R^2 = 0.92, RMSE = 0.77 gC m^{-2} day^{-1}), ET (R^2 = 0.81, RMSE = 0.52 mm day^{-1}) and other ecohydrological indicators. Seasonal patterns of ET fluxes were more dynamic than GPP due to the presence of distinct subcomponent processes that were uniquely governed by several environmental factors. A sensitivity analysis of some parameters that are common to both GPP and ET simulation revealed that the most sensitive parameters were LAI, Ω and $g_{s,\max}$. This study will serve as the basis for further research on developing environmental management strategies specific to the Landes de Gascogne region of France.

1. Introduction

Terrestrial ecosystems are important components of the climate system because they contribute to the cycling of mass and energy across the soil-plant-atmospheric continuum (SPAC). Vegetated land surfaces, owing to their unique biophysical, geomorphological, pedological and hydroclimatic characteristics, exhibit wide spatial and temporal variability in the manner in which mass and energy are cycled across the SPAC (Manzoni and Porporato, 2007; Porporato et al., 2003). The complex interactions between the hydrological, biogeochemical and energy cycles are modulated by both natural and anthropogenically-induced factors, whose individual and interactive effects are often difficult to comprehend (Govind and Kumari, 2014). Current uncertainties in our understanding of how natural factors (i.e. climate, ecosystem disturbances, and biotic stress factors) and anthropogenic factors (i.e., management, deforestation, land-use change) alter ecophysiological and biogeochemical processes across different landscapes is linked to our incomplete understanding of landscape-scale ecohydrological complexity (e.g., Gedney et al., 2006 Zimov et al., 2006; Govind et al., 2011) as well as subsequent cascading influences on biogeochemical processes with non-linear feedback mechanisms (Daly et al., 2004). Modeling of terrestrial ecohydrological processes have been conventionally conducted at multiple scales. They include, point scales (e.g., Grant et al., 2001; Ju et al.,

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2006), watershed scales (e.g., Tague and Band, 2004; Chen et al., 2005; Govind et al., 2009a), regional scales (e.g., Liu et al., 1997; Potter et al., 2001; Coops et al., 2007; Ju and Chen, 2005), and global scales (e.g., White et al., 2005; Zhao et al., 2005) modeling exercises. These studies differ widely in their degree of sophistications, complexities, temporal resolutions (half-hourly–annual), and temporal spans (hourly–decadal). Few models, however, have actively coupled the carbon (C) nitrogen (N), energy (E) and water (W) cycles in a spatially-explicit manner.

The W, E, C, and N cycles are the most important mass-energy cycles that are responsible for processes that occur at the biosphere-atmosphere interface. Although it is intuitive that these cycles operate with strong interactions, we often study them in an isolated manner leading to uncertainties in how these processes operate under different circumstances (e.g., climate change, land-use change and natural disturbances) thus often leading to inefficient environmental decisions. This knowledge-gap can be narrowed only if we employ a strong synergy between spatially-distributed ecohydrological models, remote sensing (RS) data and in situ measurements (Govind et al., 2009b).

Photosynthesis (gross primary productivity, GPP) and evapotranspiration (ET) are the fundamental ecohydrological processes where the vegetation is primarily managed (i.e., relatively young stands) and the climate is semi-arid, respectively. Landscape-scale hydrological processes critically define the local-scale water balance that in turn governs GPP and ET, warranting a coupled representation of these cycles to better understand these ecohydrological processes. Currently, coarse resolution (1000 m) GPP and ET estimates are being made using satellite-derived information of the land-surfaces' leaf abundance (quantified as LAI) and climate (e.g., global-scale MODIS GPP of Zhao et al. (2005)) and MODIS ET of Mu et al. (2011)). Such coarse resolution global-scale estimates, however, often find limited use for local-scale applications. It is at these finer spatial scales that much of the variability in landscapes is created (i.e., plot/stand-level). Additionally, because of the use of globally-generic parameterizations in these algorithms, their estimates are often unrealistic in patchy and complex landscapes.

The Landes de Gascogne region is one of the largest (~14000 km^2) forested landscapes in SW Europe (Berbigier et al., 2001; Loustau et al., 1990) (Fig. 1). This region is also a major contributor to the European carbon sink through the managed forestry sector. Apart from the effects of climate, this landscape is subjected to numerous factors that are both human-induced (such as forest harvesting and tillage, fertilizer application) and natural (such as storm-based wind throw, droughts, and pests), which, further alter the nature of land surface ecohydrological and biogeochemical processes in a complex manner. Hence, detailed research is required to advance our understanding of the ecohydrological processes occurring in the Landes de Gascogne for developing efficient strategies for environmental management solutions in the region. This landscape is complex for modeling purposes due to the presence of managed forest stands amidst croplands. The patchy characteristic (inter-stand heterogeneity and intra-stand homogeneity) of the landscape renders unique difficulties to modeling of ecohydrological processes as opposed to pristine landscapes.

The objective of this paper is to conduct a process-based spatially-explicit modelling study aimed toward simulating the fundamental ecohydrological processes in the Landes de Gascogne for developing efficient environmental management options. Specifically, we investigate the spatial and temporal heterogeneity in GPP and ET fluxes across this landscape at high spatial (50 m) and temporal (daily) resolutions by using a spatially-distributed and process-intensive modeling approach. A sensitivity analysis is also performed to cull out those parameters that must be adequately represented.

2. Study site

The current study is concentrated over the Leyre watershed that lies in the Landes de Gascogne region. The Leyre River watershed (see Fig. 1) that dominates >65% of Landes de Gascogne, drains to the Bassin d'Arcachon, a lagoon fed with a substantial volume of freshwater inflow that contains nutrients due to the management factors in the Leyre watershed. This lagoon has the largest distribution of seagrass (*Zostera* sp.) meadows in Europe (Auby and Labourg, 1996) and is a major site for oyster-farming in France. Occasionally, issues such as macroalgal blooms have been observed during the past twenty years due to increased eutrophication following changes in land-use in the Leyre watershed. Currently, the Landes de Gascogne region is comprised of managed maritime pine (*Pinus pinaster*) amidst cropped lands (maize), creating unique ecohydrological and biogeochemical interactions.

Because of the predominance of managed forestry with the practice of timber harvesting at maximum growth, most of the stands here remain a significant carbon (C) sink. This is because fluxes of C via photosysnthesis (GPP) remains higher than ecosystem respiration (TER). Studies suggest that managed maritime pine planted stands are able to sequester C (GPP > TER) as early as the third or fourth year of planting (e.g., Moreaux et al., 2011). This might probably be due to rapid plant growth (that favors GPP fluxes) and lower soil C stocks due to sandy soils (that explains lower TER). Because GPP in this region is primarily controlled by soil water status (which in turn is governed by ET), a thorough understanding of the interactions between ET and GPP fluxes is critical.

Moreaux et al. (2011) recently identified the lack of knowledge on the variability of ecohydrological responses in diverse landcover types in the Landes de Gascogne. Almost all the previous studies (e.g., Berbigier et al., 2001; Kowalski et al., 2004; Moreaux et al., 2011; Ogée et al., 2003) have been conducted in a spatially-isolated manner and mostly in mature forest stands. Thus, there is an urgent need to study the large spatial variability within this

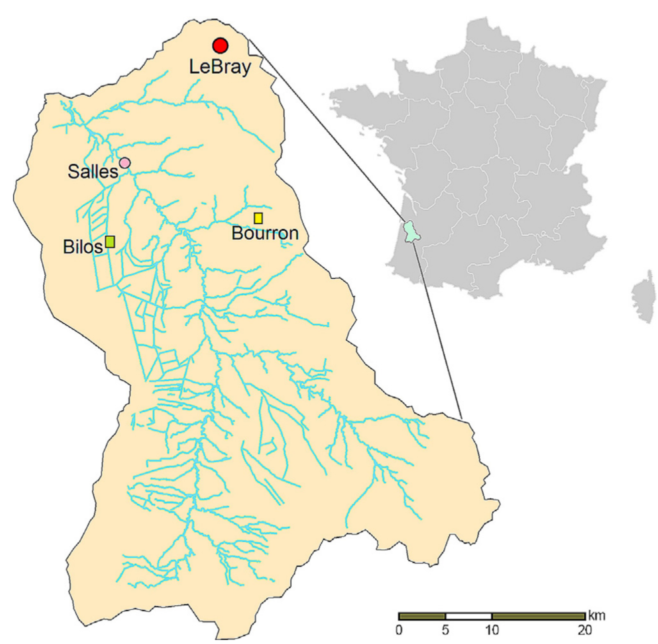

Fig.1. The location of the Leyre watershed in the Landes de Gascogne in France.