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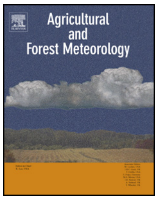

Influence of groundwater on plant water use and productivity: Development of an integrated ecosystem – Variably saturated soil water flow model

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ABSTRACT

Plant physiology influences the energy and water balance of the soil–plant–atmosphere continuum. However, impacts of soil water dynamics on plants in shallow groundwater environments are not completely understood, partially due to the limited ability of current models to simulate groundwater–vegetation interactions. In this study, we analyzed the influence of groundwater-induced soil temperature change on plant phenology, and the impact of variable depth to the water table on the net primary productivity (NPP), evapotranspiration and stomatal response, by integrating an advanced dynamic agroecosystem model (Agro-IBIS) and a variably saturated soil water flow model (Hydrus-1D) into a single framework. The model is first evaluated using field observations of soil moisture and temperature as well as annual NPP and weekly LAI measurements collected from three replicated maize plots at the Arlington Agricultural Research Station near Arlington, Wisconsin, USA. Comparisons showed reasonable agreement for each dataset without site-specific prior calibration. We then simulated the influence of groundwater on plant physiological responses as well as the energy, carbon, and water balance at the land surface. The model sensitivity analyses indicated that physiological functions of plants are sensitive to water table depth, and the aridity of a particular production site. For example, shallow groundwater limits water stress during dry years, helping to mitigate decreased NPP associated with water deficits. However, if the water table is persistently too close to the surface during the growing season, photosynthesis is negatively affected through oxygen stress on roots regardless of the aridity. To further explore factors influencing plant physiology other than oxygen stress, we designed simulations without oxygen stress effects. Results showed that under shallow groundwater conditions: (1) higher leaf level relative humidity causes higher water use efficiency because of a lower vapor pressure deficit between the leaf and atmosphere; (2) due to delayed corn plant emergence caused by cooler springtime soil temperatures reduces NPP. Our results suggest that models designed to more mechanistically simulate groundwater–vegetation interactions may lead to a more realistic representation of feedbacks between plant phenology, soil moisture, temperature, anoxia, NPP and ET. However, until critical data are collected to assess simulated feedbacks and advance our understanding of groundwater–vegetation interactions, model confidence will likely remain somewhat limited.

1. Introduction

Coupled energy and water cycling in the soil–plant–atmosphere system is largely controlled by land surface properties and plant responses to changing environmental conditions, which collectively influence evapotranspiration, runoff, and infiltration. Additionally, it has been shown that groundwater is one of the significant drivers of land surface energy and water exchange with the atmosphere by elevating soil moisture, and affecting plant water uptake (York et al., 2002; Yeh and Eltahir, 2005; Fan et al., 2007; Niu

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et al., 2007; Maxwell and Kollet, 2008; Lowry and Loheide, 2010). Specifically, the existence of shallow groundwater, as an additional moisture source for plants, might lead to increased soil evaporation and higher rates of latent heat flux due to enhanced plant transpiration through influencing plant physiology and structure as well as vegetation distribution and composition (Orellana et al., 2012). Ignoring the effect of groundwater is reported to lead to some erroneous estimates of water–energy balance components (Yeh and Eltahir, 2005; York et al., 2002; among others). Shallow groundwater can also modify the soil heat flux (Kollet and Maxwell, 2008) because the elevated volumetric water content alters the soil thermal diffusivity in a way that might lead to cooler soil temperatures depending on the soil texture (Abu-Hamdeh, 2003), and the temperature of the groundwater.

Although the impacts of groundwater on land surface energy and water balance are relatively well studied (Fan et al., 2007; Maxwell and Kollet, 2008), it remains unclear how plant physiology modulates the effects of shallow groundwater, and how vegetation may adapt to rapid or long-term fluctuations in groundwater levels due to climate change and variability. Changes in the depth to the water table attributed to increased water withdrawals for irrigation can therefore impact land surface energy and water balance (Elmore et al., 2006). Moreover, experimental studies suggest that shallow groundwater conditions contribute to excess soil moisture conditions, which negatively affects plant physiological function and can even cause plant mortality depending on the flood duration (Purvis and Williamson, 1972; Zaidi et al., 2004). However, our understanding of vegetation–groundwater interactions is currently limited due to the inability of current models to simulate groundwater–vegetation interactions that demonstrate how plants and ecosystems respond (i.e. phenology, photosynthesis, and carbon balance) to water table depth, particularly in shallow groundwater environments.

Plants regulate their stomata to control the rate of carbon assimilation and minimize water loss via transpiration to avoid drought-induced formation of xylem embolisms (Tyree and Sperry, 1989; Sparks and Black, 1999). Stomatal conductance is controlled by several factors including the leaf level environment, the photosynthetic metabolism of the leaf, the hydraulic characteristics of the soil and plant, and leaf water potential, which is related to the soil water potential at the root zone (Farquhar and Sharkey, 1982). Therefore, the hydraulic connection between roots and the water table influences stomatal conductance and hence transpiration, particularly for groundwater dependent ecosystems (Orellana et al., 2012).

Previous studies have reported that plants emerge earlier and progress more rapidly through phenological stages as air temperatures increase (Schwartz et al., 2006; Cleland et al., 2007). However, this relationship is sometimes more difficult to detect in agricultural regions because the changes in crop phenology occur more slowly than natural ecosystems (Menzel et al., 2006). Furthermore, the muted response of crop phenology to increasing air temperatures may be partly explained by farmers' decisions on: (1) crop type and hybrid selection (Cleland et al., 2007); (2) planting date (van Oort et al., 2012); and (3) advances in biotechnology and improvements in agronomic equipment and management practices (Kucharik, 2006). Additionally, land management decisions in agricultural systems, such as tillage, impact soil temperature, which is an important factor affecting plant phenology, particularly during germination, leaf emergence, seedling growth and other development stages (Al-Darby and Lowery, 1987). Because soil temperatures and not air temperature largely control seed germination and emergence, cooler soil temperatures associated with elevated volumetric soil water content in the presence of shallow groundwater could influence crop development. Yet, this potential impact has not been studied in detail mainly because of model limitations and a lack of observational data.

There are relatively few process-based ecosystem models that can simulate groundwater as a working part of the soil–vegetation–atmosphere system. Existing land surface models (LSM) simulate water and energy fluxes among soil–vegetation–atmosphere systems using a process-based approach (reviewed by Pitman, 2003), but lack detailed representation of soil water movement in the unsaturated zone when groundwater is present. Furthermore, there are only a few available LSM and/or process-based vegetation models that can simulate agroecosystems (Kucharik, 2003; Bondeau et al., 2007; Di Vittorio et al., 2010), which are significant given they occupy approximately 40% of the global land surface (Ramankutty and Foley, 1999). In contrast, current physically based, variably saturated soil water flux models such as Hydrus (Simunek et al., 2008), and COMSOL Multiphysics (Li et al., 2009) are able to accurately simulate water movement in the unsaturated zone. However, these models lack detailed plant physiology, and carbon and nutrient cycling feedbacks, thus making it difficult to understand plant responses to both variations in energy fluxes and upward capillary fluxes in shallow groundwater environments.

In this study, our first objective was to expand an agroecosystem model to represent interactions of groundwater and vegetation in a fully coupled, physically-based fashion. This would allow for a more realistic representation of carbon, water, and energy cycling within the groundwater–soil–plant–atmosphere system. To achieve this goal, we integrated the Hydrus-1D (Simunek et al., 2008) variably saturated soil water flow model with the Agro-IBIS agroecosystem model (Kucharik and Brye, 2003), validated the new model with field data for maize agroecosystems. Our second objective was to use this new tool to address the following two questions: (1) what is the influence of groundwater-induced soil temperature changes on maize phenology – specifically the accumulated time from planting to emergence? (2) How do net primary productivity (NPP), evapotranspiration (ET), and leaf level environmental conditions respond to varying water table depths?

2. Model description

2.1. Pre-existing Agro-IBIS model

Agro-IBIS is a process-based ecosystem model capable of simulating managed and natural ecosystem dynamics of North America, with coupled carbon, water, and energy cycles. Agro-IBIS was developed by adapting a Global Dynamic Vegetation Model (DGVM), called the Integrated Biosphere Simulator (IBIS) (Foley et al., 1996; Kucharik et al., 2000), to simulate corn, soybean, and wheat cropping systems across the continental US (Kucharik and Brye, 2003), and most recently miscanthus and switchgrass (VanLoocke et al., 2010, 2012). Agro-IBIS simulates the energy, water, carbon, and momentum balance of the soil–plant–atmosphere system at a 60-min time step. The model includes two vegetation layers with eight potential forest plant functional types (PFTs) in the upper canopy, and two grasses (cool and warm season) and two shrub PFTs in the lower canopy. Row crops, miscanthus, and switchgrass are simulated as part of the lower canopy layer. Physiologically-based formulations of leaf-level photosynthesis, stomatal conductance (Collatz et al., 1991) and respiration control canopy exchange processes, and parameters vary according to generalized vegetation categories (e.g., trees, shrubs, C_3 and C_4 grasses or crops).

Agro-IBIS simulates crop growth transitions through phenological stages of development using an accumulated thermal time approach, and characterizes seasonal changes in carbon (C)