Soil Oxygen Dynamics: A Key Mediator of Tile Drainage Impacts on Coupled Hydrological, Biogeochemical, and Crop Systems

Zewei Ma[1,2,3], Kaiyu Guan[1,2,3,4*], Bin Peng[1,2,5*], Wang Zhou[1,2,6], Robert Grant[7], Jinyun Tang[8], Murugesu Sivapalan[9,10], Ming Pan[11], Li Li[12], Zhenong Jin[13]

[1]Agroecosystem Sustainability Center, Institute for Sustainability, Energy, and Environment, University of Illinois Urbana-Champaign, Urbana, IL 61801, USA.
[2]Department of Natural Resources and Environmental Sciences, College of Agricultural, Consumer and Environmental Sciences, University of Illinois Urbana-Champaign, Urbana, IL 61801, USA
[3]DOE Center for Advanced Bioenergy and Bioproducts Innovation, Urbana, IL, United States
[4]National Center for Supercomputing Applications, University of Illinois Urbana-Champaign, Urbana, IL 61801, USA
[5]Department of Crop Sciences, College of Agricultural, Consumer and Environmental Sciences, University of Illinois Urbana-Champaign, IL, 61801, USA
[6]School of Agriculture, Shenzhen Campus of Sun Yat-sen University, Shenzhen, China
[7]Department of Renewable Resources University of Alberta, Alberta, T6G2E3, Canada
[8]Climate Sciences Department, Lawrence Berkeley National Laboratory, CA, 94720, USA
[9]Department of Civil and Environmental Engineering, University of Illinois Urbana-Champaign, Urbana, IL 61801, USA
[10]Department of Geography and Geographic Information Science, University of Illinois Urbana-Champaign, Urbana, IL 61801, USA
[11]Scripps Institution of Oceanography, University of California San Diego, La Jolla, CA 92037, USA
[12]Department of Civil and Environmental Engineering, The Pennsylvania State University, University Park, PA 16802, USA
[13]Department of Bioproducts and Biosystems Engineering, University of Minnesota-Twin Cities, Saint Paul, MN 55108, USA

Correspondence to: Kaiyu Guan (kaiyug@illinois.edu), Bin Peng (binpeng@illinois.edu)

Abstract. Tile drainage removes excess water and is an essential, widely adopted management practice to enhance crop productivity in the U.S. Midwest and throughout the world. Tile drainage has been shown to significantly change hydrological and biogeochemical cycles by lowering the water table and reducing the residence time of soil water, although examining the complex interactions and feedbacks in an integrated hydrology-biogeochemistry-crop system remains elusive. Oxygen dynamics are critical to unravelling these interactions and have been ignored or over-simplified in existing models. Understanding these impacts is essential, particularly so because tile drainage has been highlighted as an adaptation under projected wetter springs and drier summers in the changing climate in the U.S. Midwest. We used the *ecosys* model that uniquely incorporates first-principle soil oxygen dynamics and crop oxygen uptake mechanisms, to quantify the impacts of tile drainage on hydrological and biogeochemical cycles and crop growth at corn-soybean rotation fields. The model was validated with data from a multi-treatment, multi-year experiment in Washington, IA. The relative root mean square error (rRMSE) for corn and soybean yield in validation is 5.66% and 12.57%, respectively. The Pearson coefficient (r) of the monthly tile flow during the growing season is 0.78. Plant oxygen stress turns out as an emergent property of the equilibrium between soil oxygen supply and biological demand. Tile drainage's impact on the system is achieved through a series of coupled feedback mechanisms. Model results show that tile drainage reduces soil water content and enhances soil oxygenation.

It additionally increases subsurface discharge and elevates inorganic nitrogen leaching, with seasonal variations influenced by climate and crop phenology. The improved aerobic condition alleviated crop oxygen stress during wet springs, thereby promoting crop root growth during the early growth stage. The development of greater root density, in turn, mitigates water stress during dry summers, leading to an overall increase in crop yield by ~6%. These functions indicate the potential of tile drainage in bolstering crop resilience to climate change, and the use of this modeling tool for large-scale assessments of tile drainage. The model reveals the underlying causal mechanisms that drive agroecosystem response to drainage on the coupled hydrology, biogeochemistry, and crop system dynamics.

1 Introduction

Agricultural subsurface drainage, commonly referred to as tile drainage, is one of the most important agricultural management practices to enable timely planting and enhance crop productivity in the U.S. Midwest (Moore, 2016; Shen et al., 2013; Skaggs et al., 1994). Over 80% of tile-drained fields in the US are concentrated in six U.S. Midwestern states, covering one-third of the region's cropland (NASS-USDA, 2017; Valayamkunnath et al., 2020; Zulauf and Brown, 2019). Notably, nearly half of the fields in the 3I states (i.e., Iowa, Indiana, and Illinois) are tile-drained, and the adoption rate of tile drainage continues to grow (NASS-USDA, 2017; Valayamkunnath et al., 2020; Zulauf and Brown, 2019). Tile drainage improves drainage conditions by removing excessive water and lowering the water table (Kalita et al., 2007), which benefits seed germination and crop growth (Ashraf, 2012; Nóia Júnior et al., 2023). Tile drainage also helps reduce the risk of delays in crop planting by enabling the timely operation of farm machinery during wet spring months, and thereby extending the crop growing period (Kucharik, 2008; Shirzaei et al., 2021). Tile drainage will become even more important under climate change, as the U.S. Midwest is expected to experience wetter springs with more frequent and intense late-spring storms (Lesk et al., 2016; Li et al., 2019; Lobell et al., 2014; Schmidhuber and Tubiello, 2007; Seneviratne et al., 2022; Zhou et al., 2022a). Thus, understanding the tile drainage impacts and managing the hydrological condition over the Midwestern agroecosystem are critically needed.

Extensive studies have explored the impact of tile drainage from different perspectives, such as hydrology, soil biogeochemistry, and crop growth. Hydrologically, tile drainage induces changes in both water storage and water fluxes (Blann et al., 2009; Boland-Brien et al., 2014; Hanrahan et al., 2020). Tile drainage has been shown to lower the water table, reduce soil water content, and increase temporal soil water storage capacity, which might enhance percolation, reduce surface runoff, and mitigate flooding at the field scale (Blann et al., 2009; Rahman et al., 2014; Skaggs et al., 1994; Yimer et al., 2023). These local-scale changes additionally alter watershed hydrology (Hansen et al., 2013; Miller and Lyon, 2021; Woo and Kumar, 2019). The impacts of tile drainage on hydrology are complicated by the interacting environmental conditions and management practices, soil properties, and antecedent soil moisture (Blann et al., 2009; Cain et al., 2022; Stops et al., 2022; Thomas et al., 2016; Wiskow and van der Ploeg, 2003). For instance, tile drainage may either increase baseflow or result in a more flashier

hydrograph, depending on the specific meteorological and physical characteristics (Adelsperger et al., 2023; Miller and Lyon, 2021; Schilling et al., 2012; Schilling and Helmers, 2008; Thomas et al., 2016; Valayamkunnath et al., 2022). The impact of tile drainage on evapotranspiration (ET) is generally more associated with land conversion (Ma et al., 2023; Wiskow and van der Ploeg, 2003), and ET in tile-drained fields may be similar to that in undrained fields in the same crop systems (Khand et al., 2017; Yang et al., 2017). Tile drainage degrades stream water quality by increasing both field nitrogen and phosphate leaching (Castellano et al., 2019; David et al., 2010; Grenon et al., 2021; Ma et al., 2023; Ren et al., 2022; Sims et al., 1998). Further, tile drainage fosters a more aerobic soil condition, which would largely alter soil microbe activities, i.e., mineralization and immobilization (Brown et al., 2017; Jacinthe et al., 2015; Kumar et al., 2014). Notably, the impacts of tile drainage on both hydrology and biogeochemistry exhibit seasonal variation (Lam et al., 2016; Macrae et al., 2007; Ma et al., 2023; Williams et al., 2015). Despite the substantial attention on tile drainage, the impacts of tile drainage on hydrology, biogeochemistry, and crop growth are often studied separately within disciplinary boundaries, preventing an integrated understanding of their complex interactions.

Process-based models are promising for their capabilities of integrating physical, chemical, and biological processes, thus providing a cost-efficient and time-efficient means to advance scientific understanding and offer decision/policy support compared to field experiments (Jones et al., 2017). Tile drainage modelling has a long history and has recently gained attention for its integration into comprehensive hydrology and land surface models. (Bailey et al., 2022; De Schepper and Therrien, 2017; Hansen et al., 2013; Li et al., 2010; Muma et al., 2017; Rumph Frederiksen and Molina-Navarro, 2021; Smith et al., 2020; Valayamkunnath et al., 2022). However, many of these models are specialized for particular processes, and, in some cases, they either omit or oversimplify other critical processes. Hydrologic models primarily focus on hydrological responses but do not represent soil biogeochemistry and crop growth, such as the National Water Model, the Soil Water Assessment Tool (SWAT) and the Tsinghua Hydrological Model (THREW) (J. G. Arnold et al., 2012; Li et al., 2010; Valayamkunnath et al., 2022). Similarly, reactive transport models, such as PFLOTRAN and Advanced Terrestrial Simulator (ATS), simulate water and nutrient transport and biogeochemical transformation but lack the capability of representing crop growth and agricultural management activities (Hammond et al., 2014; Li et al., 2017, 2021). Crop growth models have recently been used to illuminate the impacts of waterlogging, but they often lack a comprehensive representation of the interconnections between hydrology, crop dynamics, and soil biogeochemistry. For instance, many such models, such as the DRAINMOD model, the Soil-Water-Atmosphere-Plant (SWAP) model, the Agricultural Production Systems sIMulator (APSIM), the decision support system for agrotechnology transfer (DSSAT) model, and the Environmental Policy Integrated Climate (EPIC) model, do not adequately represent root respiration, a key process influencing root development, maintenance, and nutrient uptake. Instead, they rely on soil water content as a proxy for oxygen stress, potentially neglecting important nuances in the interconnections between these critical processes (Ebrahimi-Mollabashi et al., 2019; Liu et al., 2020a; Pasley et al., 2020; R. W. Skaggs et al., 2012; Sharpley, 1990).

Representations of ecophysiological and biochemical mechanisms under excessive water are critical in using process-based models to understand the interlinkage and interaction between hydrology, biogeochemistry, and crop growth. The limited soil oxygen diffusion under water-saturated conditions has been recognized as a key factor altering crop growth and soil biogeochemistry (Elzenga and van Veen, 2010; Pan et al., 2020; Rubol et al., 2013). Restricted soil oxygen under excessive water will suppress root respiration, decrease root activity, and even lead to root senescence, which further affects crop yield (Pan et al., 2020). Soil oxygen availability regulates soil biogeochemistry and composition by altering the redox potential, influencing microbial processes, nutrient cycling, and the mobility of elements (Elzenga and van Veen, 2010; Rubol et al., 2013). Under saturated conditions, anaerobic microbial respiration is favored to consume electron acceptors such as nitrate, sulfate, or iron instead of oxygen for respiration, producing greenhouse gases, and changing the availability of essential nutrients for crop uptake. However, those processes are not well represented in the aforementioned process-based models.

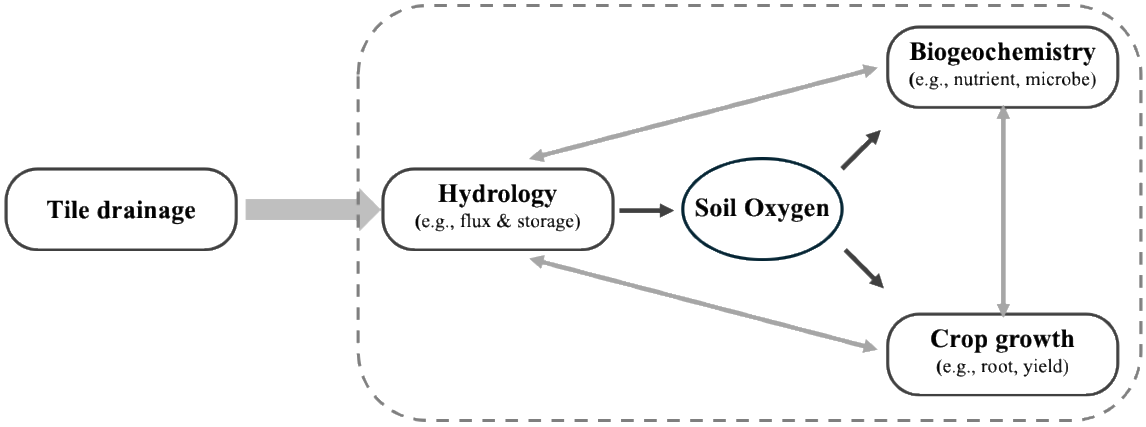


Figure 1: Hypothesis on how tile drainage impacts hydrology, soil biogeochemistry, and crop growth. Tile drainage directly changes field hydrology, and then changes soil biogeochemistry and crop growth. Among those, soil oxygen is a key mediator that links hydrology, soil biogeochemistry and crop growth in the coupled system.

Here we aim to use a process-based model, *ecosys*, that incorporates all essential physical mechanisms, especially oxygen-related dynamics, to understand the role of tile drainage in the integrated hydrology-biogeochemistry-crop agroecosystems dynamics by addressing the following questions: 1) How does tile drainage alter the agroecosystem hydrology, biogeochemistry, and crop growth? More importantly, 2) how are those impacts on the three aspects interrelated? 3) How do seasonal precipitation patterns influence tile drainage and agricultural production? We hypothesize that tile drainage positively influences crop growth by altering in-field hydrology and soil biogeochemistry, with soil oxygen acting as the critical mediator that links these three components. Specifically, tile drainage improves soil aeration by reducing soil water content. The resulting increase in oxygen availability stimulates root development and microbial activity, subsequently enhancing overall crop growth. In turn, this greater biological activity creates a feedback loop: enhanced microbial activity accelerates organic matter mineralization, and the root system alters hydrology through increased water and nutrient uptake (Fig. 1). We further hypothesize that tile drainage could bolster agricultural production and potentially serve as an efficient adaptation strategy in

the context of climate change. We first validate the *ecosys* model using data from a multi-year field experiment at a research and demonstration farm in Washington, Iowa. In Section 2, we provide an overview, and some key processes related to tile drainage and soil oxygen simulations in the *ecosys* model and introduce the data used in this study and hypothetical numerical experiment designs. Section 3 presents the model calibration and simulation results. In Section 4, we specifically discuss and answer the above-mentioned questions and draw conclusions in Section 5.

2 Model and data

2.1 *Ecosys* model

2.1.1 Overview of *ecosys* model

The *ecosys* model is an agroecosystem model with essential mechanistic representations of hydrology, soil biogeochemistry, and crop growth in the soil-vegetation-atmosphere continuum at the hourly time step (Fig. 2 and S1-3) (Grant, 2001; Grant et al., 2017). *Ecosys* can be configured to run in 1D, 2D, or 3D. For typical field-scale applications, it operates as a highly detailed, multi-layered 1D model. 2D and 3D configurations have been employed to investigate topography control on ecosystem processes (Grant et al., 2017) It has shown promising performance in simulating water fluxes (e.g., evapotranspiration), biogeochemistry (e.g., soil carbon storage, greenhouse gas emission), and crop growth (e.g., gross primary productivity, and crop yield) in different cropping systems (Grant, 1993, 1998; Li et al., 2022; Mezbahuddin et al., 2016; Qin et al., 2021; Yang et al., 2022; Zhang et al., 2021; Zhou et al., 2021). In this study, we configured the model to study tile drainage's impact to run in a 1D setting, which also ensures a greater numerical stability.

Ecosys simulates the movement of water through the soil-crop-atmosphere continuum with the representation of crop interception of precipitation, irrigation, soil and residue evaporation, crop transpiration, infiltration, surface runoff, subsurface discharge, and snow (Fig. S1). All the water fluxes in both soil and crop are driven by water potential and are tightly coupled with energy cycles (Grant et al., 1999; Mezbahuddin et al., 2016).

Soil biogeochemistry in *ecosys* is simulated by tracking the flow of carbon (C), nitrogen (N), and phosphorus (P) among various organic states within the soil (Fig. S2). The model represents organic matter into six organic states (i.e., solid organic matter, soluble organic matter, sorbed organic matter, acetate, microbial communities, and microbial residues). Each state is further divided into components with varying vulnerability to hydrolysis by microbial populations. Microbes are the agents that control the C, N, and P transformation. Microbial activity is simulated based on the energetics of oxidation-reduction reactions, driving processes such as decomposition, nitrification, denitrification, and methanogenesis. Meanwhile, the energy

generated in those processes and the nutrients will also be used for microbe maintenance and growth. Microbes also undergo decomposition (Grant et al., 1993a, b).

Ecosys simulates crop growth by representing the crop as a collection of individual branches and organs. The growth of branches and organs is driven by the balance between carbon fixation through photosynthesis and carbon losses through respiration and senescence. Carbon fixation happens in the leaves via the Farquhar model, and the fixed carbon is then mobilized to other branches and organs (Grant, 1994). Water and nutrient uptake (i.e., P and N) is simulated with a hierarchical root system (Grant, 1993, 1998), as affected by temperature, nutrient availability, and soil oxygen concentration. Similarly, the nutrients absorbed by the root (i.e., N and P) are remobilized to other branches and organs for crop growth. For example, the N mobilized to leaves determines the specific activities and surficial concentrations of leaf rubisco and chlorophyll, further affecting the CO2 fixation rate.

The three components (hydrology, soil biogeochemistry, and crop growth) are tightly interconnected within *ecosys*. For example, carbon assimilation in crop growth is tightly coupled to canopy transpiration, as stomatal conductance, affected by canopy turgor potential, determines both the transpiration rate and photosynthesis rate (Grant and Pattey, 1999). Root water uptake is the driver for root nutrient uptake in the dispersivity-diffusivity processes, see details in Text S3. The hydrological cycle in the model is also tightly linked to soil biogeochemistry. Soil water movement drives the movement of soil nutrients, determining nutrient vertical distribution and loss. In addition, the movement of water also drives the movement of soil gas, e.g., soil oxygen, and subsequently changes both root respiration and microbe activities, see details in Text S4-S8. Further, microbial activities control the release of nutrients from organic matter, influencing the availability of nitrogen and phosphorus for crop uptake, which dynamically links soil biogeochemistry with crop growth.

We used *ecosys* to evaluate the impact of tile drainage on field hydrology, soil biogeochemistry, and crop growth. We provide details about soil oxygen-related processes and tile drainage processes in the following section as soil oxygen is a critical component to link hydrology, biogeochemistry, and crop growth. More detailed processes of the various components, like ecosystem-atmosphere energy exchange, canopy carbon fixation, etc., of the *ecosys* model can be found on GitHub (https://github.com/jinyun1tang/ECOSYS/blob/master/ecosys_documentation.pdf).

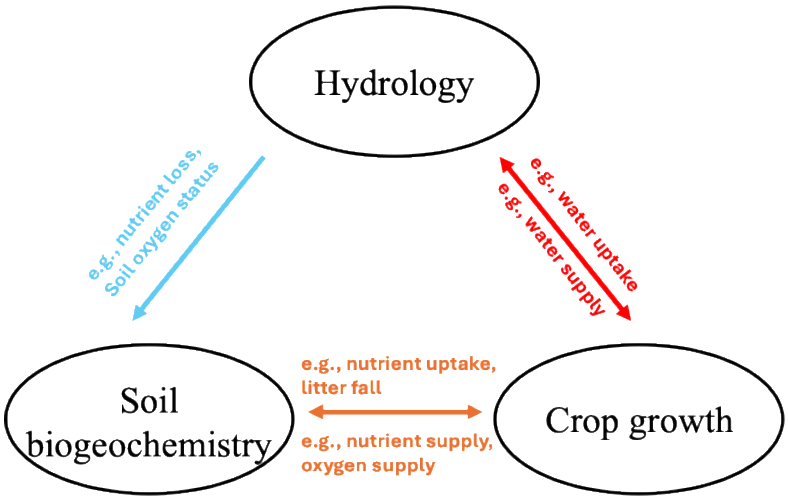


Figure 2: Examples of interplays between hydrology, soil biogeochemistry, and crop growth in the *ecosys* model

2.1.2 Soil oxygen dynamics

Oxygen is represented in two phases in *ecosys*, the gaseous oxygen in the air-filled porosity and the dissolved oxygen in soil water. The vertical transport of both gaseous and dissolved oxygen, the transfer between dissolved and gaseous oxygen, and oxygen consumption by both crop roots and soil microbes are explicitly represented in the model. The volatilization–dissolution transfer between dissolved and gaseous oxygen is driven by the oxygen difference in the two phases, and is determined by the diffusive transfer coefficient, and air–water interfacial area.

$$Q_{d,O_2} = a_g D_{d,O_2} \left(S'_{O_2} f_{t,s,O_2} \left(C_{g,O_2} - C_{s,O_2} \right) \right) \quad (1)$$

where Q_{d,O_2} is volatilization–dissolution of O_2 between solute and gaseous phases [$g\ m^{-2}\ h$]; D_{d,O_2} is the O_2 volatilization-dissolution transfer coefficient [$m^2 h^{-1}$]; a_g is the air-water interfacial area [$m^2 m^{-2}$]; S'_{O_2} is the Ostwald solubility coefficient of O_2 at 30 °C [-]; f_{t,s,O_2} is the temperature dependence function of S'_{O_2} [-]; C_{g,O_2} is the gaseous concentration of O_2 in soil [$g\ m^{-3}$]; C_{s,O_2} is the corresponding solute concentration in soil [$g\ m^{-3}$].

The vertical transport of dissolved and gaseous oxygen in the soil is calculated from the convective-dispersive equation,

$$Q_{g,O_2} = -Q_w C_{g,O_2} + D_{g,O_2} \frac{\partial C_{g,O_2}}{\partial L} \quad (2)$$

$$Q_{s,O_2} = Q_w C_s + D_{s,O_2} \frac{\partial C_{s,O_2}}{\partial L} \quad (3)$$

$$D_{g,O_2} = \frac{D'_{g,O_2} f_{t,g} \theta_g^{\ 2}}{\theta_p^{0.67}} \quad (4)$$

$$D_{s,O_2} = D_q |Q_w| + D'_a f_{t,s} \theta_w \tau \quad (5)$$

where Q_{g,O_2} is the gaseous flux of O_2 in soil [$g\ m^{-2}\ h$]; Q_w is the water flow rate in the soil [$m^3\ m^{-2}\ h^{-1}$]. C_{g,O_2} is the gaseous concentration of O_2 in soil [$g\ m^{-3}$]; D_{g,O_2} is the gaseous diffusivity of O_2 in soil [$m^2 h^{-1}$], determined by its gaseous diffusivity at 0 °C (D'_{g,O_2}) [$m^2 h^{-1}$], temperature dependence function for gaseous diffusivity ($f_{t,g}$) [-], the air-filled porosity (θ_g) [$m^3\ m^{-3}$], and soil porosity (θ_p) [$m^3 m^{-3}$]; $\frac{\partial C_{g,O_2}}{\partial L}$ is the concentration gradient of gaseous O_2 in soil [$g\ m^{-3} m^{-1}$]; Q_{s,O_2} is the solute flux of O_2 in soil [$g\ m^{-2}\ h$]; C_{s,O_2} is the solute concentration of O_2 in soil [$g\ m^{-3}$]; D_{s,O_2} is the solute diffusivity of O_2 in soil [$m^2 h^{-1}$], determined by dispersivity in soil (D_q) [m], its solute diffusivity at 0 °C (D'_{s,O_2}) [$g\ m^{-2}\ h$], Q_w, temperature dependence function for solute diffusivity ($f_{t,s}$) [-], the soil water-filled porosity (θ_w) [$m^3\ m^{-3}$], and is the soil tortuosity (τ) [-].

Soil oxygen will be used by crops, mycorrhizal, and microbes for their maintenance and growth. See sections 2.1.3 and 2.1.4 for a detailed description of crop oxygen uptake. See the supplementary and the online document on GitHub (https://github.com/jinyun1tang/ECOSYS/blob/master/ecosys_documentation.pdf) for a detailed description of microbial growth and oxygen uptake.

2.1.3 Root respiration and crop oxygen demand

Roots play a critical role in crop growth by acquiring necessary resources, including water and nutrients (i.e. nitrogen, phosphorus, etc.), from the soil for crop development, and stabilizing crop body structure (Hodge et al., 2009). Understanding the interactions between root system and soil is essential to quantify the impacts of different environmental factors on crop growth (Jin et al., 2020). *Ecosys* explicitly simulates the root system with a representation of vertical primary axes and horizontal secondary axes (details in Grant, 1993, 1998). In the model, root growth and maintenance are driven by root respiration, and the rate of root respiration at maximum turgor in each soil layer is controlled by the available carbon storage, soil moisture, temperature, oxygen availability, and nutrient status,

$$R_T = Q_R C_R f_{t,R} f_{o,R} f_{\lambda,R} \quad (6)$$

where R_T is the root respiration for maintenance and growth [$gC\ m^{-2} h^{-1}$]; Q_R is the specific respiration of CH_2O [$g\ g^{-1} h^{-1}$]; C_R is nonstructural CH_2O in root [$gC\ m^{-2}$]; $f_{t,R}$ is the temperature function for respiration [-]; $f_{o,R}$ is the oxygen function for respiration, represented as the ratio of O_2 uptake to O_2 demand [-], and will be detailed in the Section 2.1.4 below; $f_{\lambda,R}$ is the

nutrient status function for respiration [-]. The actual respiration rate is further adjusted by root turgor and soil strength (Grant, 1993, 1998). Nutrient uptake ($NO_3^-, NH_4^+, PO_4^{3-}$) also respires CH_2O,

$$R_U = \alpha \Sigma U_\lambda \tag{7}$$

where R_U is the respiration for nutrient uptake [$gC\ m^{-2}h^{-1}$]; α is the specific respiration rate for nutrient uptake [-]; U_λ is the uptake rate of nutrient Z ($NO_3^-, NH_4^+, PO_4^{3-}$) [$gN\ m^{-2}h^{-1}$ or $gP\ m^{-2}h^{-1}$]. The total root respiration is, then, the total respiration for root maintenance, root growth, and root nutrient uptake ($R_T + R_U$). The crop oxygen demand (U_O') is defined as the oxygen uptake rate without soil oxygen limits,

$$U_O' = \frac{\frac{R_T}{f_{o,R}} + R_U}{R_Q} \tag{8}$$

where R_Q is the respiratory quotient [$gC\ (gO_2)^{-1}$].

The oxygen uptake rate in *ecosys* is controlled by both the soil oxygen supply (dissolved oxygen transport rates to root surfaces) and the ability of roots to take up oxygen (active uptake rates at the root surface where respiration is modeled). The conceptualization of crop roots is depicted in Fig. 3a, with a porous core in the middle, surrounded by an aqueous zone where respiration happens, then encased in a water film. Gaseous and dissolved oxygen transport in both the root porous core and the soil contributes to root respiration. The movement of oxygen is assumed to be radial, and the rate of oxygen moving from the soil water to the root surface and the rate of oxygen moving from the aqueous zone of the root porous core to the root surface are obtained from Eq. (9) and Eq. (10), respectively.

$$U_{O,s} = U_w C_{O_2,s} + 2\pi D_{O_2} L \frac{(C_{O_2,s} - C_{O_2,R})}{\left(\frac{r_R + r_W}{r_R}\right)} \tag{9}$$

$$U_{O,P} = 2\pi D_{O_2} L \frac{C_{O_2,R} - C_{O_2,P}}{l\left(\frac{r_R}{r_P}\right)} \tag{10}$$

where $U_{O,s}$ is the rate of oxygen uptake by root from soil [$g\ m^2h^{-1}$]; $U_{O,P}$ is the rate of oxygen uptake by root from the root porous core [$g\ m^2h^{-1}$]; U_w is the root water uptake rate [$m^3m^{-2}h^{-1}$], determined by soil and root water potential and root resistances (Grant, 1998); D_{O_2} is the dispersivity-diffusivity of dissolved oxygen [m^2h^{-1}] (Bresler, 1973); L is the root length [$m\ m^{-2}$]; $C_{O_2,s}$ is the dissolved oxygen concentration in the soil [$g\ m^{-3}$]; $C_{O_2,R}$ is the oxygen concentration at the respiration site [$g\ m^{-3}$]; $C_{O_2,P}$ is the dissolved oxygen concentration in the root porous core [$g\ m^{-3}$]; r_R is root radius [m]; r_W is the thickness of the water film [m] (Kemper and Rollins, 1966); r_P is the radius of the root porous core [m]. The active oxygen uptake rate by roots is modeled in the Michaelis-Menten format,

$$U_O = \frac{U_O' C_{O_2,R}}{C_{O_2,R} + K_O} \tag{11}$$

where U_O is the root oxygen uptake rate [$g\ m^2 h^{-1}$], K_O is the Michaelis-Menten constant for root oxygen uptake [$g\ m^{-3}$]. U_O is solved iteratively from Eq. (6-8), with $U_O = U_{O,s} + U_{O,P}$. All dissolved oxygen concentrations are driven by oxygen transport in gaseous phases, and by dissolution from gaseous to aqueous phases in soil and roots, which will be affected by soil drainage conditions. Details of oxygen transport and dissolution (i.e., solute and gaseous) in soil and root could be found in (Grant, 1993). Then, the oxygen stress indicator ($f_{o,R}$) in Eq. (6) is defined as the ratio between the U_O and U'_O,

$$f_{o,R} = \frac{U_O}{U'_O} \tag{12}$$

2.1.4 Water balance

The water balance in the simulated field is given by,

$$\Delta S_i = P_i - Q_i - R_i - ET_i \tag{13}$$

All terms are defined as fluxes per unit area [$m^3\ m^{-2}$] at the time step i. Specifically, ΔS_i is the change in soil water storage; P_i is the precipitation; R_i is the surface runoff, referring to the water leaving the system above the soil surface, and it is estimated with Manning's equation (Text S1); Q_i represents the total water exchange across subsurface boundary and tile drainage. A positive value indicates outflow (subsurface discharge), and a negative value indicates inflow (subsurface recharge). Although the model operates on an hourly time step, in the following analysis, subsurface exchange was aggregated and attributed to discharge and recharge on a daily basis. The lateral water exchange is controlled by a lateral subsurface boundary condition, with a specific external water table depth and a specific lateral distance over which lateral subsurface water flow occurs (Figure S4). External water table depth represents the water table depth of the surrounding environment, for instance, the water table depth at the field boundary, channel, or nearby lakes, etc.

2.1.5 Tile drainage

The vertical soil water flow is governed by the Richards' equation,

$$\frac{\partial \theta_w}{\partial t} = \frac{\partial}{\partial z}\left(K(\theta_w)\left(\frac{\partial h}{\partial z} + 1\right)\right) - S \tag{14}$$

where θ_w is soil water content [$m^3 m^{-3}$]; $K(\theta_w)$ is the soil hydraulic conductance at θ_w [$m\ h^{-1}$]. S is soil water sink term [$m^3 m^{-3} h^{-1}$], including crop and mycorrhizal water uptake, lateral water fluxes to/from the external water table, and lateral discharge to tile drainage. To solve the equation, the soil column is discretized into several user-specified layers (Fig. 3b). Water fluxes to tile pipes are estimated laterally with Darcy's law in saturated soil layers,

$$v = \frac{K\Delta D}{d} \tag{15}$$

where v is the flow velocity $[m\ h^{-1}]$; K is the saturated hydraulic conductance $[m\ h^{-1}]$; ΔD is the pressure drop $[m]$ over a distance d $[m]$. The pressure drop is defined as the difference between the internal water table depth and the tile depth ($D_2 - D_1$), and the distance is then defined as half of the tile space (d_1). Similar to the Dupuit–Forchheimer assumption, we assume water flow horizontally. Thus, tile flow is only calculated in the soil layers above and containing tile drains. There is no tile flow if the water table in the field is below the tile pipes. The water table in the field is in the lowest unsaturated soil layer below which all soil layers are saturated. Specifically, the water table in the field is estimated with,

$$D_1 = \left(d_s - \frac{L_i \theta_i}{\theta_{i,s}}\right) \tag{16}$$

where D_1 is the water table depth $[m]$, d_s is the depth to the top of the uppermost saturated soil layer $[m]$, L_i is the thickness of the lowest unsaturated soil layer $[m]$, θ_i is the volumetric soil water content of the lowest unsaturated soil layer $[m^3 m^{-3}]$, $\theta_{i,s}$ is the saturated volumetric soil water content of the lowest unsaturated soil layer $[m^3 m^{-3}]$.

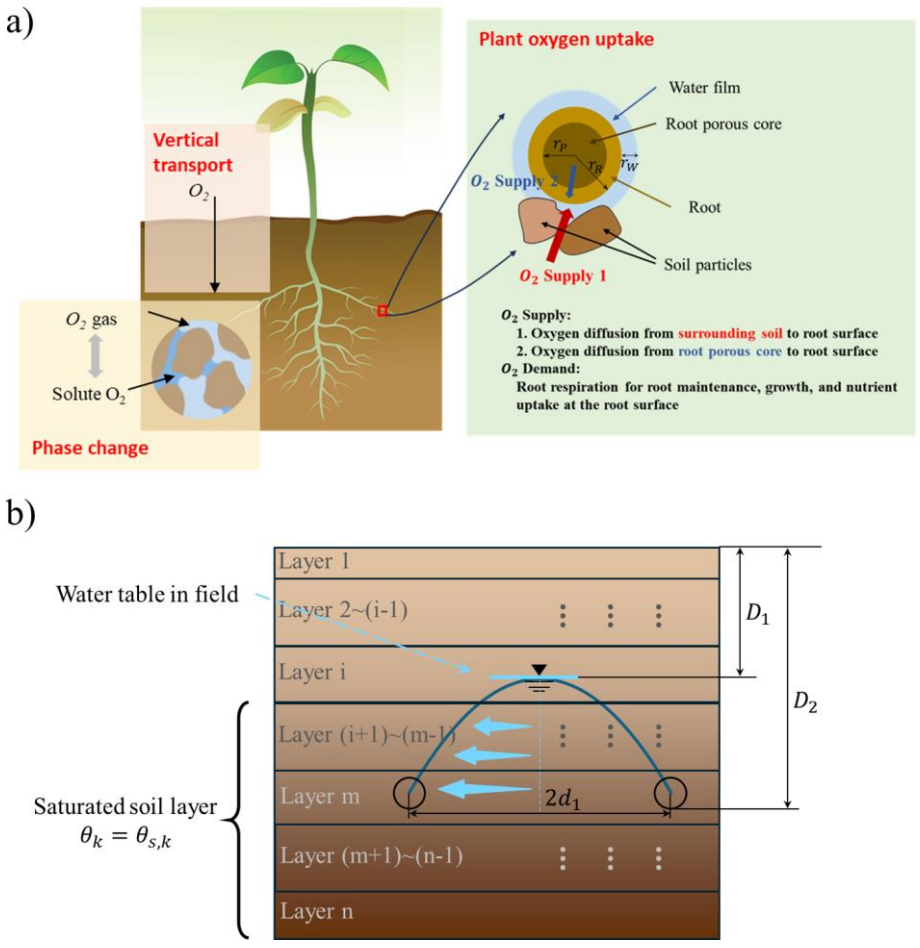


Figure 3: Representation of a) oxygen dynamics and root oxygen uptake, and b) subsurface tile flow in the *ecosys* model. r_R is root radius $[m]$; r_W is the thickness of the water film $[m]$; r_P is the radius of the root porous core $[m]$. D_1: Water table depth in the field $[m]$;

$\boldsymbol{D_2}$: Tile depth [$\boldsymbol{m}$]; $\boldsymbol{2d_1}$: Tile spacing [$\boldsymbol{m}$]; $\boldsymbol{\theta_k}$: Soil water content in the k-th soil layer [$\boldsymbol{m^3m^{-3}}$]; $\boldsymbol{\theta_{s,k}}$: Saturated soil water content in the k-th soil layer [$\boldsymbol{m^3m^{-3}}$]. In this schematic, the field water table is in the i-th soil layer, and tile drainage is installed in the m-th soil layer. The vertical dots represent the intermediate soil layers not shown. The diagram only represents the case that water table in the field is higher than tile drainage.

2.2 Model setups

2.2.1 Field data

Data from an experimental field site (Fig. 4) in the Iowa State University Southeast Research and Demonstration Farm in Washington County (41.20°, -91.49°), was used for model setup and validation (Chighladze et al., 2021). The major soil types in this site are Tanitor and Kalona soils (silty clay loam soil) (Fig. S5). The study site consists of four tile drainage treatments: conventional drainage, shallow drainage, controlled drainage, and no drainage. Each of these treatments had two replicates with corn-soybean rotations. Border tiles without monitoring were installed to reduce the interaction between adjacent plots. Only the conventional drainage and no drainage plots were used in this study. Tile drainage was installed in 2006 and tile flow, crop yield, and daily water table depth were monitored from 2007 to 2017. The tile diameter, tile depth, and tile spacing between are 25.4 cm, 122 cm, and 18.3 m, respectively. Management practices, such as tillage and fertilizer application, were documented and used as model inputs. On-site daily precipitation was monitored from 2007 to 2017. The precipitation data in 2007 was removed due to quality issues (Fig. S6). All these data can be accessed at a website at Iowa State University (https://datateam.agron.iastate.edu/td/).

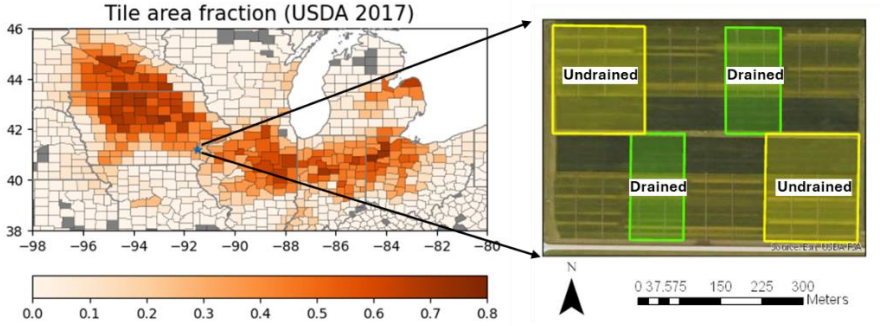


Figure 4: Tile fractions over the U.S. Midwest region, and the location and layout of the selected experiment field. The yellow boxes represent sub-fields without tile drainage, and the green boxes represent sub-fields with conventional drainage**.**

2.2.2 Model calibration, validation, and experiment design

Soil properties, weather, management practice data, and tile drainage settings are required to drive the *ecosys* model. The North American Land Data Assimilation System (NLDAS-2) dataset was used as the major meteorology driver, including temperature, solar radiation, humidity, and wind speed (Xia et al., 2012). Daily precipitation data from on-site observations

for the years 2008 to 2017 were substituted for the NLDAS-2 dataset to better capture the local rainfall pattern. As hourly data were unavailable, daily precipitation totals were uniformly distributed over two separate hours on each rainy day. This approach was chosen because common downscaling techniques, such as AWE-GEN (Ivanov et al., 2007), require sub-daily precipitation statistics that were not available for our site. Furthermore, this simplification is justified as our analysis focuses on the system's response at monthly and annual time scales. The soil information was obtained from the Gridded Soil Survey Geographic Database (gSSURGO) dataset, and the detailed soil information used in the study can be found in Figure S5 and Table S2 (Soil Survey Staff, 2023). The settings for tile drainage in the tile field are shown in Table 1. We referred to one observation well in the undrained field to set the subsurface boundary condition. Specifically, external water table depth was set as the mean value of the observed water table depths (1.00 m), and the distance to the external water table was set as 50 m, which is around half of the length of the experimental field. The tile drainage depth was set as the lowest point of the tile drainage, which was the depth of the tile drainage plus the radius of the tile drainage, 1.35 m. Tile drainage spacing was 18.3 m.

Table 1. Tile drainage parameter settings.

Parameters	Values
External water table depth	1.00 m
Distance to the external water table	50.00 m
Tile drainage depth	1.35 m
Tile drainage spacing	18.30 m

Ecosys simulation started in 1990, with the initial 17 years (1990-2006) as the initialization period to stabilize the model, followed by an 11-year analysis period (2007-2017). Due to the limited length of the observational record, the model was calibrated against the undrained field and validated against the tile-drained field. The configuration of the model relied on established crop parameters in the U.S. Midwest conditions (Li et al., 2022). Key parameters sensitive to local conditions were calibrated using observed crop yields from the undrained field, such as the maturity group and maximum rate of carboxylation (VCMX). The parameter ranges and final values were shown in Table S1. The Pearson coefficient (r), percent error (PE), root mean square error (RMSE), and relative root mean square error (rRMSE) were used to assess the model's performance, comparing the simulated yield with the observed yield. The tile flow simulation was assessed on a monthly basis by comparing the simulated and observed values through r, RMSE, and Nash–Sutcliffe model efficiency coefficient (NSE),

$$r = \frac{\Sigma(x_i-\bar{x})(y_i-\bar{y})}{\sqrt{\Sigma(x_i-\bar{x})^2\Sigma(y_i-\bar{y})^2}} \quad (16)$$

$$PE = \frac{\bar{x}-\bar{y}}{\bar{x}} \quad (17)$$

$$RMSE = \sqrt{\frac{\Sigma^N{}_{i=1}(x_i-(y_i)^2)}{N}} \quad (18)$$

$$rRMSE = \sqrt{\frac{\frac{\Sigma^{N}_{i=1}(x_i - y_i)^2}{N}}{\Sigma^{N}_{i=1}(x_i)^2}} \quad (19)$$

$$NSE = 1 - \frac{\Sigma^{N}_{i=1}(x_i - y_i)^2}{\Sigma^{T}_{t=1}(x_i - \bar{x})^2} \quad (20)$$

where x_i is the observation, y_i is the simulation, $\bar{x}$ and $\bar{y}$ is the mean value of observation and simulation, respectively. N is the number of observations.

To investigate the effects of tile drainage in wetter conditions, we ran the calibrated model to simulate hydrological processes, biogeochemical dynamics, and crop growth across a spectrum of precipitation scenarios. Specifically, we manually adjusted the precipitation inputs with a scale factor, λ, to evaluate wetter conditions (Fig. S7),

$$\boldsymbol{P} = (p_1, p_2, \cdots, p_n) \quad (21)$$

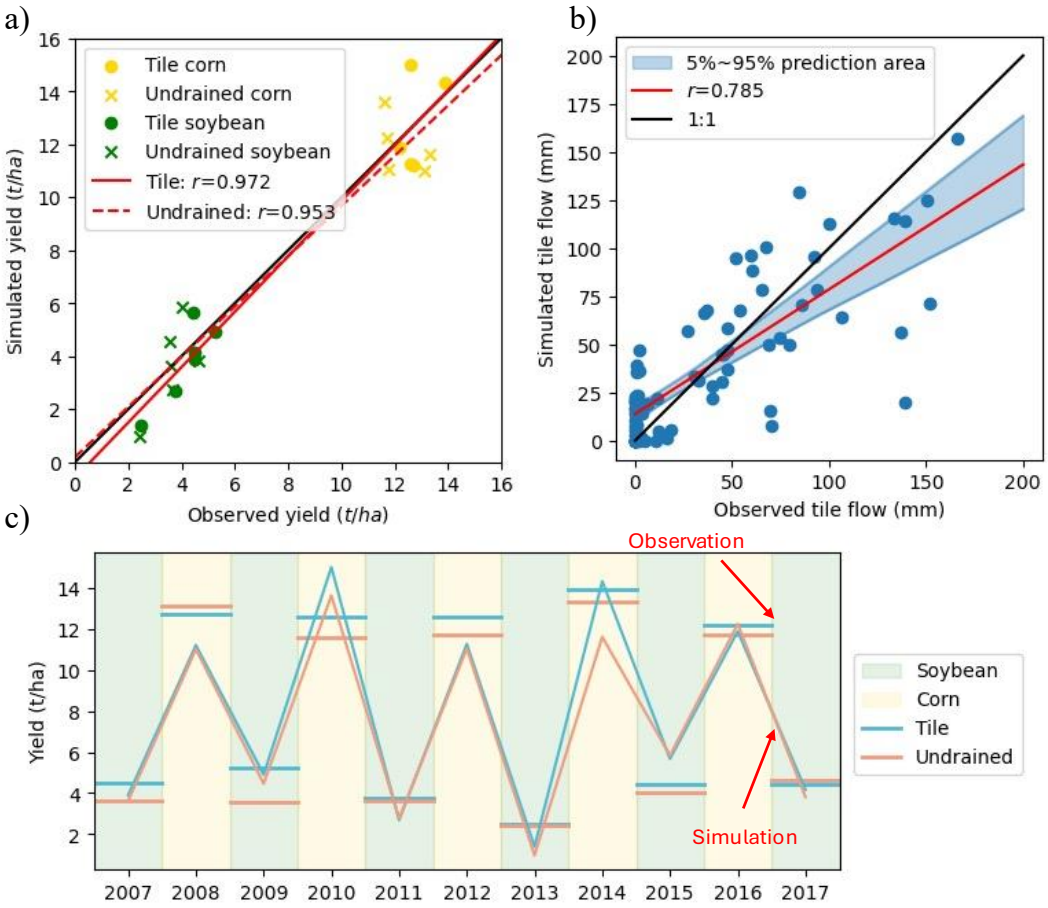
$$\boldsymbol{P_\lambda} = (\lambda p_1, \lambda p_2, \cdots, \lambda p_n) \quad (22)$$

where $\boldsymbol{P}$ is the original precipitation time series that drives the model, and p_i is the precipitation at i-th time step $[mm]$. $\boldsymbol{P_\lambda}$ is the precipitation time series with the scale factor $\lambda \in \{0.9, 1.0, 1.1, 1.2, 1.3\}$ corresponding to five hypothetical scenarios. Given temperature, which dominates vapor pressure deficit, is more influential to crop yield in drought over the U.S. Midwest (Lobell et al., 2014), this hypothetical experiment mainly targeted at understanding the system's response to flooding with more precipitation.

3 Results

3.1 Model validation

The *ecosys* model's crop yield simulations were evaluated against field observations (Fig. 5 and Table 3). Overall, the Pearson coefficient r for the yield simulation was over 0.95 for both calibration and validation. Specifically, the PE for corn in calibration and validation was -0.50% and -3.10%, respectively. The PE for soybean in calibration and validation were -8.75% and -1.57%, respectively. The rRMSE for corn and soybean in validation was 5.66% and 12.57%, respectively. Both the observations and simulation showed the benefit of tile drainage for crop yield. For corn, tile drainage increased yield by 0.830 $t\ ha^{-1}$ (6.97%) and 0.515 $t\ ha^{-1}$ (4.20%) in model simulation and observations, respectively. For soybean, tile drainage increased yield by 0.193 $t\ ha^{-1}$ (5.37%) and 0.498 $t\ ha^{-1}$ (13.66%) in model simulation and observations, respectively (Table 3). Besides, the model successfully captured the seasonal pattern of more tile flow in late spring and early summer (Fig. 6). The observations suggested that there was no observed tile flow in January and February, and we hypothesized that this was due to the low temperature that disabled the measurement device. Thus, we only validated tile flow in the growing season (April to October). The r, RMSE, and NSE for monthly tile flow simulation in the growing season were 0.785, 28.42 mm/month, and 0.43, respectively. These results indicate that the *ecosys* model is promising for estimating both crop yield and tile drainage flow.



380 **Figure 5: Validation for crop yield and tile flow.** Comparison of *ecosys*-simulated and ground-measured **a**) maize (15 % moisture) and soybean (13 % moisture) grain yield, and **b**) monthly tile flow in the growing season (April to October). **c**) Time series of simulated and observed yield. Corn years (light gold) and soybean years (light green) are indicated with different background color.

Table 2. Goodness-of-fit statistics for crop growth for calibration and validation. PE: percent error; rRMSE: relative root mean square error; RMSE: root mean square error.

	Statistic	Tile (validation)	Undrained (calibration)
Corn Yield	PE	-0.50%	-3.10%
	rRMSE	4.90%	5.66%
	RMSE ($t\ ha^{-1}$)	1.41	1.56
Soybean Yield	PE	-8.75%	-1.57%
	rRMSE	8.34%	12.57%
	RMSE ($t\ ha^{-1}$)	0.87	1.14

Table 3. Observed and simulated crop yield under tile and undrained conditions.

	Tile ($t\ ha^{-1}$)		Undrained ($t\ ha^{-1}$)		Tile benefit ($t\ ha^{-1}$)	
	Obs.	Sim.	Obs.	Sim.	Obs.	Sim.
Corn	12.800	12.734	12.285	11.904	0.515 (4.20%)	0.830 (6.97%)
Soybean	4.150	3.787	3.651	3.594	0.498 (13.66%)	0.193 (5.37%)

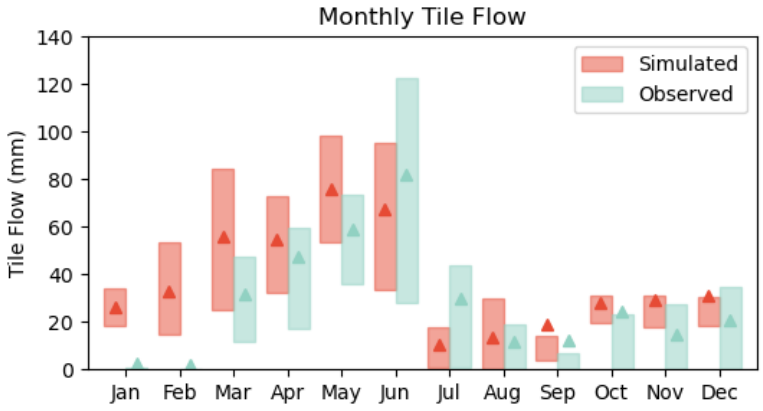


Figure 6: *Ecosys*-simulated and observed tile flow. Boxes represent 25%-75% of tile flow for the simulated period (2007-2017), and triangles represent the mean tile flows. The triangles represent the multi-year mean tile flow in a certain month.

3.2 The impacts of tile drainage on hydrology

We first evaluated water fluxes and partitioning with the *ecosys* model under tile and undrained conditions at the study site. The annual mean precipitation was 881 mm from 2007 to 2017, and most of the precipitation (66.4%) occurred from April to August (Fig. 7 and S8). The simulations indicated that tile drainage primarily altered subsurface water exchange (Fig. 7). Compared to the undrained condition, tile drainage increased the annual mean subsurface discharge from 216 mm to 276 mm and increased subsurface recharge from 34 mm to 104 mm. In contrast, tile drainage had a limited impact on other fluxes. Annual mean evapotranspiration (ET) was similar under tile (659 mm) and undrained (655 mm) conditions, as was surface runoff (48 mm and 46 mm, respectively). As a direct consequence of the increased subsurface drainage, the simulations showed that tile drainage reduced soil water content (Fig. S11a).

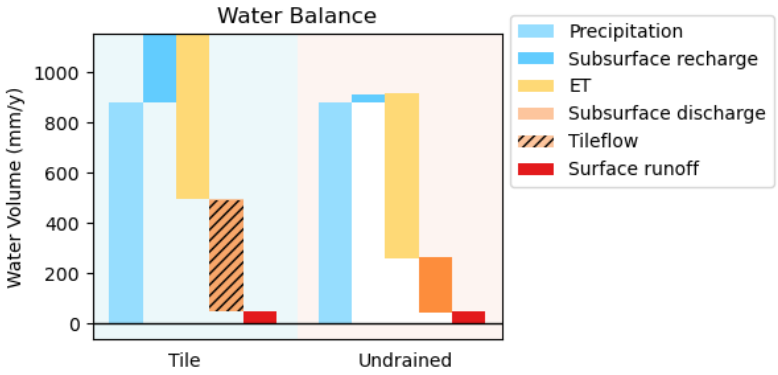
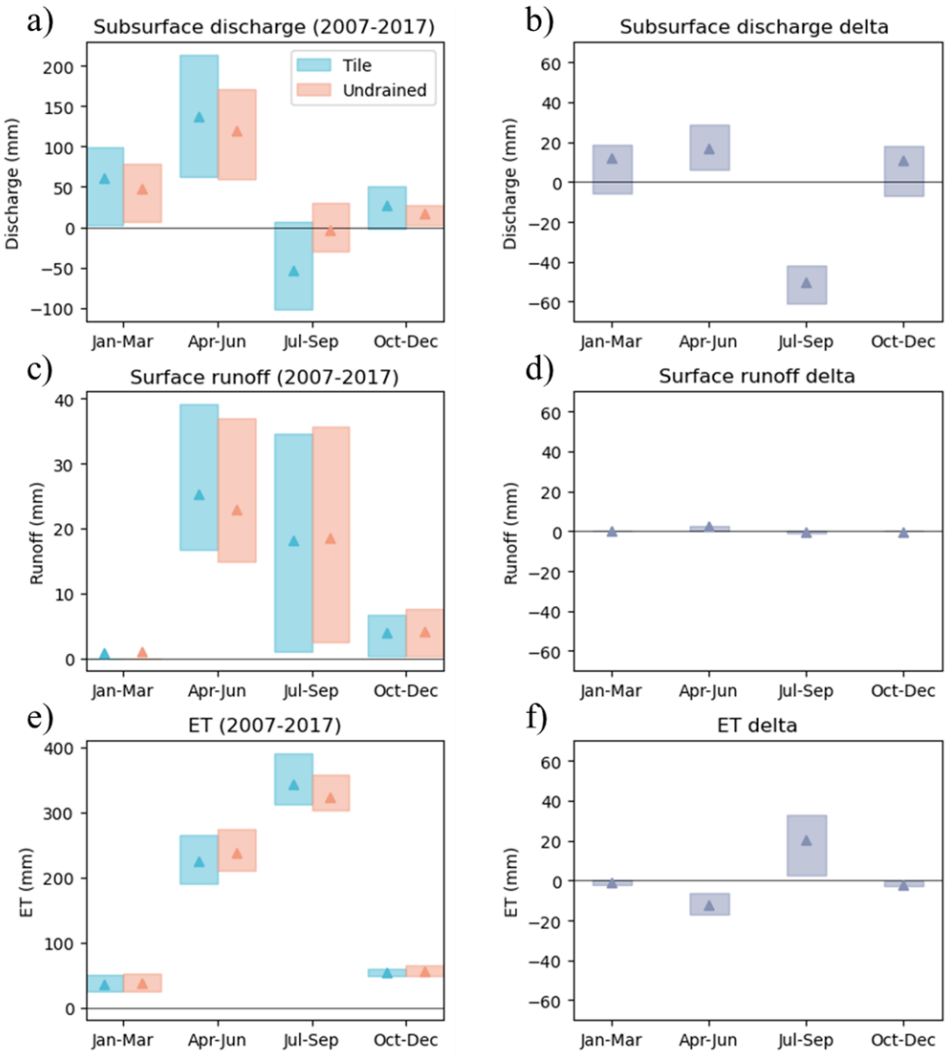


Figure 7: *Ecosys*-simulated annual water balance under tile and undrained conditions. Overall, tile drainage increases both subsurface discharge (water coming out of the field) and subsurface recharge (water going into the field), and ET and surface runoff are similar under tile and undrained conditions. The imbalance between influxes and outfluxes is subject to storage change.



405 **Figure 8: *Ecosys*-simulated water fluxes under tile and undrained conditions from 2007 to 2017. a**) Boxplot of the quarterly net subsurface discharge (subsurface discharge - subsurface recharge); **b**) Boxplot of the quarterly net subsurface discharge difference between tile and undrained conditions; **c**) Boxplot of the quarterly surface runoff; **d**) Boxplot of the quarterly surface runoff difference between tile and undrained conditions; **e**) Boxplot of the quarterly ET, **f**) Boxplot of the quarterly ET difference between tile and undrained conditions. The upper and lower parts of the boxplots indicate 25% and 75% quantiles, and the boxes indicate the interquartile variation. The triangles
410 indicate the mean values. Delta is the difference between tile and undrained conditions. The corresponding monthly results are shown in Fig. S10.

Results indicated that the effects of tile drainage followed a seasonal pattern (Fig. 6). For the study site, tile drainage actively removed excess water in spring, leading to an increase in net subsurface discharge from 120 mm to 137 mm, corresponding to
415 high precipitation and low ET during those months. Less water was drained by tile drainage in summer due to high crop water consumption despite high precipitation (Fig. 6, 8, and S10). On average, the net subsurface discharge was -53 mm in summer

under tile conditions, indicating a significant recharge from surrounding soils to the tile-drained field. Tile drainage increased net subsurface discharge from 17 mm to 28 mm and from 48 mm to 60 mm in autumn and winter, respectively, when compared to the undrained condition. Tile drainage slightly raised ET in the summer months from 226 mm to 238 mm, and slightly reduced ET in other months (Fig. 8).

3.3 The impacts of tile drainage on soil biogeochemistry and the subsequent crop growth

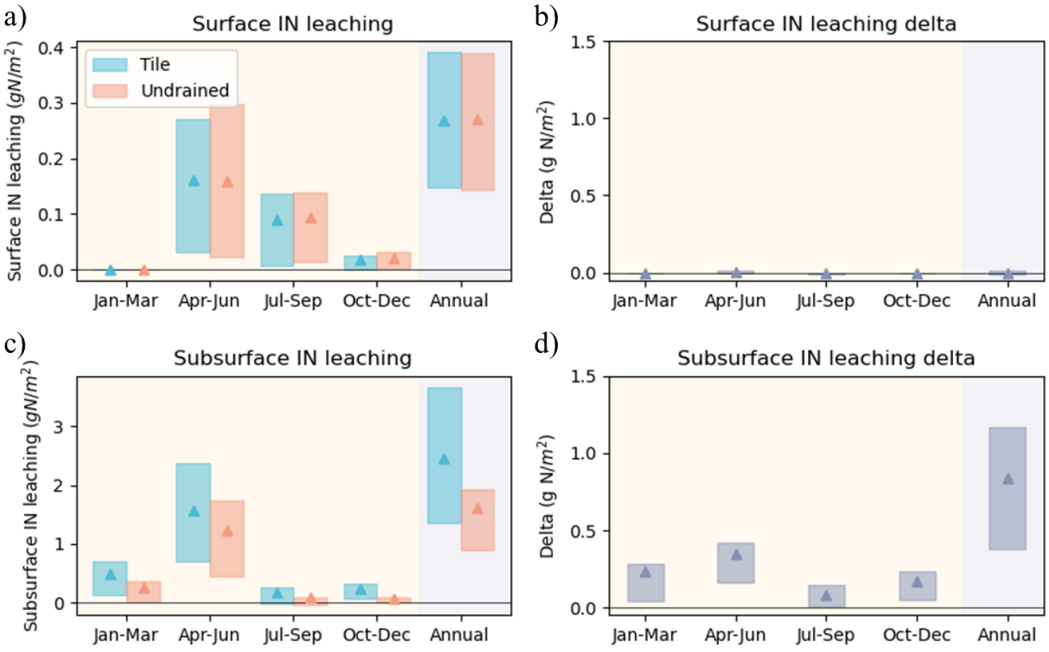


Figure 9: ***Ecosys*****-simulated inorganic nitrogen (IN) lost under tile and undrained conditions from 2007 to 2017. a**) Boxplot of the quarterly and annual subsurface inorganic nitrogen discharge, **b**) Boxplot of difference of the quarterly and annual subsurface inorganic nitrogen loss between tile and undrained conditions, **c**) Boxplot of the quarterly and annual surface inorganic nitrogen loss, and d) Boxplot of difference of the quarterly and annual surface inorganic nitrogen loss between tile and undrained conditions.

In addition to altering water fluxes, the model showed that tile drainage significantly changed the fate and transport of inorganic nitrogen (IN). At the study site, the annual mean total inorganic nitrogen (IN) loss was 2.72 $g\ Nm^{-2}$ and 1.89 $g\ Nm^{-2}$ for tile and undrained conditions, respectively (Fig. 9). Tile drainage primarily increased subsurface inorganic nitrogen loss, with values rising from 1.89 $g\ Nm^{-2}$ to 2.45 $g\ Nm^{-2}$, while surface inorganic nitrogen loss remained relatively constant, with no significant differences noted between tile and undrained conditions, around 0.27 $g\ Nm^{-2}$. These values were within the range of riverine nitrogen yield in the central U.S. Midwest reported by (David et al., 2010). Over 85% of inorganic nitrogen left the system through the subsurface in both tile and undrained conditions. Most inorganic nitrogen loss happened in spring, coinciding with fertilizer application and the peak precipitation period. The impacts of tile drainage on inorganic nitrogen loss also exhibited a seasonality. Our model revealed that subsurface inorganic loss had the most substantial increase in spring with

an increase of 0.35 $g\ Nm^{-2}$, while the increase of subsurface inorganic loss in summer was only 0.08 $g\ Nm^{-2}$. Furthermore, model results showed that nitrogen loss increased with the total precipitation in the hypothetical experiments (Fig. S12).

The model suggested that tile drainage increased soil oxygen concentration (Fig. S11), further affecting soil biogeochemistry and crop growth. Figure 10a-b suggests that tile drainage promoted soil microbe activity and accelerated soil organic nitrogen mineralization and soil heterotrophic respiration (Brown et al., 2017; Castellano et al., 2019). Our model showed that the annual mean inorganic nitrogen generated in mineralization-immobilization processes increases by 0.36 $g\ Nm^{-2}$, from 9.39 $g\ Nm^{-2}$ to 9.75 $g\ Nm^{-2}$, with tile drainage. The elevated oxygen concentration also promoted crop root growth and nutrient uptake, as indicated by the increase of mean annual root respiration from 182 $g\ Cm^{-2}$, to 193 $g\ Cm^{-2}$ (Fig. 10c).

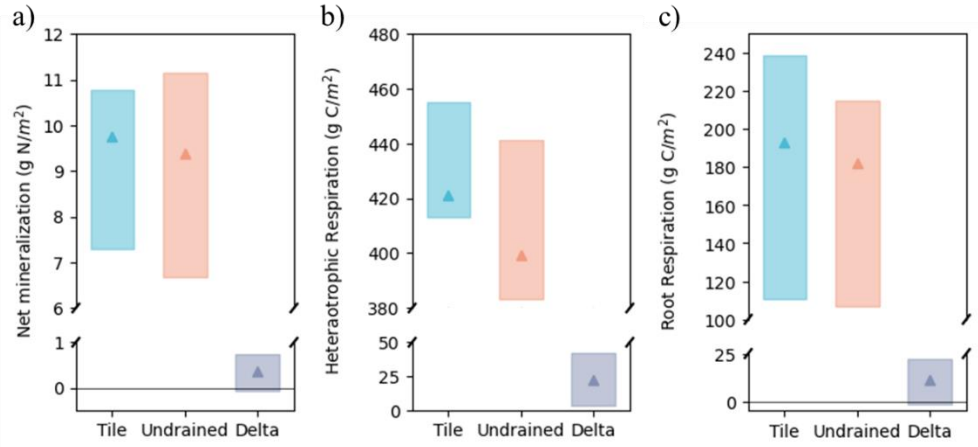


Figure 10: *Ecosys* simulated soil root and soil microbe activities from 2007 to 2017. Boxplot of *ecosys*-simulated **a**) annual soil net mineralization (mineralization - immobilization) under tile and undrained conditions and their difference, **b**) annual root respiration under tile and undrained conditions and their difference, and **c**) annual heterotrophic respiration under tile and undrained conditions and their difference. The upper and lower parts of the boxplots indicate 25% and 75% quantile, and the boxes indicate the interquartile variation. The triangles indicate the mean values. Delta is the difference between tile and undrained conditions.

To understand the role of tile drainage on crop growth under excessive precipitation, we specifically looked into a typical wet year, 2009. This year was characterized by high annual precipitation, and June in particular received 197 mm of rain, surpassing the multi-year average of 158 mm. Both the simulation and the observation showed that tile drainage helped to increase soybean yield during 2009 (Fig. S11). The profile of soil water content (SWC), O_2, and root density in the soil column on June 30th are presented in Fig. 11. Under undrained conditions, the soil profile was nearly saturated below a 0.4 m depth. In contrast, the tile-drained profile was not saturated until below 1.1 m, which demonstrated that tile drainage effectively mitigated excess water accumulation in the soil. Consequently, soil oxygen concentration is higher under the tile condition (Fig. 11b), which provides aerated conditions for crop root growth. This improved oxygen availability contributes to denser and deeper root development (Fig. 11c). Figure 11e shows the time series of the O_2 stress indicator, defined in section 2.1.3, which showed that tile drainage helped to reduce the O_2 stress. We observed that tile promoted crop transpiration especially during the early

growth season (Fig. 11f and g). Similar impacts of tile drainage on crop yield and soil conditions were observed for corn during another wet year, 2010 (Fig. S14).

Results also showed the potential of tile drainage to enhance crop resilience to drought in summer with a wet spring. The annual precipitation in 2013 was 874 mm, slightly below the annual mean value of 881 mm. 2013 experienced the most severe drought in summer, with 71 mm of precipitation recorded during the summer months (Fig. S8), and the drought led to a yield drop (Fig. S13). The precipitation in May reached 230.61 mm, which saturated the soil in the early stage of crop growth. Both the observation and model showed an increase in soybean yield under the tile drainage condition, although our model underestimated the yield (Fig. 5 and Text S9). Our results suggested that tile drainage reduced soil water content while increasing soil oxygen concentration and promoting root growth (Fig. 11h-j). Figure 11k shows that the tile drainage increases the minimum canopy water potential modeled in summer, indicating soybeans suffered less water stress under tile conditions. Our model also suggested that crop transpired more water during summer drought under the tile condition, even with less soil water content (Fig. 11h-n), which evidenced that the more developed root system helped crops access soil water in deeper soil (Fan et al., 2017; Schenk and Jackson, 2005; Steudle, 2001).

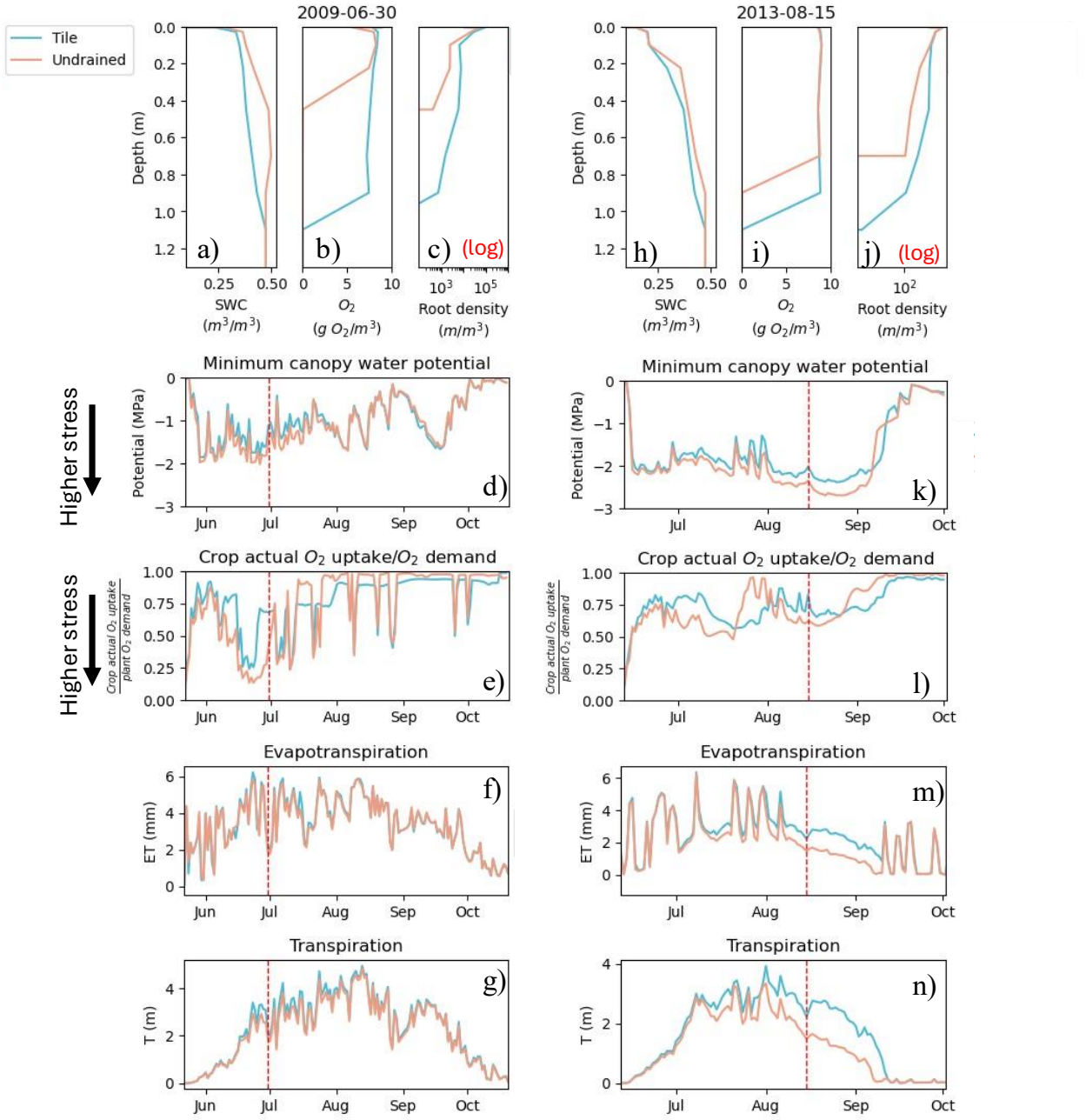


Figure 11: *Ecosys*-simulated soil profile and time series of water stress, oxygen stress, and evapotranspiration in typical wet and dry soybean years. The profile of **a**) Soil water content, **b**) soil $\boldsymbol{O_2}$ concentration, and **c**) root density profiles in the soil column on June 30th, 2009. Time series of **d**) minimum canopy water potential, **e**) crop actual $\boldsymbol{O_2}$ uptake rate/$\boldsymbol{O_2}$ demand (potential $\boldsymbol{O_2}$ uptake rate under non-limiting $\boldsymbol{O_2}$ condition), **f**) evapotranspiration, **g**) crop transpiration in the 2009 growing season (a typical wet year for soybeans). The profile of **h**) Soil water content, **i**) soil $\boldsymbol{O_2}$ concentration, and **j**) root density profiles in the soil column on August 15th, 2013. Time series of **k**) minimum canopy water potential, **l**) crop actual $\boldsymbol{O_2}$ uptake rate/$\boldsymbol{O_2}$ demand (potential $\boldsymbol{O_2}$ uptake rate under non-limiting $\boldsymbol{O_2}$ condition), **m**) evapotranspiration, **n**) crop transpiration in the 2013 growing season (a typical year with wet spring and dry summer for soybean). The

vertical red lines indicate the days to get soil profiles. The x axis of **c**) and **j**) is in log-scale, see Fig. S29 for the plots showing root density in the linear scale.

3.4 The impact of tile drainage on crop growth under different precipitation amounts

The validated model was then used to assess the impact of tile drainage under various precipitation amounts in hypothetical numerical experiments. Our simulation revealed that the mean crop yield over the assessment period decreases for both corn and soybeans, as precipitation levels increase. The yield reductions with the increase of precipitation are more pronounced under undrained conditions, and the yield difference between tile and undrained conditions becomes increasingly substantial with rising precipitation levels (Fig. 12). Those findings indicate that tile drainage provides a yield benefit, and this benefit becomes even more pronounced in conditions of higher precipitation in the sites that already have relatively abundant precipitation. Tile drainage would increase the resilience of crops to precipitation increase, indicated by higher crop yield variation with the change of precipitation (Fig. S18).

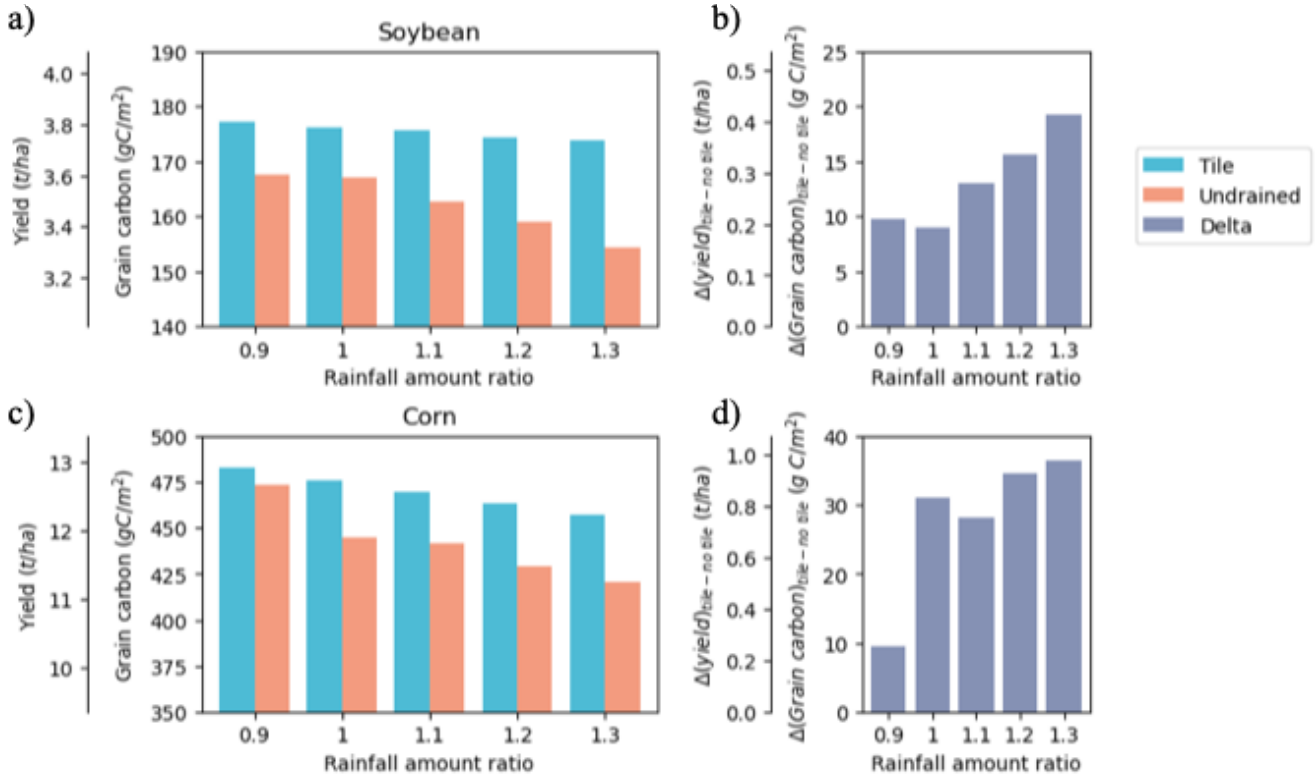


Figure 12: *Ecosys*-simulated crop yield in the hypothetical numerical experiment under different precipitations. a) Multiyear-mean soybean yield under tile and undrained conditions. **b**) The soybean yield benefit (yield/grain carbon difference between tile and undrained conditions). **c**) Multiyear-mean corn yield under tile and undrained conditions. **d**) The corn yield benefit (yield/grain carbon difference between tile and undrained conditions). The x-axis, rainfall amount ratio, is the scale factor in the hypothetical numerical experiment. For example, 1.3 represents that the precipitation amount at each time step is 1.3 times of the original precipitation.

To examine the impacts of increased precipitation and tile drainage on crop growth, we examined the responses of biogeochemistry and crop growth to varying precipitation levels under tile and undrained conditions in a typical wet year for soybeans (2009). Figure 13a shows that the mean soil O_2 content in the top 1 m soil during June decreases with rising precipitation, under both tile and undrained conditions (r=-0.943 and -0.977 for tile and undrained conditions, respectively). Higher oxygen concentration further leads to lower crop oxygen stress, indicated by elevated values of the O_2 stress indicator under conditions of high soil O_2 (Fig. 13b, r=0.931 and 0.995 for tile and undrained conditions, respectively). Crops suffering from less oxygen stress tend to develop denser root systems (Fig. 13c, r=0.982 and 0.984 for tile and undrained conditions, respectively). Our results reveal that the grain carbon reduces as precipitation increases (Fig. 13d). Furthermore, the soil O_2 concentration, crop O_2 stress indicator, root density, and grain carbon under the tile conditions are consistently higher compared with those under the undrained condition (Fig. 13), which indicates that tile drainage would benefit crop growth by elevating soil O_2 content and then reducing crop oxygen stress. Besides, the steeper slopes in Fig. 13 under the undrained conditions suggested that the crop system without tile drainage exhibits higher sensitivity to changes in precipitation. This implies that tile drainage could bolster the system's resilience to precipitation variability, and the benefits of tile drainage become more pronounced with more precipitation. Similar results are also shown in the typical wet year for corn (Fig. S19).

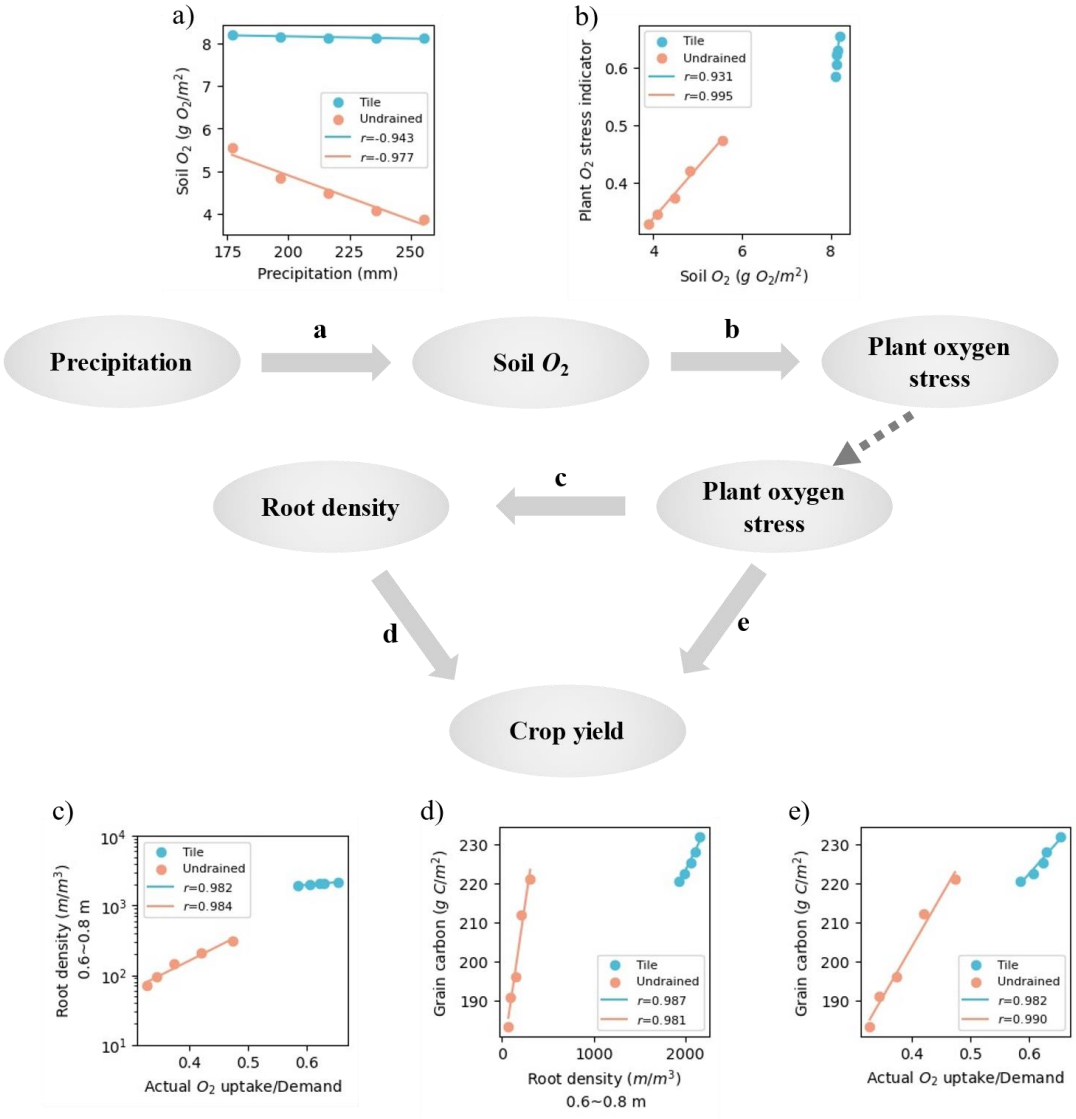


Figure 13: *Ecosys*-simulated responses of biogeochemistry and crop growth to precipitation amounts in a typical wet year for soybeans (2009) under tile and undrained conditions. The relationships between **a**) soil $\boldsymbol{O_2}$ concentration in the top 1m soil column and precipitation in June, **b**) crop $\boldsymbol{O_2}$ stress indicator and soil $\boldsymbol{O_2}$ concentration in the top 1m soil column in June, **c**) root density (0.6 m~ 0.8m soil layer) and crop actual $\boldsymbol{O_2}$ uptake rate/potential $\boldsymbol{O_2}$ uptake rate under non-limiting $\boldsymbol{O_2}$ condition in June, **d**) grain carbon and root density (0.6 m~ 0.8m soil layer) in June, and **e**) grain carbon and crop $\boldsymbol{O_2}$ stress indicator in June.

4. Discussion

4.1 On the necessary processes to simulate tile drainage impacts and the effectiveness of the *ecosys* model

A central challenge in quantifying the full impact of tile drainage is capturing the complex interactions between hydrology, soil biogeochemistry, and crop growth. In this study, we utilized the *ecosys* model for its first-principles approach to simulating

the coupled feedbacks between soil water, aeration, biogeochemistry, and crop growth (Grant, 2001), which offers a unique lens to investigate the underlying causal mechanisms that drive agroecosystem response to drainage. To evaluate the benefits of improved soil aeration, this study relies on the model's mechanistic simulation of the complete soil oxygen cycle, including its transport, phase changes, and biological consumption (Section 2.1.2). This provides a direct biophysical connection between a lowered water table and the oxygen available for root function. In *ecosys*, oxygen stress is an emergent property of the balance between supply and biological demand, while many crop models either ignore this stress or approximate it by applying empirical functions tied to soil water status (Ebrahimi-Mollabashi et al., 2019; Feddes et al., 1978, 2001; Šimůnek and Hopmans, 2009; Vrettas and Fung, 2017). The crop's response to drainage also emerges from a series of simulated feedbacks in the model. For instance, soil oxygen availability regulates root respiration, which provides the energy for root maintenance and growth, and root nutrient uptake (Section 2.1.3). Then, the impact on root system further cascades to the whole crop through processes, such as coupled plant hydraulics and photosynthesis model over the soil-crop-atmosphere continuum, nitrogen remobilization in crop root, shoot, and leaf, etc (Section 2.1.1). The effectiveness of this approach is demonstrated in our results, which show how improved soil oxygen under tile drainage alleviates crop oxygen stress, particularly during wet springs, leading to denser root systems (Fig. 11 and 13). By mechanistically linking the hydrological modification to these detailed physiological responses, this modeling approach allows us to dissect the causal chains driving crop yield benefits, providing a more transferable and systematic process-level understanding (Warren et al., 2015).

The application of the model, despite recent advances in modeling capability and process realism, is limited by the availability of observation data. *Ecosys* relies on hourly weather input to drive the water and energy cycles. However, accurate hourly weather data is not always available. Here we downscaled daily in-situ precipitation data to provide hourly inputs by assuming even precipitation within two hours in a day. However, precipitation intensity is a key factor that determines the runoff generation mechanisms (i.e., infiltration-excess runoff and saturation-excess runoff) (Horton, 1933; Nanda and Safeeq, 2023; Tromp-van Meerveld and McDonnell, 2006). Our results under different precipitation amounts also show that the proportion of water leaving the system through surface runoff increases with the increase of precipitation amount/intensity (Fig. S20). The simple downscaling method (Section 2.2.2) inadvertently reduces the occurrence of intense precipitation events while increasing the frequency of smaller, milder precipitation events, which might underestimate the surface runoff and overestimate subsurface discharge. Further, to fully leverage the capability of the *ecosys* and improve its accuracy, a wealth of observational data is necessary for both model calibration and validation. For instance, we did not find work that directly contrasts the root system and soil oxygen status in tile and undrained conditions, potentially due to the difficulty in measuring the quantities. We suggest that future field and greenhouse experiments prioritize systematic collections of data on various variables such as water fluxes, solute nutrient fluxes, greenhouse gas emissions, root development, above-ground crop biomass, and more. These datasets would serve a dual purpose: facilitating model validation and performance assessment while deepening our understanding of the underlying physical processes. This improved understanding can then be leveraged to refine model mechanisms and parameterization (Liu et al., 2020b; Nóia Júnior et al., 2023; Warren et al., 2015). Expanding

the availability of such data would be invaluable in advancing our modeling efforts and increasing their applicability to real-world scenarios. In this case, observation, experiments, and measurement are integrated together, which aligns with the DOE well-proposed model–data experimentation (ModEx) framework (Hoffman et al., 2017).

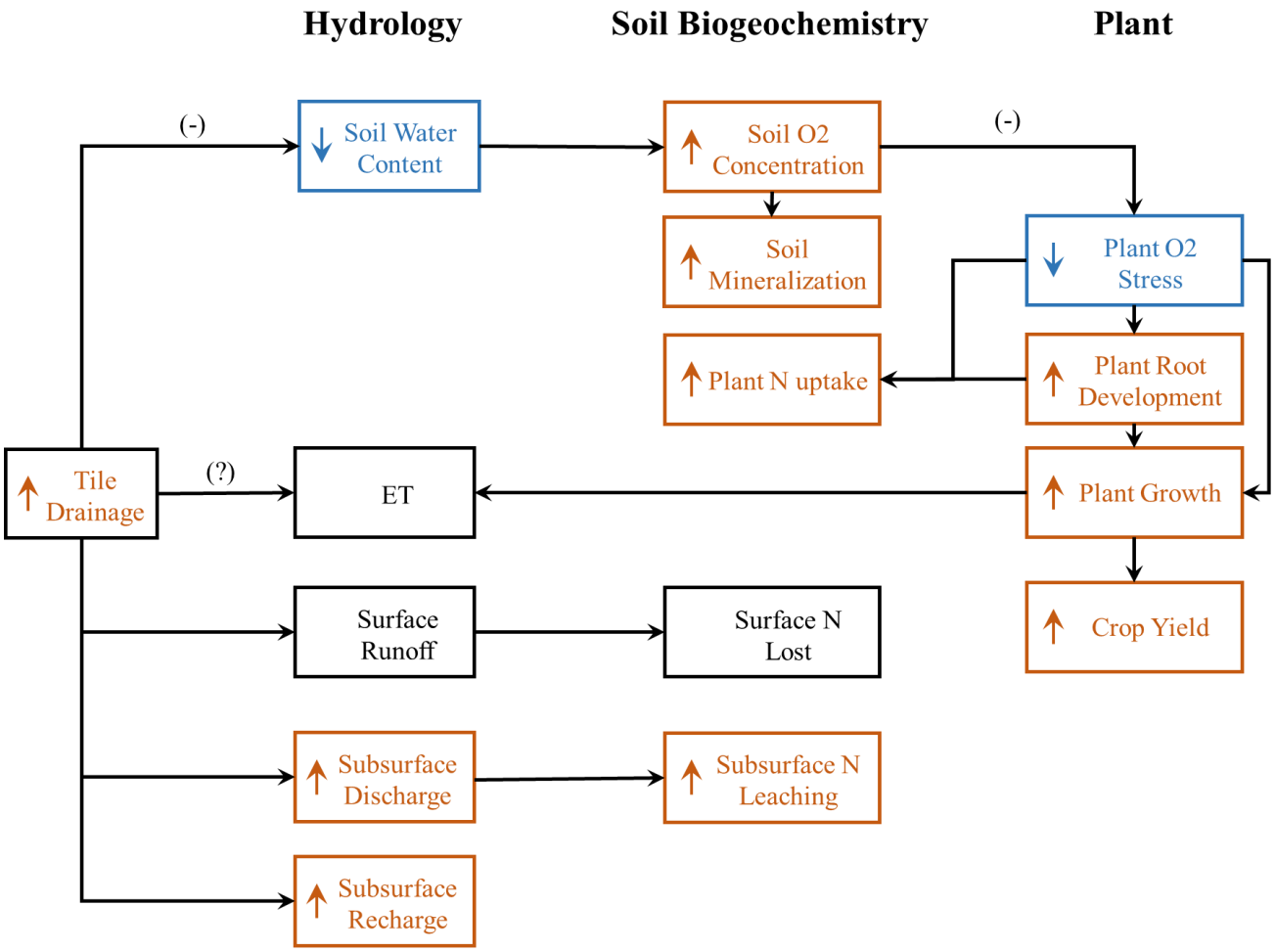


Figure 14: Schematic of the impact of tile drainage on hydrology, soil biogeochemistry, and crops for the U.S. Midwest agroecosystems with sufficient precipitation in the spring.

4.2 The impact of tile drainage on hydrology

Our results demonstrate that tile drainage has a pronounced impact on field hydrological cycles, influencing both water storage and water fluxes (Fig. 14). Overall, tile drainage functions as an efficient conduit for expediting subsurface water drainage (Gramlich et al., 2018; Miller and Lyon, 2021; Pluer et al., 2020; Schilling et al., 2012), directly contributing to an increase in subsurface discharge (Fig. 7). Concurrently, tile drainage leads to a reduction in soil water content (Fig. S11). Besides, we

found that precipitation alone cannot sustain both tile flow and field evapotranspiration, and recharge from an external source is required to close the system water balance at the study site (Fig. S21). Our model indicates that tile drainage increases the subsurface recharge (Fig. 7), and tile drainage has a limited impact on surface runoff at our study sites (Fig. 7). Though the model predicted less soil water content under tile conditions, the topsoil layer might be more affected by soil atmospheric interaction and the soil water content there is similar (Fig. S13). The infiltration rate is largely affected by the soil water content in the top soil layer, which might account for the similar surface runoff in tile and undrained conditions. Our simplified 1-D column representation of the field limits surface water holding capacity, which might in turn diminish the perceived role of tile drainage in managing surface water. We also acknowledge that we currently do not consider the macropores that directly connect tile drainage with surface soil, which might underestimate the effects of tile drainage on surface runoff (Askar et al., 2020; Williams et al., 2023). We found that tile drainage does not significantly change annual ET in the study site, similar to some previous studies (Khand et al., 2017; Yang et al., 2017).

The impact of tile drainage on the hydrological cycle exhibits a seasonality, coinciding with the seasonality of climate and crop phenology. Tile drainage actively functions from May to June, corresponding to high precipitation in this period, and tile drainage significantly increases the subsurface discharge (Fig. 6 and 8). In summer, crops actively draw water from the soil, which reduces soil water content. High ET, coupled with reduced soil water storage under tile conditions, results in an increase in subsurface recharge (Fig. 8). Tile drainage slightly increases ET during the peak growing seasons, which is balanced by the decrease in the early growing season. In the early growing season, soil evaporation might be reduced due to the reduction of soil water content under tile conditions (Yang et al., 2017). In summer, crop transpiration dominates the total evapotranspiration (Paul-Limoges et al., 2022; Song et al., 2018), and higher crop productivity under tile conditions (Fig. 11) would increase ET in the peak growing season (Beer et al., 2009; Guerrieri et al., 2016; Yang et al., 2017). The hydrological and crop phenological seasonality has informed the design of the controlled drainage and subirrigation system. Specifically, excessive water was removed in wet Springs, and retained in dry Summers and the non-growing season in controlled drainage (Helmers et al., 2022). With an irrigation system, the removed water can be cycled and irrigate the field crop in summers with less precipitation (Singh et al., 2022).

4.3 The impact of tile drainage on biogeochemistry

The impacts of tile drainage on hydrology further lead to downstream ramifications for soil biogeochemistry (Fig. 14). Tile drainage has long been recognized as a major contributor to nitrate exporting from agricultural landscapes (David et al., 1997, 2010). Results here similarly suggest that tile drainage increases subsurface inorganic nitrogen loss by 28.5%, accompanied by a 29.6% increase of subsurface discharge in water partitioning at the study site (Fig. 7 and 9). Furthermore, the impact of tile drainage on nitrogen loss exhibits a seasonal variation, mirroring the seasonality in water partitioning, with a more pronounced increase in the early growing season, corresponding to high tile flow (Fig. 6 and 9) (Ma et al., 2023; Williams et

al., 2015). The reduction of soil water content under tile conditions also leads to an increase in soil oxygen concentration, which subsequently promotes soil microbe activities (Linn and Doran, 1984), indicated by higher heterotrophic respiration (Fig. 10b). The elevated soil oxygen content also hastens both the mineralization and immobilization (Castellano et al., 2019; Randall and Mulla, 2001), ultimately increasing the net mineralization (Fig. 10a). The increased net mineralization compensates for the decreased soil inorganic nitrogen through subsurface loss.

4.4 The impact of tile drainage on crop growth

The impacts of tile drainage through hydrology and biogeochemistry on crop growth and yield are intricate and multifaceted. Tile drainage reduces soil water content, which may limit crop water availability while reducing crop oxygen stress (Fig. 11). The increased inorganic nitrogen loss by tile drainage reduces the soil inorganic nitrogen content, while the increased net mineralization, contradictorily, increases the soil inorganic nitrogen content (Fig. 9 and 10). They, together, might also alter the temporal variation of soil inorganic nitrogen content (Castellano et al., 2019; Drinkwater and Snapp, 2007). Crops and soil microbe communities can also adapt to environmental changes (Fan et al., 2017; Waldrop and Firestone, 2006). As a result, the intricate interplay between tile drainage, hydrology, biogeochemistry, and crop responses can collectively exert a significant influence on crop growth. Also, the intricate interactions are likely to change with environmental variations and make it challenging to gain a full understanding of their impacts on crop growth.

Here we use the root system as a proxy to understand the tile drainage's impact on crop growth, as crop roots are the key mediator between soil hydrological and biogeochemical changes and crop growth (Hodge, 2004; Hodge et al., 2009; Jochen Schenk, 2005; Wang et al., 2021). In wet springs, tile drainage alleviates crop oxygen stress by reducing soil water content and elevating soil oxygen concentration (Fig. 11 and 13), which guarantees the early growth of both the root system and the above-ground part of the crop under excessive precipitation. Deeper and denser root systems are observed under tile drainage conditions (Fig. 11), which further benefits the crop water and nutrient uptake (Ebrahimi-Mollabashi et al., 2019). Further, we observed that the developed root system also helped to reduce water stress in the dry summer, potentially due to accessibility to water in deep soil with a developed root system (Fig. 11f-j). The lower oxygen stress and developed root system together benefit crop growth (Fig. 14). The findings are consistent with previous field and greenhouse studies showing shallower root development under waterlogged conditions and high water tables (Ebrahimi-Mollabashi et al., 2019; Follett et al., 1974; Ordóñez et al., 2018; Ren et al., 2016). This modeling study also provides valuable insights into these complex and difficult-to-observe processes and provides a reference for future field investigations.

In summary, our study reveals that tile drainage significantly enhances the production of both corn and soybeans at the study site that has abundant precipitation in the spring. Firstly, tile drainage proves beneficial for crop yield by directly mitigating crop oxygen stress during wet years (Fig. 11 and S14). Secondly, the crop with better developed roots under tile conditions

would have a better ability to absorb soil water and thus reduce crop water stress and benefit crop yield (Fig. 11). Lastly, our hypothetical numerical experiments indicate that the yield benefit of tile drainage amplifies with increasing precipitation across various amounts (Fig. 12).

4.5 The implications of tile drainage for climate change adaptation

Our results at the study site indicate that tile drainage might be a valuable adaptation strategy to enhance agricultural production under climate change. Our results at the study site have demonstrated that tile drainage has the potential to increase crop yield under excessive precipitation conditions (Fig. 11, 12, and S14), and it might play a more critical role in sustaining high crop yields in the future, especially given the projected increase in spring precipitation and the likelihood of more intense precipitation events in the US Midwest (Seneviratne et al., 2022; Zhou et al., 2022b). Furthermore, our results suggest that tile drainage enhances yield stability under different precipitation amounts (Fig. S18), which implies that tile drainage might also help mitigate the risks associated with variable weather conditions, especially the excessive precipitation conditions. Our results also reveal that tile drainage has the potential to sustain a high crop yield under a projected increase in summer drought due to the better developed root systems under tile drainage conditions (Fig. 11) (Zhou et al., 2022b). While tile drainage benefits crop yield in a severe drought (2013), the crop still faces high water stress, resulting in a relatively low yield (Fig. 12 and S13). We advocate other approaches to sustain high crop yield with increasing summer drought risks, for instance, subirrigation systems and control drainage systems (Singh et al., 2022; Youssef et al., 2023).

However, tile drainage also poses threats to downstream water quality under climate change. Tile drainage increases the nitrogen loss to freshwater systems and, ultimately, coastal regions, degrading downstream and coastal water quality (David et al., 2010; Ma et al., 2023). Under climate change, the increased spring precipitation may flush more nitrogen through tile drainage (Fig. S12), further burdening impaired water systems (Jiang et al., 2020; Sinha et al., 2017; Wang et al., 2015). Recent initiatives are focused on mitigating nitrate loading in tile-drained systems through within-field management practices (e.g., improved fertilizer management and cover crops) and edge-of-field practices (e.g., controlled drainage, saturated buffers, woodchip bioreactors, and subirrigation systems) (Mitchell et al., 2023; USDA NRCS, 2017, 2023). While many studies suggest promising outcomes of these conservation practices in terms of reducing nitrogen loss and enhancing other ecosystem services, debates persist on their effectiveness for controlling nutrient loss under different environments and socioeconomic feasibility for a broad adoption (Frankenberger et al., 2023; Mitchell et al., 2023). For instance, the controlled drainage, involving a water control structure at the tile drainage system outlet, holds water in the field when drainage is unnecessary, which may help reduce nitrogen loss and potentially provide yield benefits under dry conditions (Delbecq et al., 2012; Ghane et al., 2012; Singh and Nelson, 2021; Youssef et al., 2023). Controlled drainage could potentially enhance yield with more available water in such cases. Nevertheless, existing study shows that controlled drainage might have negative impacts on yield during wet seasons (Youssef et al., 2023). Moreover, the efficacy of controlled drainage in reducing nitrogen loads

remains highly uncertain (Mitchell et al., 2023; Ross et al., 2016; Shedekar et al., 2021). While controlled drainage directly reduces nitrogen loading by retaining water, uncertainties arise as the retained water and nitrogen may exit the system through other pathways, such as surface/subsurface runoff, adjacent tile systems, or deep percolation (Lavaire et al., 2017; Ross et al., 2016; Shedekar et al., 2021). Furthermore, higher financial costs for the control structure installation also prevent its adoption by farmers and landowners. Similar issues of high uncertainty and additional financial costs are faced by other practices aiming to reduce nitrogen loading. Consequently, more research is needed to comprehensively understand the impacts of conservation practices on agricultural productivity, nutrient loss reduction, and other ecosystem services as well as their tradeoffs and balance in the context of climate change mitigation and adaptation in tile-drained agricultural ecosystems.

5. Conclusions

In this study, we used a process-based model to evaluate the impact of tile drainage on the coupled hydrology, biogeochemistry, and crop system. Our results reveal that soil oxygen dynamics are the key emergent property and central mediator that links the physical alterations in hydrology to the profound responses in biogeochemical cycles and crop growth in tile-drained systems. Specifically, crop oxygen stress in the root system emerges as the competition between the crop oxygen demand and the soil oxygen supply, governed by oxygen transport, phase changes, and biological consumption mechanisms in the model. Tile drainage influences the system firstly by altering water fluxes and storage, which subsequently changes soil aeration and further regulates crop oxygen stress. Its impacts on the root zone further cascade to the whole crop system through the tightly coupled soil-crop-atmosphere processes. Meanwhile, biological oxygen consumption also drives the change of soil biogeochemistry processes and further affects crop growth. The model performance is validated with field crop yield data and tile flow observation. We systematically compared model simulations under both tile-drained and undrained conditions to quantitatively evaluate the influence of tile drainage on hydrology, biogeochemistry, and crop growth of the agroecosystem. Further, through a series of numerical experiments, we revealed the pivotal role of tile drainage in the face of climate change, considering various precipitation scenarios.

- *The impact of tile drainage on hydrology:* We found that tile drainage firstly modifies the hydrological cycles, influencing both water storage and water fluxes. At the study site, our results reveal that tile drainage reduces soil water content, and increases annual subsurface discharge and subsurface recharge, while it does not significantly change surface runoff and ET. Those impacts on hydrology exhibit a seasonality, controlled by the seasonality of climate and crop phenology. Specifically, tile drainage mainly increases subsurface discharge when there is high precipitation or low ET and increases subsurface recharge when crops actively transpire water from the soil.

- *The impact of tile drainage on soil biogeochemistry:* The changes in hydrology further propagate through the agroecosystem, instigating ramifications within the biogeochemical cycles. Specifically, tile drainage increases subsurface nitrogen leaching with the increase of subsurface discharge. Tile drainage also elevates soil oxygen content, as fewer soil pores are occupied by water. The elevated soil oxygen content further increases soil net mineralization.

- *The impact of tile drainage on crop growth and its implications under climate change:* Those changes in hydrology and biogeochemistry substantially benefit crop growth under both wet springs and dry summers. High soil oxygen concentration under tile-drained conditions provides an aeration condition that mitigates crop oxygen stress, promoting robust root development and overall crop growth in wet springs. The developed root system also enhances crop resilience to summer drought. We also found that the yield benefit of tile drainage increases with the increase of precipitation and higher crop resilience to precipitation variation under tile drainage conditions.

In conclusion, this study reveals the underlying causal mechanisms that drive agroecosystem response to drainage on hydrology, biogeochemistry, crop growth, and their interconnections with oxygen dynamics as the key mediator. Our study also highlights tile drainage as a promising and adaptable climate change adaptation and mitigation strategy with the potential to enhance agricultural resilience in the U.S. Midwest agroecosystems.

Code/Data availability

Ecosys can be freely downloaded from GitHub (https://github.com/jinyun1tang/ECOSYS). Field experiment data can be freely accessed via a website at Iowa State University (https://datateam.agron.iastate.edu/td/). The meteorological variables from the North American Land Data Assimilation System (NLDAS-2) can be freely accessed from https://ldas.gsfc.nasa.gov/nldas/v2/forcing. The soil information from the Gridded Soil Survey Geographic Database (gSSURGO) data sets can be freely accessed from https://data.nal.usda.gov/dataset/gridded-soil-survey-geographic-database-gssurgo.

Author contribution

ZWM: conceptualization, investigation, methodology, software, writing – original draft, writing – review and editing. KYG, PB: methodology, writing – original draft, writing – review and editing. WZ, RG, MS: conceptualization, methodology, writing – review and editing, validation, supervision. JYT, MP, LL, ZNJ: supervision and review.

Competing interests

The authors declare that they have no conflict of interest.

Acknowledgments

The authors acknowledge the financial support from NSF CAREER Award managed by NSF Environmental Sustainability Program (Award # 1847334), the USDA NIFA program and the Foundation for Food & Agriculture Research (FFAR) Seeding Solutions Award (Grant 602757). KYG, PB and ZWM are also funded by the DOE Center for Advanced Bioenergy and Bioproducts Innovation (CABBI), funded by U.S. Department of Energy, Office of Science, Office of Biological and Environmental Research under award no. DE-SC0018420. JYT was supported by the Director, Office of Science, Office of Biological and Environmental Research of the US Department of Energy under contract no. DE-AC02-05CH11231 as part of the Reducing Uncertainties in Biogeochemical Interactions through Synthesis and Computation (RUBISCO) Scientific Focus Area.

References

Adelsperger, S. R., Ficklin, D. L., and Robeson, S. M.: Tile drainage as a driver of streamflow flashiness in agricultural areas of the Midwest, USA, Hydrol. Process., 37, https://doi.org/10.1002/hyp.15021, 2023.

Ashraf, M. A.: Waterlogging stress in plants: A review, Afr. J. Agric. Res., 1976, 1981, 2012.

Askar, M. H., Youssef, M. A., Chescheir, G. M., Negm, L. M., King, K. W., Hesterberg, D. L., Amoozegar, A., and Skaggs, R. W.: DRAINMOD Simulation of macropore flow at subsurface drained agricultural fields: Model modification and field testing, Agric. Water Manage., 242, 106401, 2020.

Bailey, R. T., Bieger, K., Flores, L., and Tomer, M.: Evaluating the contribution of subsurface drainage to watershed water yield using SWAT+ with groundwater modeling, Sci. Total Environ., 802, 149962, 2022.

Beer, C., Ciais, P., Reichstein, M., Baldocchi, D., Law, B. E., Papale, D., Soussana, J.-F., Ammann, C., Buchmann, N., Frank, D., Gianelle, D., Janssens, I. A., Knohl, A., Köstner, B., Moors, E., Roupsard, O., Verbeeck, H., Vesala, T., Williams, C. A., and Wohlfahrt, G.: Temporal and among-site variability of inherent water use efficiency at the ecosystem level, Global Biogeochem. Cycles, 23, https://doi.org/10.1029/2008gb003233, 2009.

Blann, K. L., Anderson, J. L., Sands, G. R., and Vondracek, B.: Effects of Agricultural Drainage on Aquatic Ecosystems: A Review, Crit. Rev. Environ. Sci. Technol., 39, 909–1001, 2009.

Boland-Brien, S. J., Basu, N. B., and Schilling, K. E.: Homogenization of spatial patterns of hydrologic response in artificially drained agricultural catchments, Hydrol. Process., 28, 5010–5020, 2014.

Bresler, E.: Simultaneous transport of solutes and water under transient unsaturated flow conditions, Water Resources Research, 9, 975–986, 1973.

Brown, R. L., Hangs, R., Schoenau, J., and Bedard-Haughn, A.: Soil nitrogen and phosphorus dynamics and uptake by wheat grown in drained prairie soils under three moisture scenarios, Soil Sci. Soc. Am. J., 81, 1496–1504, 2017.

Cain, M. R., Woo, D. K., Kumar, P., Keefer, L., and Ward, A. S.: Antecedent conditions control thresholds of tile-runoff generation and nitrogen export in intensively managed landscapes, Water Resour. Res., 58, https://doi.org/10.1029/2021wr030507, 2022.

Castellano, M. J., Archontoulis, S. V., Helmers, M. J., Poffenbarger, H. J., and Six, J.: Sustainable intensification of agricultural drainage, Nature Sustainability, 2, 914–921, 2019.

Chighladze, G., Abendroth, L. J., Herzmann, D., Helmers, M., Ahiablame, L., Allred, B., Bowling, L., Brown, L., Fausey, N., Frankenberger, J., and Others: Transforming Drainage Research Data (USDA-NIFA Award No. 2015-68007-23193), National Agricultural Library--ARS--USDA, 2021.

David, M. B., Gentry, L. E., Kovacic, D. A., and Smith, K. M.: Nitrogen balance in and export from an agricultural watershed, J. Environ. Qual., 26, 1038–1048, 1997.

David, M. B., Drinkwater, L. E., and McIsaac, G. F.: Sources of nitrate yields in the Mississippi River Basin, J. Environ. Qual., 39, 1657–1667, 2010.

Delbecq, B. A., Brown, J. P., Florax, R. J. G. M., Kladivko, E. J., Nistor, A. P., and Lowenberg-DeBoer, J. M.: The impact of drainage water management technology on corn yields, Agron. J., 104, 1100–1109, 2012.

De Schepper, G. and Therrien, R.: Simulating seasonal variations of tile drainage discharge in an agricultural catchment, Resources Research, https://doi.org/10.1002/2016WR020209, 2017.

Drinkwater, L. E. and Snapp, S. S.: Nutrients in Agroecosystems: Rethinking the Management Paradigm, in: Advances in Agronomy, vol. 92, edited by: Sparks, D. L., Academic Press, 163–186, 2007.

Ebrahimi-Mollabashi, E., Huth, N. I., Holzwoth, D. P., Ordóñez, R. A., Hatfield, J. L., Huber, I., Castellano, M. J., and Archontoulis, S. V.: Enhancing APSIM to simulate excessive moisture effects on root growth, Field Crops Res., 236, 58–67, 2019.

Elzenga, J. T. M. and van Veen, H.: Waterlogging and Plant Nutrient Uptake, in: Waterlogging Signalling and Tolerance in Plants, edited by: Mancuso, S. and Shabala, S., Springer Berlin Heidelberg, Berlin, Heidelberg, 23–35, 2010.

Fan, Y., Miguez-Macho, G., Jobbágy, E. G., Jackson, R. B., and Otero-Casal, C.: Hydrologic regulation of plant rooting depth, Proc. Natl. Acad. Sci. U. S. A., 114, 10572–10577, 2017.

Feddes, R., Kowalik, P., and Zaradny, H.: Simulation of field water use and crop yield, https://www.semanticscholar.org › paper › Simulation-of...https://www.semanticscholar.org › paper › Simulation-of..., 1978.

Feddes, R. A., Hoff, H., Bruen, M., Dawson, T., de Rosnay, P., Dirmeyer, P., Jackson, R. B., Kabat, P., Kleidon, A., Lilly, A., and Pitman, A. J.: Modeling Root Water Uptake in Hydrological and Climate Models, Bull. Am. Meteorol. Soc., 82, 2797–2810, 2001.

Follett, R. F., Allmaras, R. R., and Reichman, G. A.: Distribution of corn roots in sandy soil with a declining water table[1], Agron. J., 66, 288–292, 1974.

Frankenberger, J., McMillan, S. K., Williams, M. R., Mazer, K., Ross, J., and Sohngen, B.: Drainage water management: A review of nutrient load reductions and cost effectiveness, Journal of the ASABE, 0, 0, 2023.

Ghane, E., Fausey, N. R., Shedekar, V. S., Piepho, H. P., Shang, Y., and Brown, L. C.: Crop yield evaluation under controlled drainage in Ohio, United States, J. Soil Water Conserv., 67, 465–473, 2012.

Gramlich, A., Stoll, S., Stamm, C., Walter, T., and Prasuhn, V.: Effects of artificial land drainage on hydrology, nutrient and pesticide fluxes from agricultural fields--A review, Agric. Ecosyst. Environ., 266, 84–99, 2018.

Grant, R.: Simulation of competition between barley and wild oats under different managements and climates, Ecol. Modell., 71, 269–287, 1994.

Grant, R.: A Review of the Canadian Ecosystem Model — ecosys, https://doi.org/10.1201/9781420032635.ch6, 2001.

Grant, R. F.: Simulation model of soil compaction and root growth, Plant Soil, 150, 1–14, 1993.

Grant, R. F.: Simulation in ecosys of root growth response to contrasting soil water and nitrogen, Ecol. Modell., 107, 237–264, 1998.

Grant, R. F. and Pattey, E.: Mathematical modeling of nitrous oxide emissions from an agricultural field during spring thaw, Global Biogeochemical Cycles, 13, 679–694, 1999.

Grant, R. F., Juma, N. G., and McGill, W. B.: Simulation of carbon and nitrogen transformations in soil: microbial biomass and metabolic products, Soil Biol. Biochem., 1993a.

Grant, R. F., Juma, N. G., and McGill, W. B.: Simulation of carbon and nitrogen transformations in soil: Mineralization, Soil Biol. Biochem., 25, 1317–1329, 1993b.

Grant, R. F., Mekonnen, Z. A., Riley, W. J., Wainwright, H. M., Graham, D., and Torn, M. S.: Mathematical modelling of arctic polygonal tundra with *ecosys*: 1. Microtopography determines how active layer depths respond to changes in temperature and precipitation: Active layer depth in polygonal tundra, J. Geophys. Res. Biogeosci., 122, 3161–3173, 2017.

Grant, R. F., Wall, G. W., Kimball, B. A., Frumau, K. F. A., Pinter, P. J., Jr, Hunsaker, D. J., and Lamorte, R. L.: Crop water relations under different CO2 and irrigation: testing of ecosys with the free air CO2 enrichment (FACE) experiment, Agric. For. Meteorol., 95, 27–51, 1999.

Grenon, G., Singh, B., De Sena, A., Madramootoo, C. A., von Sperber, C., Goyal, M. K., and Zhang, T.: Phosphorus fate, transport and management on subsurface drained agricultural organic soils: a review, Environ. Res. Lett., 16, 013004, 2021.

Guerrieri, R., Lepine, L., Asbjornsen, H., Xiao, J., and Ollinger, S. V.: Evapotranspiration and water use efficiency in relation to climate and canopy nitrogen in U.S. forests, J. Geophys. Res. Biogeosci., 121, 2610–2629, 2016.

Hammond, G. E., Lichtner, P. C., and Mills, R. T.: Evaluating the performance of parallel subsurface simulators: An illustrative example with PFLOTRAN, Water Resour. Res., 50, 208–228, 2014.

Hanrahan, B. R., King, K. W., Macrae, M. L., Williams, M. R., and Stinner, J. H.: Among-site variability in environmental and management characteristics: Effect on nutrient loss in agricultural tile drainage, J. Great Lakes Res., 46, 486–499, 2020.

Hansen, A. L., Refsgaard, J. C., Christensen, B. S. B., and Jensen, K. H.: Importance of including small-scale tile drain discharge in the calibration of a coupled groundwater-surface water catchment model, Water Resour. Res., 49, 585–603, 2013.

Helmers, M. J., Abendroth, L., Reinhart, B., Chighladze, G., Pease, L., Bowling, L., Youssef, M., Ghane, E., Ahiablame, L., Brown, L., Fausey, N., Frankenberger, J., Jaynes, D., King, K., Kladivko, E., Nelson, K., and Strock, J.: Impact of controlled drainage on subsurface drain flow and nitrate load: A synthesis of studies across the U.S. Midwest and Southeast, Agric. Water Manag., 259, 107265, 2022.

Hodge, A.: The plastic plant: root responses to heterogeneous supplies of nutrients, New Phytol., 162, 9–24, 2004.

Hodge, A., Berta, G., Doussan, C., Merchan, F., and Crespi, M.: Plant root growth, architecture and function, Plant Soil, 321, 153–187, 2009.

Hoffman, F. M., Koven, C. D., Keppel-Aleks, G., Lawrence, D. M., Riley, W. J., Randerson, J. T., Ahlström, A., Abramowitz, G., Baldocchi, D. D., Best, M. J., Bond-Lamberty, B., De Kauwe, M. G., Denning, A. S., Desai, A. R., Eyring, V., Fisher, J. B., Fisher, R. A., Gleckler, P. J., Huang, M., Hugelius, G., Jain, A. K., Kiang, N. Y., Kim, H., Koster, R. D., Kumar, S. V., Li, H., Luo, Y., Mao, J., McDowell, N. G., Mishra, U., Moorcroft, P. R., Pau, G. S. H., Ricciuto, D. M., Schaefer, K., Schwalm, C. R., Serbin, S. P., Shevliakova, E., Slater, A. G., Tang, J., Williams, M., Xia, J., Xu, C., Joseph, R., and Koch, D.: 2016 International Land Model Benchmarking (ILAMB) Workshop Report, USDOE Office of Science, Washington, DC (United States), https://doi.org/10.2172/1330803, 2017.

Horton, R. E.: The role of infiltration in the hydrologic cycle, Eos, Transactions American Geophysical Union, 14, 446–460, 1933.

Ivanov, V. Y., Bras, R. L., and Curtis, D. C.: A weather generator for hydrological, ecological, and agricultural applications, Water Resour. Res., 43, https://doi.org/10.1029/2006wr005364, 2007.

Jacinthe, P. A., Vidon, P., Fisher, K., Liu, X., and Baker, M. E.: Soil Methane and Carbon Dioxide Fluxes from Cropland and Riparian Buffers in Different Hydrogeomorphic Settings, J. Environ. Qual., 44, 1080–1090, 2015.

J. G. Arnold, D. N. Moriasi, P. W. Gassman, K. C. Abbaspour, M. J. White, R. Srinivasan, C. Santhi, R. D. Harmel, A. van Griensven, M. W. Van Liew, N. Kannan, and M. K. Jha: SWAT: Model use, calibration, and validation, Trans. ASABE, 55, 1491–1508, 2012.

Jiang, Q., Qi, Z., Xue, L., Bukovsky, M., Madramootoo, C. A., and Smith, W.: Assessing climate change impacts on greenhouse gas emissions, N losses in drainage and crop production in a subsurface drained field, Sci. Total Environ., 705, 135969, 2020.

Jin, W., Aufrecht, J., Patino-Ramirez, F., Cabral, H., Arson, C., and Retterer, S. T.: Modeling root system growth around obstacles, Sci. Rep., 10, 15868, 2020.

Jochen Schenk, H.: Vertical Vegetation Structure Below Ground: Scaling from Root to Globe, in: Progress in Botany: Genetics Physiology Systematics Ecology, edited by: Esser, K., Lüttge, U., Beyschlag, W., and Murata, J., Springer Berlin Heidelberg, Berlin, Heidelberg, 341–373, 2005.

Jones, J. W., Antle, J. M., Basso, B., Boote, K. J., Conant, R. T., Foster, I., Godfray, H. C. J., Herrero, M., Howitt, R. E., Janssen, S., Keating, B. A., Munoz-Carpena, R., Porter, C. H., Rosenzweig, C., and Wheeler, T. R.: Brief history of agricultural systems modeling, Agric. Syst., 155, 240–254, 2017.

Kalita, P. K., Cooke, R. A. C., Anderson, S. M., Hirschi, M. C., and Mitchell, J. K.: Subsurface drainage and water quality: The Illinois experience, Transactions of the ASABE, 50, 1651–1656, 2007.

Kemper, W. D. and Rollins, J. B.: Osmotic efficiency coefficients across compacted clays, Soil Sci. Soc. Am. J., 30, 529–534, 1966.

Khand, K., Kjaersgaard, J., Hay, C., and Jia, X.: Estimating Impacts of Agricultural Subsurface Drainage on Evapotranspiration Using the Landsat Imagery-Based METRIC Model, Hydrology, 4, 49, 2017.

Kucharik, C. J.: Contribution of planting date trends to increased maize yields in the central United States, Agron. J., 100, 328–336, 2008.

Kumar, S., Nakajima, T., Kadono, A., Lal, R., and Fausey, N.: Long-term tillage and drainage influences on greenhouse gas fluxes from a poorly drained soil of central Ohio, J. Soil Water Conserv., 69, 553–563, 2014.

Lam, W. V., Macrae, M. L., English, M. C., O'Halloran, I. P., Plach, J. M., and Wang, Y.: Seasonal and event-based drivers of runoff and phosphorus export through agricultural tile drains under sandy loam soil in a cool temperate region, Hydrol. Process., 30, 2644–2656, 2016.

Lavaire, T., Gentry, L. E., David, M. B., and Cooke, R. A.: Fate of water and nitrate using drainage water management on tile systems in east-central Illinois, Agric. Water Manage., 191, 218–228, 2017.

Lesk, C., Rowhani, P., and Ramankutty, N.: Influence of extreme weather disasters on global crop production, Nature, 529, 84–87, 2016.

Li, H., Sivapalan, M., Tian, F., and Liu, D.: Water and nutrient balances in a large tile-drained agricultural catchment: a distributed modeling study, Hydrol. Earth Syst. Sci., 14, 2259–2275, 2010.

Li, L., Maher, K., Navarre-Sitchler, A., Druhan, J., and Meile, C.: Expanding the role of reactive transport models in critical zone processes, Earth-Sci. Rev., 2017.

Li, L., Sullivan, P. L., Benettin, P., Cirpka, O. A., Bishop, K., Brantley, S. L., Knapp, J. L. A., Meerveld, I., Rinaldo, A., Seibert, J., Wen, H., and Kirchner, J. W.: Toward catchment hydro-biogeochemical theories, WIREs Water, 8, https://doi.org/10.1002/wat2.1495, 2021.

Linn, D. M. and Doran, J. W.: Effect of water-filled pore space on carbon dioxide and nitrous oxide production in tilled and nontilled soils, Soil Sci. Soc. Am. J., 48, 1267–1272, 1984.

Liu, K., Harrison, M. T., Shabala, S., Meinke, H., Ahmed, I., Zhang, Y., Tian, X., and Zhou, M.: The state of the art in modeling waterlogging impacts on plants: What do we know and what do we need to know, Earths Future, 8, https://doi.org/10.1029/2020ef001801, 2020a.

Liu, K., Harrison, M. T., Shabala, S., Meinke, H., Ahmed, I., Zhang, Y., Tian, X., and Zhou, M.: The state of the art in modeling waterlogging impacts on plants: What do we know and what do we need to know, Earths Future, 8, https://doi.org/10.1029/2020ef001801, 2020b.

Li, Y., Guan, K., Yu, A., Peng, B., Zhao, L., Li, B., and Peng, J.: Toward building a transparent statistical model for improving crop yield prediction: Modeling rainfed corn in the U.S, Field Crops Res., 234, 55–65, 2019.

Li, Z., Guan, K., Zhou, W., Peng, B., Jin, Z., Tang, J., Grant, R. F., Nafziger, E. D., Margenot, A. J., Gentry, L. E., DeLucia, E. H., Yang, W. H., Cai, Y., Qin, Z., Archontoulis, S. V., Fernández, F. G., Yu, Z., Lee, D., and Yang, Y.: Assessing the impacts of pre-growing-season weather conditions on soil nitrogen dynamics and corn productivity in the U.S. Midwest, Field Crops Res., 284, 108563, 2022.

Lobell, D. B., Roberts, M. J., Schlenker, W., Braun, N., Little, B. B., Rejesus, R. M., and Hammer, G. L.: Greater sensitivity to drought accompanies maize yield increase in the U.S. Midwest, Science, 344, 516–519, 2014.

Macrae, M. L., English, M. C., Schiff, S. L., and Stone, M.: Intra-annual variability in the contribution of tile drains to basin discharge and phosphorus export in a first-order agricultural catchment, Agric. Water Manage., 92, 171–182, 2007.

Ma, Z., Guan, K., Peng, B., Sivapalan, M., Li, L., Pan, M., Zhou, W., Warner, R., and Zhang, J.: Agricultural nitrate export patterns shaped by crop rotation and tile drainage, Water Res., 229, 119468, 2023.

Mezbahuddin, M., Grant, R. F., and Flanagan, L. B.: Modeling hydrological controls on variations in peat water content, water table depth, and surface energy exchange of a boreal western Canadian fen peatland, Journal of Geophysical Research: Biogeosciences, https://doi.org/10.1002/2016JG003501, 2016.

Miller, S. A. and Lyon, S. W.: Tile drainage causes flashy streamflow response in Ohio watersheds, Hydrol. Process., 35, https://doi.org/10.1002/hyp.14326, 2021.

Mitchell, M. E., Newcomer-Johnson, T., Christensen, J., Crumpton, W., Dyson, B., Canfield, T. J., Helmers, M., and Forshay, K. J.: A review of ecosystem services from edge-of-field practices in tile-drained agricultural systems in the United States Corn Belt Region, J. Environ. Manage., 348, 119220, 2023.

Moore, J.: Literature review: tile drainage and phosphorus losses from agricultural land, Lake Champlain Basin Program, 2016.

Muma, M., Rousseau, A. N., and Gumiere, S. J.: Modeling of subsurface agricultural drainage using two hydrological models with different conceptual approaches as well as dimensions and spatial scales, Canadian Water Resources Journal / Revue canadienne des ressources hydriques, 42, 38–53, 2017.

Nanda, A. and Safeeq, M.: Threshold controlling runoff generation mechanisms in Mediterranean headwater catchments, J. Hydrol., 620, 129532, 2023.

NASS-USDA: 2017 Census of Agriculture, 2017.

Nóia Júnior, R. de S., Asseng, S., García-Vila, M., Liu, K., Stocca, V., dos Santos Vianna, M., Weber, T. K. D., Zhao, J., Palosuo, T., and Harrison, M. T.: A call to action for global research on the implications of waterlogging for wheat growth and yield, Agric. Water Manage., 284, 108334, 2023.

Ordóñez, R. A., Castellano, M. J., Hatfield, J. L., Helmers, M. J., Licht, M. A., Liebman, M., Dietzel, R., Martinez-Feria, R., Iqbal, J., Puntel, L. A., Córdova, S. C., Togliatti, K., Wright, E. E., and Archontoulis, S. V.: Maize and soybean root front velocity and maximum depth in Iowa, USA, Field Crops Res., 215, 122–131, 2018.

Pan, J., Sharif, R., Xu, X., and Chen, X.: Mechanisms of Waterlogging Tolerance in Plants: Research Progress and Prospects, Front. Plant Sci., 11, 627331, 2020.

Pasley, H. R., Huber, I., Castellano, M. J., and Archontoulis, S. V.: Modeling Flood-Induced Stress in Soybeans, Front. Plant Sci., 11, 62, 2020.

Paul-Limoges, E., Revill, A., Maier, R., Buchmann, N., and Damm, A.: Insights for the partitioning of ecosystem evaporation and transpiration in short-statured croplands, J. Geophys. Res. Biogeosci., 127, https://doi.org/10.1029/2021jg006760, 2022.

Pluer, W. T., Macrae, M., Buckley, A., and Reid, K.: Contribution of preferential flow to tile drainage varies spatially and temporally, Vadose Zone J., 19, https://doi.org/10.1002/vzj2.20043, 2020.

Qin, Z., Guan, K., Zhou, W., Peng, B., Villamil, M. B., Jin, Z., Tang, J., Grant, R., Gentry, L., Margenot, A. J., Bollero, G., and Li, Z.: Assessing the impacts of cover crops on maize and soybean yield in the U.S. Midwestern agroecosystems, Field Crops Res., 273, 108264, 2021.

Rahman, M. M., Lin, Z., Jia, X., Steele, D. D., and DeSutter, T. M.: Impact of subsurface drainage on streamflows in the Red River of the North basin, J. Hydrol., 511, 474–483, 2014.

Randall, G. W. and Mulla, D. J.: Nitrate nitrogen in surface waters as influenced by climatic conditions and agricultural practices, J. Environ. Qual., 30, 337–344, 2001.

Ren, B., Zhang, J., Dong, S., Liu, P., and Zhao, B.: Root and shoot responses of summer maize to waterlogging at different stages, Agron. J., 108, 1060–1069, 2016.

Ren, D., Engel, B., Mercado, J. A. V., Guo, T., Liu, Y., and Huang, G.: Modeling and assessing water and nutrient balances in a tile-drained agricultural watershed in the U.S. Corn Belt, Water Res., 210, 117976, 2022.

Ross, J. A., Herbert, M. E., Sowa, S. P., Frankenberger, J. R., King, K. W., Christopher, S. F., Tank, J. L., Arnold, J. G., White, M. J., and Yen, H.: A synthesis and comparative evaluation of factors influencing the effectiveness of drainage water management, Agric. Water Manage., 178, 366–376, 2016.

Rubol, S., Manzoni, S., Bellin, A., and Porporato, A.: Modeling soil moisture and oxygen effects on soil biogeochemical cycles including dissimilatory nitrate reduction to ammonium (DNRA), Adv. Water Resour., 62, 106–124, 2013.

Rumph Frederiksen, R. and Molina-Navarro, E.: The importance of subsurface drainage on model performance and water balance in an agricultural catchment using SWAT and SWAT-MODFLOW, Agric. Water Manage., 255, 107058, 2021.

R. W. Skaggs, M. A. Youssef, and G. M. Chescheir: DRAINMOD: Model use, calibration, and validation, Trans. ASABE, 55, 1509–1522, 2012.

Schenk, H. J. and Jackson, R. B.: Mapping the global distribution of deep roots in relation to climate and soil characteristics, Geoderma, 126, 129–140, 2005.

Schilling, K. E. and Helmers, M.: Effects of subsurface drainage tiles on streamflow in Iowa agricultural watersheds: Exploratory hydrograph analysis, Hydrol. Process., 22, 4497–4506, 2008.

Schilling, K. E., Jindal, P., Basu, N. B., and Helmers, M. J.: Impact of artificial subsurface drainage on groundwater travel times and baseflow discharge in an agricultural watershed, Iowa (USA), Hydrol. Process., 26, 3092–3100, 2012.

Schmidhuber, J. and Tubiello, F. N.: Global food security under climate change, Proc. Natl. Acad. Sci. U. S. A., 104, 19703–19708, 2007.

Seneviratne, S. I., Adnan, M., Badi, W., Dereczynski, C., Luca, A. D., Ghosh, S., Iskandar, I., Kossin, J., Lewis, S., Otto, F., Pinto, I., Satoh, M., Vicente-Serrano, S. M., Wehner, M., and Zhou, B.: Weather and climate extreme events in a changing climate, Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, 1513–1766, 2022.

Sharpley, A. N.: EPIC-erosion/productivity impact calculator : 1, model documentation, USDA Techn. Bull. 1759, 235, 1990.

Shedekar, V. S., King, K. W., Fausey, N. R., Islam, K. R., Soboyejo, A. B. O., Kalcic, M. M., and Brown, L. C.: Exploring the effectiveness of drainage water management on water budgets and nitrate loss using three evaluation approaches, Agric. Water Manage., 243, 106501, 2021.

Shen, C., Niu, J., and Phanikumar, M. S.: Evaluating controls on coupled hydrologic and vegetation dynamics in a humid continental climate watershed using a subsurface-land surface processes model, Water Resour. Res., 49, 2552–2572, 2013.

Shirzaei, M., Khoshmanesh, M., Ojha, C., Werth, S., Kerner, H., Carlson, G., Sherpa, S. F., Zhai, G., and Lee, J.-C.: Persistent impact of spring floods on crop loss in U.S. Midwest, Weather and Climate Extremes, 34, 100392, 2021.

Sims, J. T., Simard, R. R., and Joern, B. C.: Phosphorus loss in agricultural drainage: Historical perspective and current research, J. Environ. Qual., 27, 277–293, 1998.

Šimůnek, J. and Hopmans, J. W.: Modeling compensated root water and nutrient uptake, Ecol. Modell., 220, 505–521, 2009.

Singh, G. and Nelson, K. A.: Long-term drainage, subirrigation, and tile spacing effects on maize production, Field Crops Res., 262, 108032, 2021.

Singh, N., Kogan, C., Chaudhary, S., Rajagopalan, K., and LaHue, G. T.: Controlled drainage and subirrigation suitability in the United States: A meta-analysis of crop yield and soil moisture effects, Vadose Zone J., 21, https://doi.org/10.1002/vzj2.20219, 2022.

Sinha, E., Michalak, A. M., and Balaji, V.: Eutrophication will increase during the 21st century as a result of precipitation changes, Science, 357, 405–408, 2017.

Skaggs, R. W., Brevé, M. A., and Gilliam, J. W.: Hydrologic and water quality impacts of agricultural drainage∗, Crit. Rev. Environ. Sci. Technol., 24, 1–32, 1994.

Smith, W., Grant, B., Qi, Z., He, W., VanderZaag, A., Drury, C. F., and Helmers, M.: Development of the DNDC model to improve soil hydrology and incorporate mechanistic tile drainage: A comparative analysis with RZWQM2, Environmental Modelling & Software, 123, 104577, 2020.

Soil Survey Staff: Gridded Soil Survey Geographic (gSSURGO) Database for the Conterminous United States. United States Department of Agriculture, Natural Resources Conservation Service, 2023.

Song, L., Liu, S., Kustas, W. P., Nieto, H., Sun, L., Xu, Z., Skaggs, T. H., Yang, Y., Ma, M., Xu, T., Tang, X., and Li, Q.: Monitoring and validating spatially and temporally continuous daily evaporation and transpiration at river basin scale, Remote Sens. Environ., 219, 72–88, 2018.

Steudle, E.: THE COHESION-TENSION MECHANISM AND THE ACQUISITION OF WATER BY PLANT ROOTS, Annu. Rev. Plant Physiol. Plant Mol. Biol., 52, 847–875, 2001.

Stops, M. W., Sullivan, P. L., Peltier, E., Young, B., and Brookfield, A. E.: Tracking the hydrologic response of agricultural tile outlet terraces to storm events, Agric. Water Manage., 263, 107382, 2022.

Thomas, N. W., Arenas, A. A., Schilling, K. E., and Weber, L. J.: Numerical investigation of the spatial scale and time dependency of tile drainage contribution to stream flow, J. Hydrol., 538, 651–666, 2016.

Tromp-van Meerveld, H. J. and McDonnell, J. J.: Threshold relations in subsurface stormflow: 2. The fill and spill hypothesis, Water Resources Research, 42, https://doi.org/10.1029/2004WR003800, 2006.

USDA NRCS: Conservation Practice Standard: Saturated Riparian Buffers. Federal Register.604-CPS, 2017.

USDA NRCS: Conservation Practice Standard: Drainage Water Management. Federal Register.554-CPS, 2023.

Valayamkunnath, P., Barlage, M., Chen, F., Gochis, D. J., and Franz, K. J.: Mapping of 30-meter resolution tile-drained croplands using a geospatial modeling approach, Sci Data, 7, 257, 2020.

Valayamkunnath, P., Gochis, D. J., Chen, F., Barlage, M., and Franz, K. J.: Modeling the hydrologic influence of subsurface tile drainage using the national water model, Water Resour. Res., 58, https://doi.org/10.1029/2021wr031242, 2022.

Vrettas, M. D. and Fung, I. Y.: Sensitivity of transpiration to subsurface properties: Exploration with a 1-D model, Journal of Advances in Modeling Earth Systems, 9, 1030–1045, 2017.

Waldrop, M. P. and Firestone, M. K.: Response of microbial community composition and function to soil climate change, Microb. Ecol., 52, 716–724, 2006.

Wang, Z., Qi, Z., Xue, L., Bukovsky, M., and Helmers, M. J.: Modeling the impacts of climate change on nitrogen losses and crop yield in a subsurface drained field, Clim. Change, 129, 323–335, 2015.

Wang, Z., Timlin, D., Li, S., Fleisher, D., Dathe, A., Luo, C., Dong, L., Reddy, V. R., and Tully, K.: A diffusive model of maize root growth in MAIZSIM and its applications in Ridge-Furrow Rainfall Harvesting, Agric. Water Manag., 254, 106966, 2021.

Warren, J. M., Hanson, P. J., Iversen, C. M., Kumar, J., Walker, A. P., and Wullschleger, S. D.: Root structural and functional dynamics in terrestrial biosphere models--evaluation and recommendations, New Phytol., 205, 59–78, 2015.

Williams, M. R., King, K. W., and Fausey, N. R.: Contribution of tile drains to basin discharge and nitrogen export in a headwater agricultural watershed, Agric. Water Manage., 158, 42–50, 2015.

Williams, M. R., Penn, C. J., King, K. W., and McAfee, S. J.: Surface-to-tile drain connectivity and phosphorus transport: Effect of antecedent soil moisture, Hydrol. Process., 37, https://doi.org/10.1002/hyp.14831, 2023.

Wiskow, E. and van der Ploeg, R. R.: Calculation of drain spacings for optimal rainstorm flood control, J. Hydrol., 272, 163–174, 2003.

Woo, D. K. and Kumar, P.: Impacts of subsurface tile drainage on age—Concentration dynamics of inorganic nitrogen in soil, Water Resour. Res., https://doi.org/10.1029/2018WR024139, 2019.

Xia, Y., Mitchell, K., Ek, M., Sheffield, J., Cosgrove, B., Wood, E., Luo, L., Alonge, C., Wei, H., Meng, J., Livneh, B., Lettenmaier, D., Koren, V., Duan, Q., Mo, K., Fan, Y., and Mocko, D.: Continental-scale water and energy flux analysis and validation for the North American Land Data Assimilation System project phase 2 (NLDAS-2): 1. Intercomparison and application of model products, J. Geophys. Res., 117, https://doi.org/10.1029/2011jd016048, 2012.

Yang, Y., Anderson, M., Gao, F., Hain, C., Kustas, W., Meyers, T., Crow, W., Finocchiaro, R., Otkin, J., Sun, L., and Yang, Y.: Impact of Tile Drainage on Evapotranspiration in South Dakota, USA, Based on High Spatiotemporal Resolution Evapotranspiration Time Series From a Multisatellite Data Fusion System, IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing, 10, 2550–2564, 2017.

Yang, Y., Liu, L., Zhou, W., Guan, K., Tang, J., Kim, T., Grant, R. F., Peng, B., Zhu, P., Li, Z., Griffis, T. J., and Jin, Z.: Distinct driving mechanisms of non-growing season N2O emissions call for spatial-specific mitigation strategies in the US Midwest, Agric. For. Meteorol., 324, 109108, 2022.

Yimer, E. A., Riakhi, F.-E., Bailey, R. T., Nossent, J., and van Griensven, A.: The impact of extensive agricultural water drainage on the hydrology of the Kleine Nete watershed, Belgium, Sci. Total Environ., 885, 163903, 2023.

Youssef, M. A., Strock, J., Bagheri, E., Reinhart, B. D., Abendroth, L. J., Chighladze, G., Ghane, E., Shedekar, V., Fausey (Ret.), N. R., Frankenberger, J. R., Helmers, M. J., Jaynes (Ret.), D. B., Kladivko, E., Negm, L., Nelson, K., and Pease, L.: Impact of controlled drainage on corn yield under varying precipitation patterns: A synthesis of studies across the U.S. Midwest and Southeast, Agric. Water Manage., 275, 107993, 2023.

Zhang, J., Guan, K., Peng, B., Pan, M., Zhou, W., Jiang, C., Kimm, H., Franz, T. E., Grant, R. F., Yang, Y., Rudnick, D. R., Heeren, D. M., Suyker, A. E., Bauerle, W. L., and Miner, G. L.: Sustainable irrigation based on co-regulation of soil water supply and atmospheric evaporative demand, Nat. Commun., 12, 5549, 2021.

Zhou, W., Guan, K., Peng, B., Tang, J., Jin, Z., Jiang, C., Grant, R., and Mezbahuddin, S.: Quantifying carbon budget, crop yields and their responses to environmental variability using the ecosys model for U.S. Midwestern agroecosystems, Agric. For. Meteorol., 307, 108521, 2021.

Zhou, W., Ruby Leung, L., and Lu, J.: Seasonally Dependent Future Changes in the U.S. Midwest Hydroclimate and Extremes, J. Clim., 35, 17–27, 2022a.

Zhou, W., Ruby Leung, L., and Lu, J.: Seasonally Dependent Future Changes in the U.S. Midwest Hydroclimate and Extremes, J. Clim., 35, 17–27, 2022b.

Zulauf, C. and Brown, B.: Use of tile, 2017 US Census of agriculture, farmdoc daily, 9, 2019.