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Hydrology and Earth System Sciences
Discussions

# Impacts of tile drainage on hydrology, soil biogeochemistry, and crop yield in the U.S. Midwestern agroecosystems

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**Abstract.** Tile drainage removes excess water and is an essential, widely adopted management practice to enhance crop productivity in the U.S. Midwest. 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 such impacts and their connections are poorly understood and highly uncertain. 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, uniquely incorporating soil oxygen dynamics and crop oxygen uptake, to quantify the impacts of tile drainage on hydrological and biogeochemical cycles and crop growth at corn-soybean rotation fields. Tiles are represented as a water sink in the soil, characterized by tile depth and spacing in *ecosys*. Water flow from saturated soil layers to tiles is governed by the lateral hydraulic gradient defined by the water table depth in the field, tile depth, and tile spacing. 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. 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

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oxygen stress during wet springs, thereby promoting crop root growth during the early growth stage. The development of greater root density, in turn, mitigated 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 inherent connections of tile drainage's impacts on hydrology, soil biogeochemistry, and plant growth.

## 1 Introduction

Agricultural subsurface drainage, commonly referred to as tile drainage, is one of the most important agriculture 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 (Kalita et al., 2007), which benefits seed germination and crop growth Ashraf (Ashraf, 2012; Nóia Júnior et al., 2023). Tile drainage also helps reduce the risk of delays in crop planting by enabling timely operation of farm machinery during wet spring months, and therefore extending the crop growing period (Kucharik, 2008; Shirzaei et al., 2021). Additionally, with climate change, the U.S. Midwest is expected to experience wetter springs and drier summers, with more frequent and intense late-spring storms and severe summer droughts (Lesk et al., 2016; Li et al., 2019; Lobell et al., 2014; Schmidhuber and Tubiello, 2007; Seneviratne et al., 2022; Zhou et al., 2022a). Understanding the tile drainage impacts and managing the hydrological condition over the Midwestern agroecosystem are therefore 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. 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 would either increase baseflow or result in a more flashy 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 no-tile 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). The development of tile drainage modules has recently attracted lots of attention (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. Hydrology 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, like 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, plant dynamics, and soil biogeochemistry. For instance, many models, do not adequately represent root respiration, a key process influencing root development, maintenance, and nutrient uptake, 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. 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 interlink and interaction between hydrology, biogeochemistry, and crop growth. The limited soil oxygen diffusion in water-saturated conditions has been recognized as a key factor altering plant 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 like nitrate, sulfate, or iron instead of oxygen for respiration, producing greenhouse gasses, and changing the availability of essential nutrients for plant uptake. However, those processes are not well represented in the aforementioned process-based models.

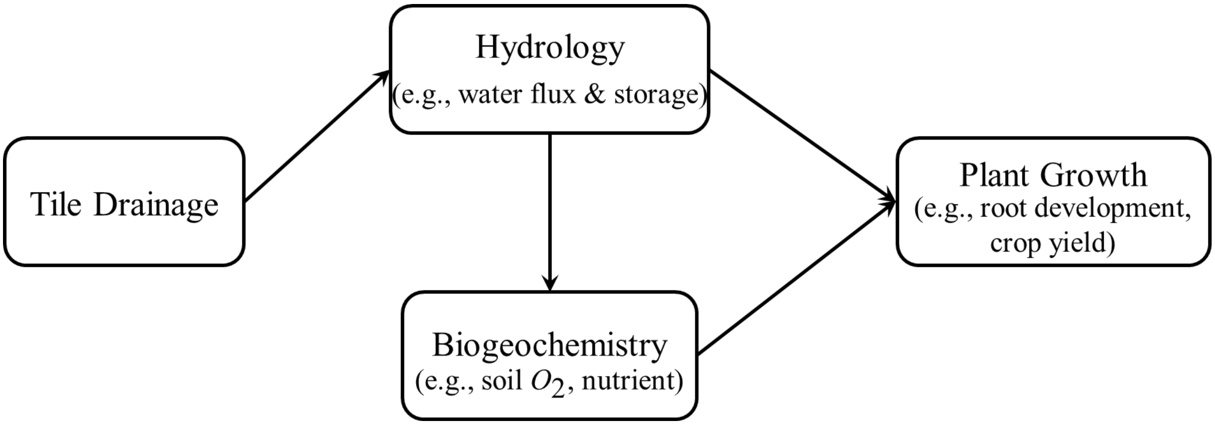

**Figure 1: Hypothesis on how tile drainage impacts hydrology, soil biogeochemistry, and crop growth.**

Here we aim to use a process-based model, *ecosys*, with essential physical mechanisms especially oxygen-related dynamics to understand the role of tile drainage in the integrated hydrology-biogeochemistry-crop agroecosystems by addressing the following questions: 1) How does tile drainage alter the agroecosystem hydrology, biogeochemistry, and crop grow? More importantly, 2) how do those impacts on the three aspects are interrelated? 3) How do seasonal precipitation patterns influence tile drainage and agricultural production? We hypothesize that tile drainage alters in-field hydrology and soil biogeochemical processes in ways that positively influence crop growth (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 validated 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 step (Fig. S1-3) (Grant, 2001). 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).

*Ecosys* simulates the movement of water through the soil-plant-atmosphere continuum with the representation of plant interception of precipitation, irrigation, soil and residue evaporation, plant transpiration, infiltration, surface runoff, subsurface discharge, and snow (Fig. S1). All the water fluxes in both soil and plant 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 plant 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 uptaked nutrients 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 surficia1 concentrations of leaf rubisco and chlorophyll, further affecting the CO2 fixation rate.

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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 hydrology cycle in the model is also tightly linked to soil biogeochemistry. Soil water movement drives the movement of soil nutrients, determining the leaching and nutrient vertical distribution. Besides, 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 plant uptake, which dynamically links soil biogeochemistry with plant growth.

We, here, 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).

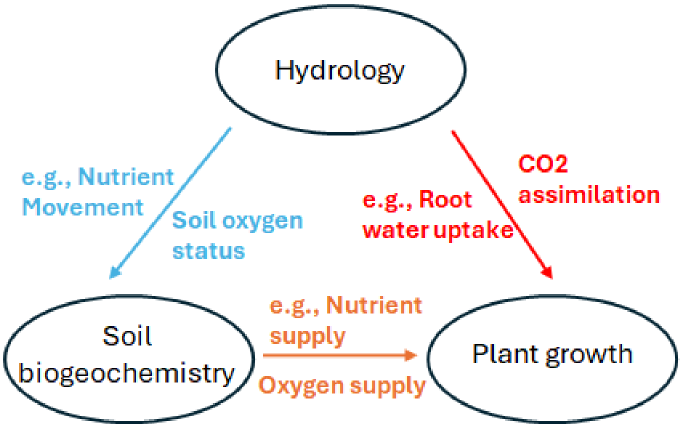

**Figure 2: Examples of interplays between hydrology, soil biogeochemistry, and crop growth in the *ecosys* model**

### 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, 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 oxygen difference in the two phases, and is determined by the diffusive transfer coefficient, and air–water interfacial area.

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

where $Q_{d,O_2}$ is volatilization – dissolution of $O_2$ between solute and gaseous phases $[g\ m^{-2}\ h]$; $a_g$ 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 convective-dispersive equation,

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

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

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

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

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 ($\theta_g$) $[m^3\ m^{-3}]$, and soil porosity ($\theta_p$) $[m^3 m^{-3}]$; $\frac{\partial C_{g,O_2}}{\partial L}$ is the concentration gradient of gaseous $O_2$ in soil $[g\ m^{-3} m^{-1}]$; $Q_{a,O_2}$ is the solute flux of $O_2$ in soil $[g\ m^{-2}\ h]$; $C_{a,O_2}$ is the solute concentration of $O_2$ in soil $[g\ m^{-3}]$; $D_{a,O_2}$ 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 ($D'_{a,O_2}$) $[g\ m^{-2}\ h]$, $Q_w$, temperature dependence function for solute diffusivity ($f_{t,s}$) [-], the soil water-filled porosity ($\theta_w$) $[m^3\ m^{-3}]$, and is the soil tortuosity ($\tau$) [-].

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 plant 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

Root plays 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 interactive 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,

$$R_T = Q_R C_R f_{t,R} f_{o,R} f_{\lambda,R} \tag{6}$$

where $R_T$ is the root respiration for maintenance and growth [$gCm^{-2}h^{-1}$]; $Q_R$ 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 [$g\ Cm^{-2}h^{-1}$]; $\alpha$ is the specific respiration rate for nutrient uptake [-]; $U_\lambda$ 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 [$gC\ (gO_2)^{-1}$].

### 2.1.4 Root respiration and crop oxygen demand

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 root surface where respiration is modeled). The conceptualization of crop roots is depicted in Fig. 2a, 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 contribute to root respiration. The movement of oxygen is assumed to be radial, so 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.

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

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

where $U_{O,s}$ is the rate of oxygen uptake by root from soil $[g\ m^2\ h^{-1}]$; $U_{O,P}$ is the rate of oxygen uptake by root from the root porous core $[g\ m^2\ h^{-1}]$; $U_w$ is the root water uptake rate $[m^3\ m^{-2}\ h^{-1}]$, determined by soil and root water potential and root resistances (Grant, 1998); $D_{O_2}$ is the dispersivity-diffusivity of dissolved oxygen $[m^2\ h^{-1}]$ (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,

$$U_O = \frac{U_O' C_{O_2,R}}{C_{O_2,R} + K_O} \quad (11)$$

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. aqueous 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 $U_O'$,

$$f_{o,R} = \frac{U_O}{U_O'} \quad (12)$$

### 2.1.5 Tile drainage

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

$$\frac{\partial \theta_w}{\partial t} = \frac{\partial}{\partial z}\left(K(\theta_w)\left(\frac{\partial h}{\partial z} + 1\right)\right) - S \quad (13)$$

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

$$v = \frac{K\Delta D}{d} \tag{14}$$

where $v$ is the flow velocity $[m\ h^{-1}]$; $K$ is the saturated hydraulic conductance $[m\ h^{-1}]$; $\Delta D$ is the pressure drop $[m]$ over a distance $d$ $[m]$. The pressure drop is defined as the difference between internal water table depth and tile depth $(D_2 - D_1)$, and the distance is then defined as half of the tile space $(d_1)$. Tile flow only occurs in soil layers above the tile pipes. 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,

$$D_1 = \left(d_s - \frac{L_i \theta_i}{\theta_{i,s}}\right) \tag{15}$$

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 $[m]$, $\theta_i$ 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 $[m^3\ m^{-3}]$.

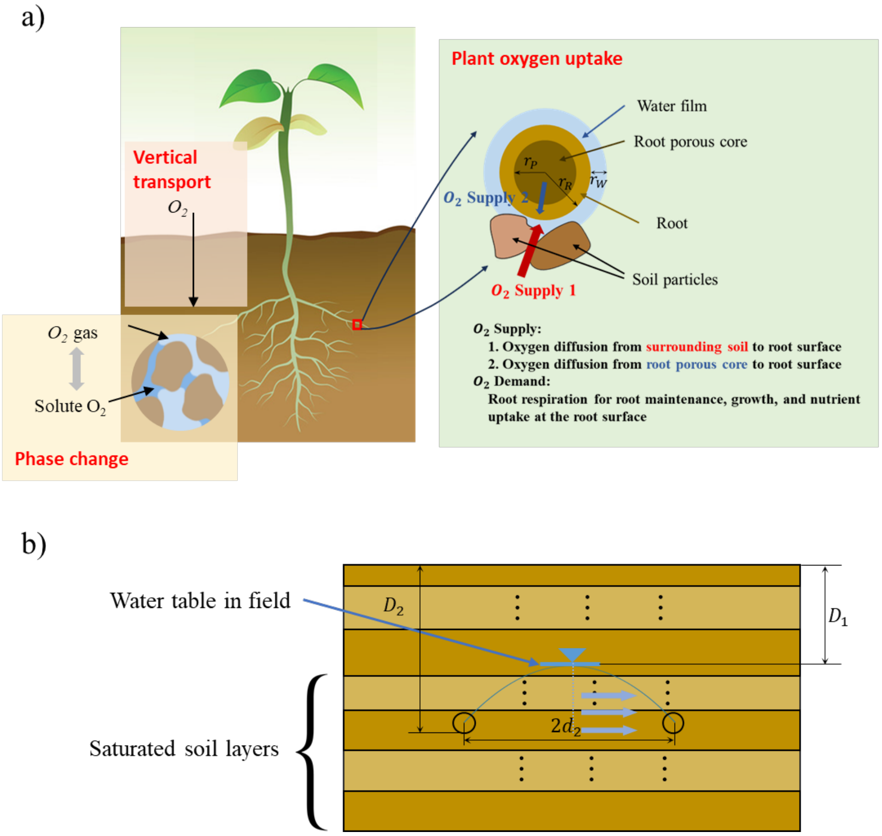

**Figure 3: Representation of a) oxygen dynamics and root oxygen uptake, and b) subsurface tile flow in the *ecosys* model.** $r_R$ is root radius $[m]$; $r_W$ is the thickness of the water film $[m]$; $r_P$ is the radius of the root porous core $[m]$. $D_1$: Water table depth in the field $[m]$; $D_2$: Tile depth $[m]$; $2d_1$: Tile spacing $[\boldsymbol{m}]$; $\theta_k$: Soil water content in kth soil layer $[m^3 m^{-3}]$; $\theta_{s,k}$: Saturated soil water content in kth soil layer $[m^3 m^{-3}]$; $L_i$: Thickness of the ith soil layer $[m]$.

### 2.2 Model setups

Here the *ecosys* model is implemented to address a specific issue, i.e., the impact of tile drainage on the hydrology, biogeochemistry, and crop productivity in the U.S. Midwest agroecosystems. There is considerable spatial variation in the extent of tile drainage in the Midwest. The first step in the modeling effort is model validation under the Midwestern conditions. This is followed by diagnostic analyses with the validated model to address the scientific questions about the effects of tile drainage posed previously. A regional application of the model, allowing for spatial variations of tile drainage extent can follow subsequently, but will be left for future work.

#### 2.2.1 Field data

Data from an experimental field site (Fig. S5) 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. The study site consists of four tile drainage treatments: conventional drainage, shallow drainage, controlled drainage, and no drainage. Each of these treatments has 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 pipes were 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 spacing between neighboring pipes are 0.254 m, 1.22 m, and 18.3 m, respectively. Management practices, like 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/).

#### 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. Since only daily precipitation data were available, we simply assumed that precipitation is uniformly distributed over two distinct hours on rainy days. The soil information was obtained from The Gridded Soil Survey Geographic Database (gSSURGO) dataset (Soil Survey Staff, 2023). The drainage setting in the tile field is shown in Table 1. External water table depth is set as the mean value of the observed water table depths in the field without tile pipes (1.00 m), and the distance to the external water table is set as 50 m, which is around half of the length of the experimental field. The tile depth is set as the lowest point of the tile pipe, which is the depth of the tile plus the radius of the tile pipe, 1.35 m. Half of the tile spacing is 9.15 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 depth | 1.35 m |
| Half of the tile spacing | 9.15 m |

*Ecosys* simulation started in 1990, with the initial 17 years (1990-2006) as the spin-up period to stabilize the model, followed by an 11-year analysis period (2007-2017). Model calibrations were performed on the field without tile drainage during the analysis period. The configuration of the model relied on established parameters for most crop cultivars (Li et al., 2022). The crop yield in the no-tile field was used to calibrate key crop parameters, like the maturity group and maximum rate of carboxylation (VCMX), to account for site-specific conditions (Table S1). Then, the calibrated model was validated in the tile-drained field. The Pearson coefficient (r), percent error (PE), root mean square error (RMSE), and relative root mean square error (rRMSE) between the simulated yield and observed yield were used to assess the model performance. 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).

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

$$PE = \frac{\bar{x}-\bar{y}}{\bar{x}} \tag{17}$$

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

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

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

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 daily precipitation inputs with a scale factor (i.e., 0.9, 1.0, 1.1, 1.2, 1.3) to mimic the change of precipitation (Fig. S7)

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## 3 Results

### 3.1 Model validation

We found that *ecosys* is promising in estimating both crop yield and tile drained flow in the tile drainage system, as shown by the selected statistical metrics in Fig. 4 and Table 3. Overall, the Pearson coefficient r for the yield simulation is over 0.95 for both calibration and validation. Specifically, the PE for corn in calibration and validation are -0.50% and -3.10%, respectively. The PE for soybean in calibration and validation are -8.75% and -1.57%, respectively. The rRMSE for corn and soybean in validation is 5.66% and 12.57%, respectively. Both the observations and simulation show the benefit of tile drainage to crop yield. For corn, tile drainage increases yield by 12.34 bu/acre (6.97%) and 7.66 bu/acre (4.20%) in model simulation and observations. For soybean, tile drainage increases yield by 2.87 bu/acre (5.37%) and 7.41 bu/acre (13.64%) in model simulation and observations (Table 3). Besides, the model successfully captured the seasonal pattern of more tile flow in late spring and early summer (Fig. 5). The observations suggest that there is no observed tile flow in January and February, and we hypothesized that this might be 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 are 0.784, 28.42 mm/month, and 0.43, respectively.

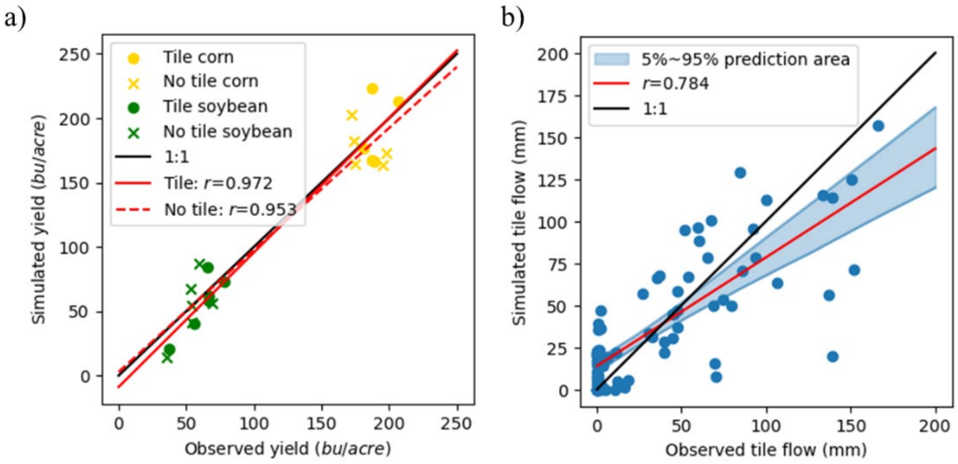

**Figure 4: Validation for crop yield and tile flow.** Comparison of *ecosys*-simulated and ground-measured **a**) maize (15 % moisture) and soybean (13 % moisture) grain yield, and **b**) monthly tile flow in the growing season (April to October).

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

| | Statistic | Tile field | No tile field |
|---|---|---|---|
| Corn Yield | PE | -0.50% | -3.10% |
| | rRMSE | 4.90% | 5.66% |
| | RMSE (bu/acre) | 21.03 | 23.17 |
| Soybean Yield | PE | -8.75% | -1.57% |
| | rRMSE | 8.34% | 12.57% |
| | RMSE (bu/acre) | 12.91 | 17 |

**Table 3. Observed and simulated crop yield under tile and no tile conditions.**

| | Tile (bu/acre) | | No tile (bu/acre) | | Tile benefit (bu/acre) | |
|---|---|---|---|---|---|---|
| | Obs. | Sim. | Obs. | Sim. | Obs. | Sim. |
| Corn | 190.33 | 189.35 | 182.67 | 177.01 | 7.66 (4.20%) | 12.34 (6.97%) |
| Soybean | 61.71 | 56.31 | 54.3 | 53.44 | 7.41 (13.64%) | 2.87 (5.37%) |

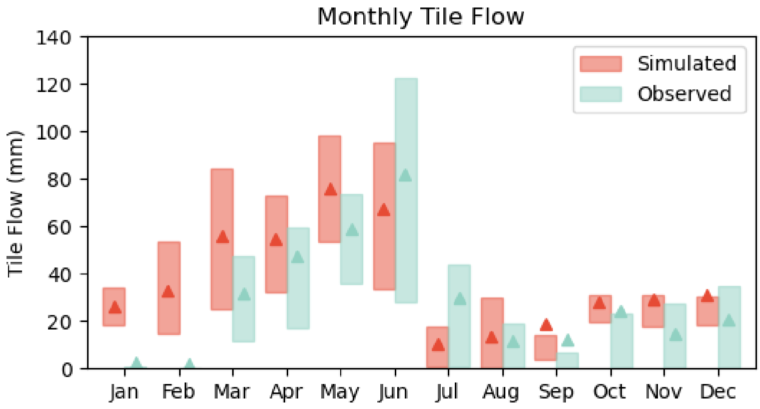

**Figure 5: *Ecosys*-simulated and observed tile flow.** Boxes represent 25%-75% of tile flow for the simulated period (2007-2017), and triangles represent the mean tile flows. The triangles represent the multi-year mean stream flow in a certain month.

### 3.2 The impacts of tile drainage on hydrology

We first evaluated water fluxes and partitioning with the *ecosys* model under tile and no-tile conditions at the study site. The annual mean precipitation is 881 mm from 2007 to 2017, and most of the precipitation (66.4%) occurs from April to August (Fig. 6 and S8). Tile drainage increased subsurface discharge (water coming out of the field) and subsurface recharge (water going into the field) when compared to the no-tile condition (Fig. 6). Specifically, the annual mean subsurface discharge rises from 216 mm to 276 mm, and the annual mean subsurface recharge rises from 34 mm to 104 mm. However, tile drainage has a limited impact on surface runoff and ET. The annual mean ET is 659 mm and 655 mm for tile and no-tile conditions, respectively, and surface runoff is 48 mm and 46 mm for tile and no-tile conditions. Besides, tile drainage has been shown to reduce soil water content in our simulations (Fig. S11a).

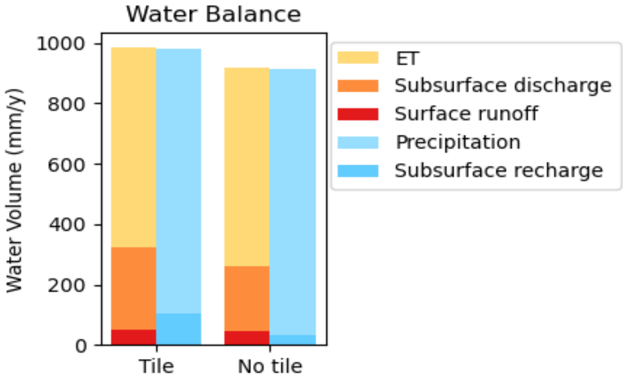

**Figure 6: *Ecosys*-simulated annual water balance under tile and no-tile conditions.** Overall, tile drainage increases both subsurface discharge (water coming out of the field) and subsurface recharge (water going into the field), and ET and surface runoff are similar under tile and no-tile conditions. The imbalance between influxes and outfluxes is subject to storage change.

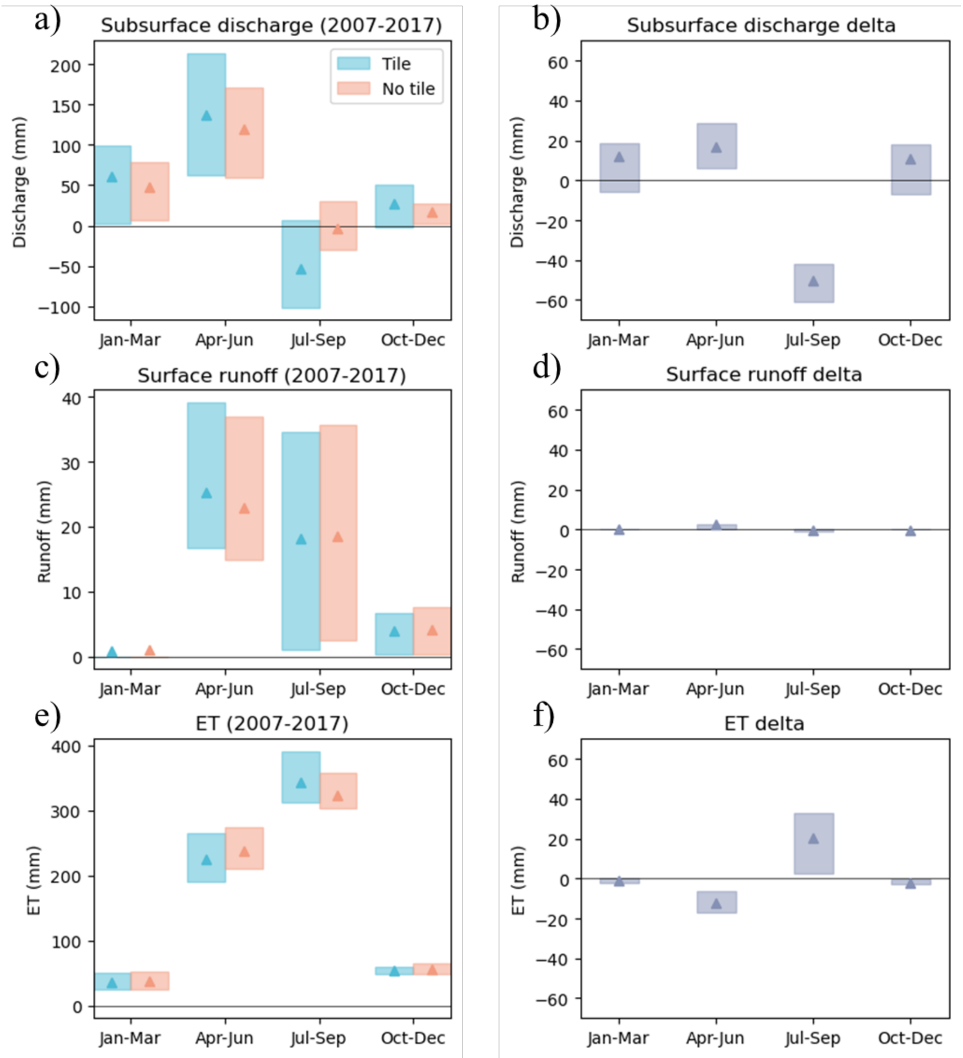

**Figure 7: *Ecosys*-simulated water fluxes under tile and no-tile conditions from 2007 to 2017. a**) Boxplot of the quarterly net subsurface discharge (subsurface discharge - subsurface recharge); **b**) Boxplot of the quarterly net subsurface discharge difference between tile and no-tile conditions; **c**) Boxplot of the quarterly surface runoff; **d**) Boxplot of the quarterly surface runoff difference between tile and no-tile conditions; **e**) Boxplot of the quarterly ET, **f**) Boxplot of the quarterly ET difference between tile and no-tile conditions. The upper and lower parts of the boxplots indicate 25% and 75% quantiles, and the boxes indicate the interquartile variation. The triangles indicate the mean values. Delta is the difference between tile and no tile conditions. The corresponding monthly results are shown in Fig. S10.

Results indicate that the effects of tile drainage follow a seasonal pattern (Fig. 5). For the study site, tile drainage actively removes excess water in spring, leading to an increase of net subsurface discharge from 120 mm to 137 mm, corresponding to high precipitation and low ET during those months. Less water is drained by tile drainage in summer due to high crop water consumption despite high precipitation (Fig. 5, 7 and S10). On average, the net subsurface discharge is -53 mm in summer under tile conditions, indicating a significant recharge from surrounding soils to the tile-drained field. Tile drainage increases 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 no-tile condition. Furthermore, tile drainage results in a minor increase in surface runoff in the spring, from 22 mm to 25 mm. It also slightly raises ET in the summer months from 226 mm to 238 mm, and slightly reduces ET in other months (Fig. 7).

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

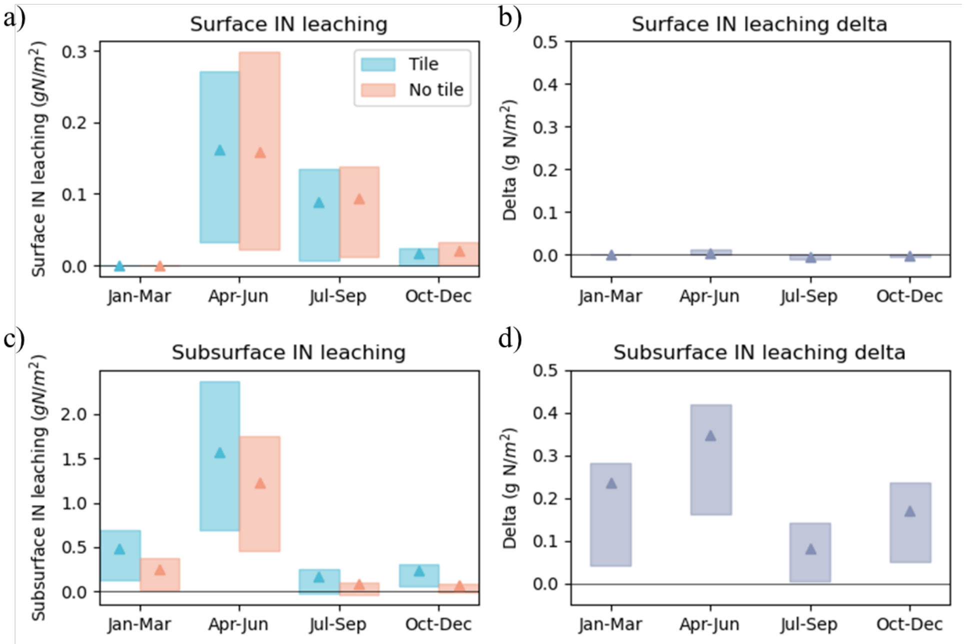

**Figure 8: *Ecosys*-simulated inorganic nitrogen (IN) lost under tile/no-tile conditions from 2007 to 2017. a)** Boxplot of the quarterly subsurface inorganic nitrogen discharge, **b)** Boxplot of difference of the quarterly subsurface inorganic nitrogen leaching between tile and no-tile conditions, **c)** Boxplot of the quarterly surface inorganic nitrogen leaching, and d) Boxplot of difference of the quarterly surface inorganic nitrogen leaching between tile and no-tile conditions.

Tile drainage changes soil biogeochemical processes and crop growth. At the study site, the annual mean total inorganic nitrogen (IN) loss from surface runoff and subsurface discharge is 2.72 $g\ Nm^{-2}$ and 1.89 $g\ Nm^{-2}$ for tile and no-tile conditions, respectively (Fig. 8). Tile drainage primarily increases subsurface inorganic nitrogen leaching, with values rising from 1.89 $g\ Nm^{-2}$ to 2.45 $g\ Nm^{-2}$, while surface inorganic nitrogen loss remains relatively constant, with no significant differences noted between tile and no-tile conditions, around 0.27 $g\ Nm^{-2}$. These values are within the range of riverine nitrogen yield in the central U.S. Midwest reported by (David et al., 2010). Over 85% of inorganic nitrogen leaves the system through the subsurface in both tile and no-tile conditions. Most inorganic nitrogen leaching happens in spring, coinciding with fertilizer application and the peak precipitation period. The impacts of tile drainage on inorganic nitrogen leaching also exhibit a seasonality. Our model results reveal that subsurface inorganic leaching has the most substantial increase in spring with an increase of $0.35\ g\ Nm^{-2}$, while the increase of subsurface inorganic leaching in summer is only $0.08\ g\ Nm^{-2}$. Furthermore, model results show that nitrogen leaching increases with the total precipitation (Fig. S12).

The model results suggest that tile drainage would increase soil oxygen concentration (Fig. S11), further affecting soil biogeochemistry and crop growth. Figure 9a-b suggests that tile drainage promotes soil microbe activity and accelerates soil organic nitrogen mineralization and soil heterotrophic respiration (Brown et al., 2017; Castellano et al., 2019). Model results show 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 promotes crop root growth and nutrient uptake, indicated by the increase of mean annual root respiration from $182\ g\ Cm^{-2}$, to $193\ g\ Cm^{-2}$.

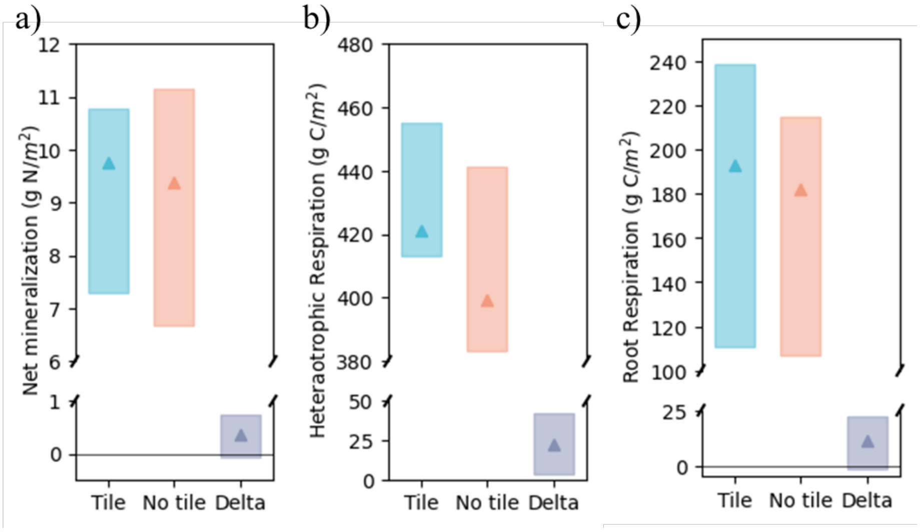

**Figure 9: *Ecosys* simulated soil root and soil microbe activities from 2007 to 2017.** Boxplot of *ecosys*-simulated **a**) annual soil net mineralization (mineralization - immobilization) under tile/no-tile conditions and their difference, **b**) annual root respiration under tile/no-tile conditions and their difference, and **c**) annual heterotrophic respiration under tile/no-tile 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 no tile conditions.

To understand the role of tile drainage on crop growth under excessive precipitation, we specifically looked into a typical wet year (2009) with high annual precipitation and elevated precipitation during the growing season (Fig. S8). June is generally the month with the highest precipitation, and the precipitation in June of 2009 is 197 mm, surpassing the multi-year average of 158 mm. Both the simulation and the observation show that tile drainage helps to increase soybean yield this year (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. 10. Figure 10a shows that soil is nearly saturated at depths deeper than 0.4 m under no-tile conditions, while saturation is not observed until the depth below 1.1 m under tile-drained conditions. This suggests that tile drainage effectively mitigates excess water accumulation in the soil. Correspondingly, soil oxygen concentration is higher under the tile condition, as shown in Fig. 10b, which provides aerated conditions for crop root growth. This improved oxygen availability contributes to denser and deeper root development (Fig. 10c). Figure 10e shows the time series of the $O_2$ stress indicator, defined in section 2.1.4, which shows that tile drainage helps to reduce the $O_2$ stress, especially in June. The impacts of tile drainage on crop yield, soil water content, soil oxygen concentration, and root growth are similar in the typical wet year for corn in 2010 (Fig. S14).

Results also show 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 a mere 71 mm of precipitation recorded during the summer months (Fig. S8), and the drought lead to a yield drop (Fig. S13). Besides, the precipitation in May reached 230.61 mm, which might saturate the soil in the early stage of crop growth. Both the observation and model simulation show an increase in soybean yield under the tile drainage condition, despite our model underestimating the yield (Fig. S13 and Text S9). Our results suggest that tile drainage reduces soil water content while increasing soil oxygen concentration and promoting root growth (Fig. 10f-h). Figure 10i shows that the tile drainage increases the minimum canopy water potential modeled in summer, indicating soybean suffers less water stress under tile conditions. The more developed root system might help crops access soil water in deeper soil (Fan et al., 2017; Schenk and Jackson, 2005; Steudle, 2001).

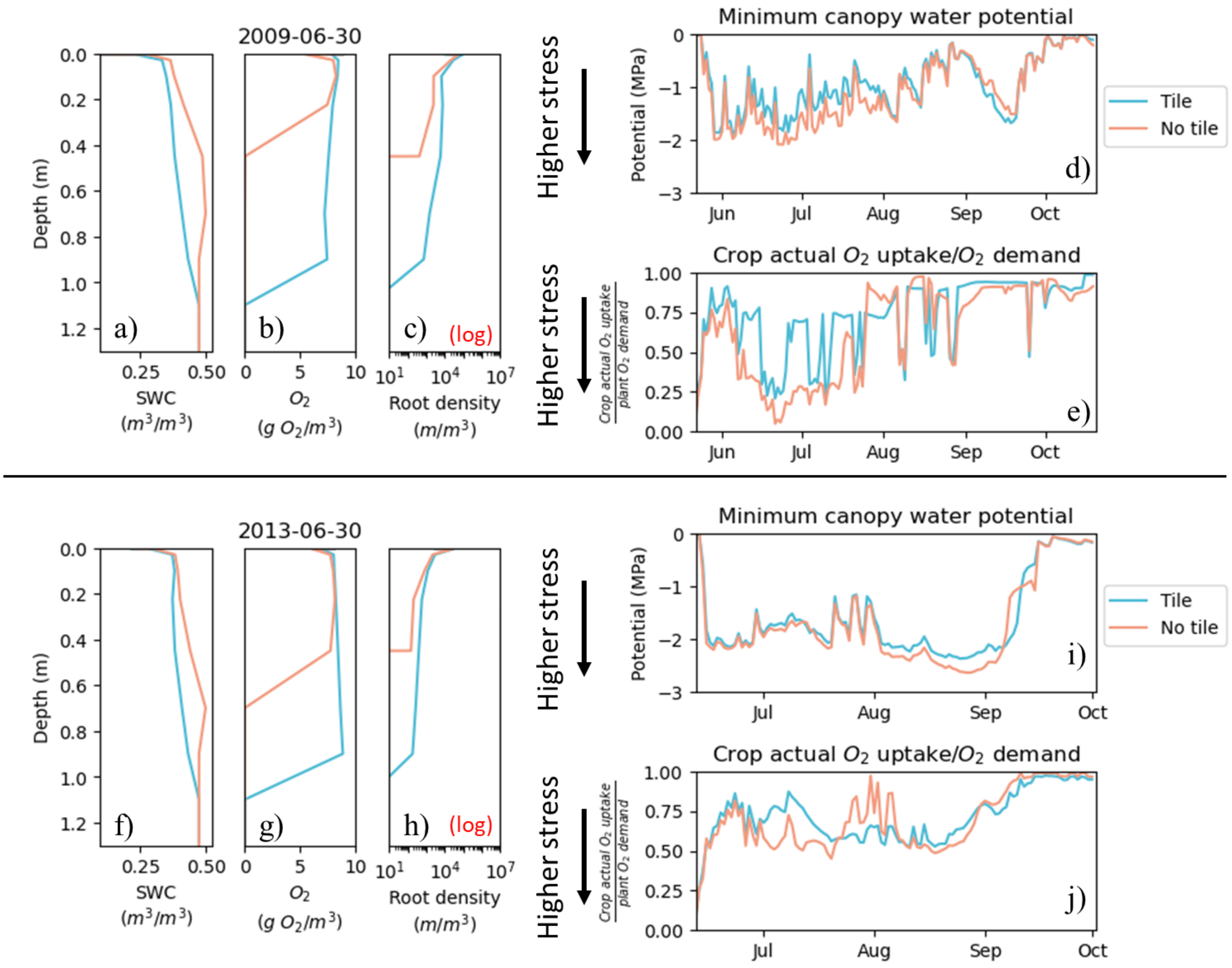

**Figure 10: *Ecosys*-simulated soil profile and time series of water and oxygen stress in typical wet and dry soybean years.** The profile of **a**) Soil water content, **b**) soil $\boldsymbol{O_2}$ concentration, and **c**) root density profiles in the soil column on June 30th, 2009. Time series of **d**) minimum canopy water potential and **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) in 2009 (a typical wet year for soybeans). The profile of **f**) Soil water content, **g**) soil $\boldsymbol{O_2}$ concentration, and **h**) root density profiles in the soil column on June 30th, 2013. Time series of **i**) minimum canopy water potential and **j**) crop actual $\boldsymbol{O_2}$ uptake rate/$\boldsymbol{O_2}$ demand (potential $\boldsymbol{O_2}$ uptake rate under non-limiting $\boldsymbol{O_2}$ condition) in 2013 (a typical year with wet spring and dry summer for soybean). The x axis of **c**) and **h**) 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 results reveal 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 no-tile conditions, and the yield difference between tile and no-tile conditions becomes increasingly substantial with rising precipitation levels (Fig. 11). 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).

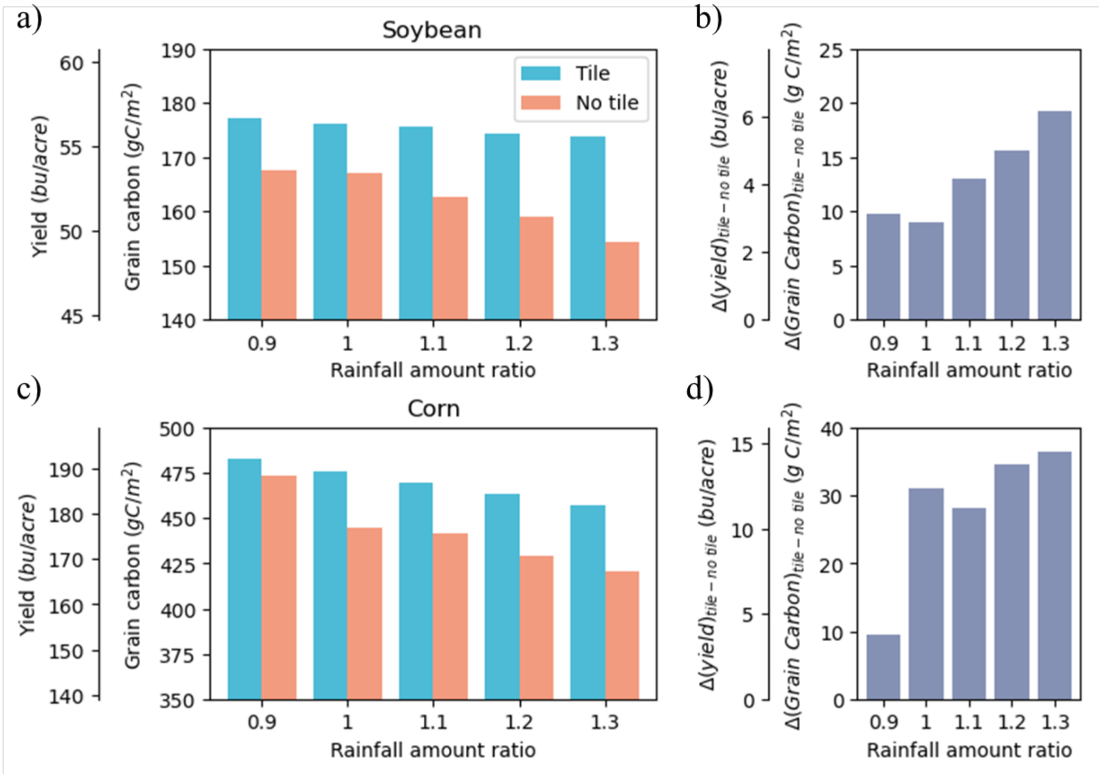

**Figure 11: *Ecosys*-simulated crop yield in the hypothetical numerical experiment under different precipitations. a**) Multiyear-mean corn yield under tile and no-tile conditions. **b**) The corn yield benefit (yield/grain carbon difference between tile and no-tile conditions). **c**) Multiyear-mean soybean yield under tile and no-tile conditions. **d**) The soybean yield benefit (yield/grain carbon difference between tile and no-tile 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 greater than 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 no-tile conditions in a typical wet year for soybeans (2009). Figure 12a shows that the mean soil $O_2$ content in the top 1 m soil during June decreases with rising precipitation, under both tile and no-tile conditions (r=-0.943 and -0.977 for tile and no-tile 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. 12b, r=0.931 and 0.995 for tile and no-tile conditions, respectively). Crops suffering from less oxygen stress tend to develop denser root systems (Fig. 12c, r=0.982 and 0.984 for tile and no-tile conditions, respectively). Our results reveal that the grain carbon reduces as precipitation increases (Fig. 12d). 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 no-tile condition (Fig. 12), 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. 12 under the no-tile 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 viability, 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).

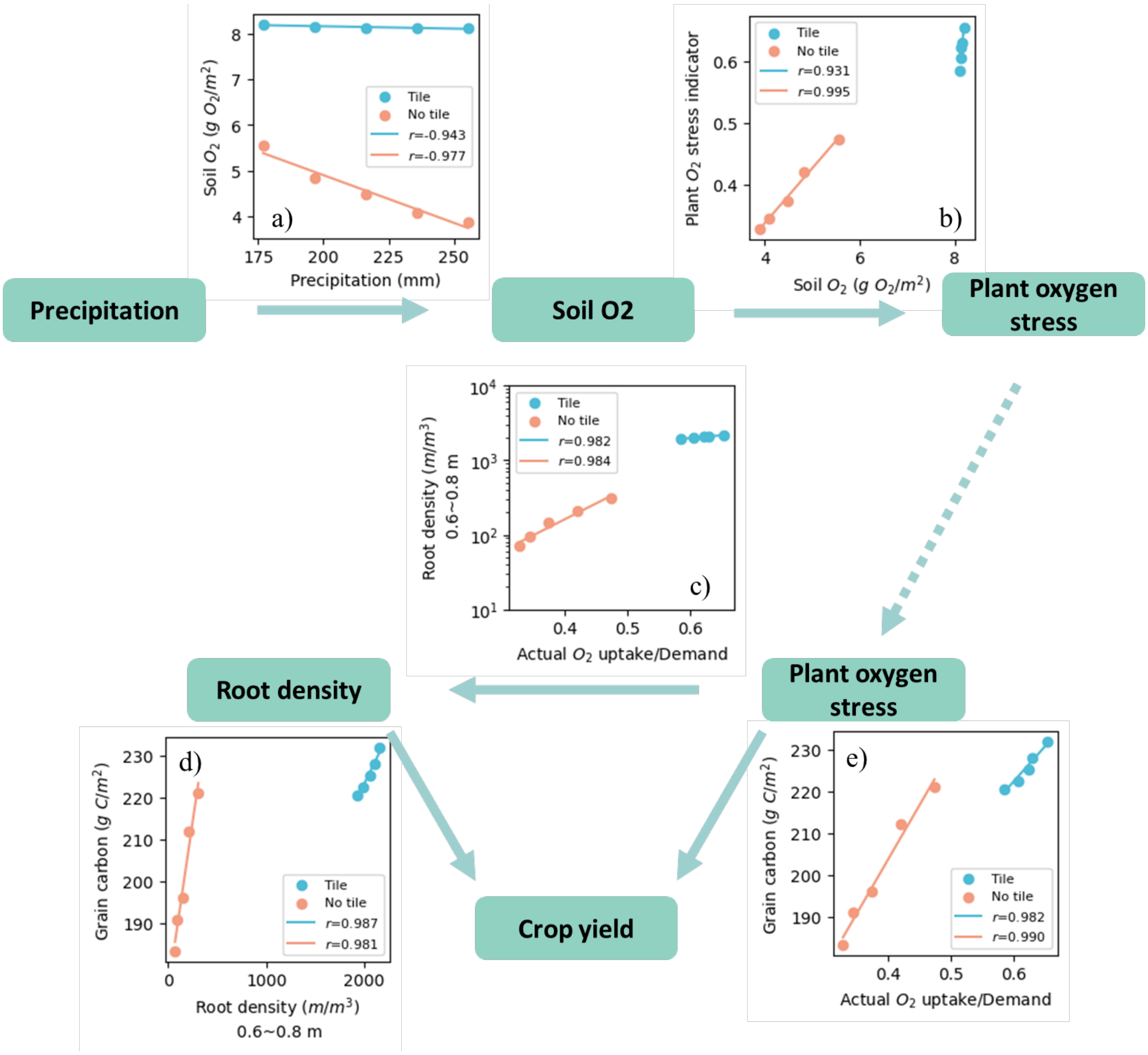

**Figure 12: *Ecosys*-simulated responses of biogeochemistry and crop growth to precipitation amounts in a typical wet year for soybeans (2009) under tile and no-tile conditions.** The relationships between **a)** soil $\boldsymbol{O_2}$ concentration in the top 1m soil column and

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 plant 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 effectiveness of the ecosys model

The *ecosys* model effectively represents the complex interactions within soil-vegetation-atmosphere systems, enabling the simulation of a wide range of processes under wet conditions and tile-drained conditions in this study (Grant, 2001). Specifically, crop root systems are the key component that links vegetation and soil through water and nutrient fluxes extraction from soil, and they help crops adapt to resource availability or environmental conditions, including flooding and drought (Hodge, 2004; Hodge et al., 2009; Jochen Schenk, 2005). *Ecosys* employs a microscopic approach to root system modeling, which provides intricate and comprehensive representations of root structure, production, and mycorrhizal colonization within the model (Grant, 1998). The microscopic approach relies on physical first-principle mechanisms in water and nutrient flow simulations (Warren et al., 2015). For instance, root water uptake is driven by root and soil water potential, accounting for root and stem resistance. Root nutrient uptake (i.e. nitrogen, phosphate, oxygen, etc.) is then driven by water exchange between root and soil and nutrient concentration gradients through the advection-diffusion equation (Grant, 2001, 1998). The nutrient uptake is also constrained by crop C/N/P allocations and root respirations, which are regulated by soil moisture, soil oxygen concentration, and soil nutrient status (e.g., Section 2.1) (Grant, 1998). These mechanisms provide a robust physical basis for modeling root-soil interactions and their responses to environmental change (i.e., wet conditions and tile drainage conditions) (Warren et al., 2015). While the macroscopic approach, like the widely used Feddes reduction function in root water uptake, may offer simplicity and ease of adaptation (Ebrahimi-Mollabashi et al., 2019; Feddes et al., 1978, 2001; Šimůnek and Hopmans, 2009; Vrettas and Fung, 2017), the first-principle mechanisms in the microscopic approach are likely to have higher transferability under various environmental conditions, which enhances model's reliability and applicability under both artificial and natural environmental changes (Warren et al., 2015). The results here suggested that the *ecosys* model is promising in estimating crop yield and tile flow and in quantifying the effects of tile drainage and excessive precipitation on agroecosystems. Further, we only calibrated the parameters related to crop traits in model calibration (Table 2), and the soil parameters related to soil water dynamics are obtained from the gSSURGO dataset (i.e., saturated hydraulic conductance, bulk density, etc.), which shows the potential of the use of *ecosys* to understand the role of tile drainage and environmental changes over a large scale.

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, such that 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. 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).

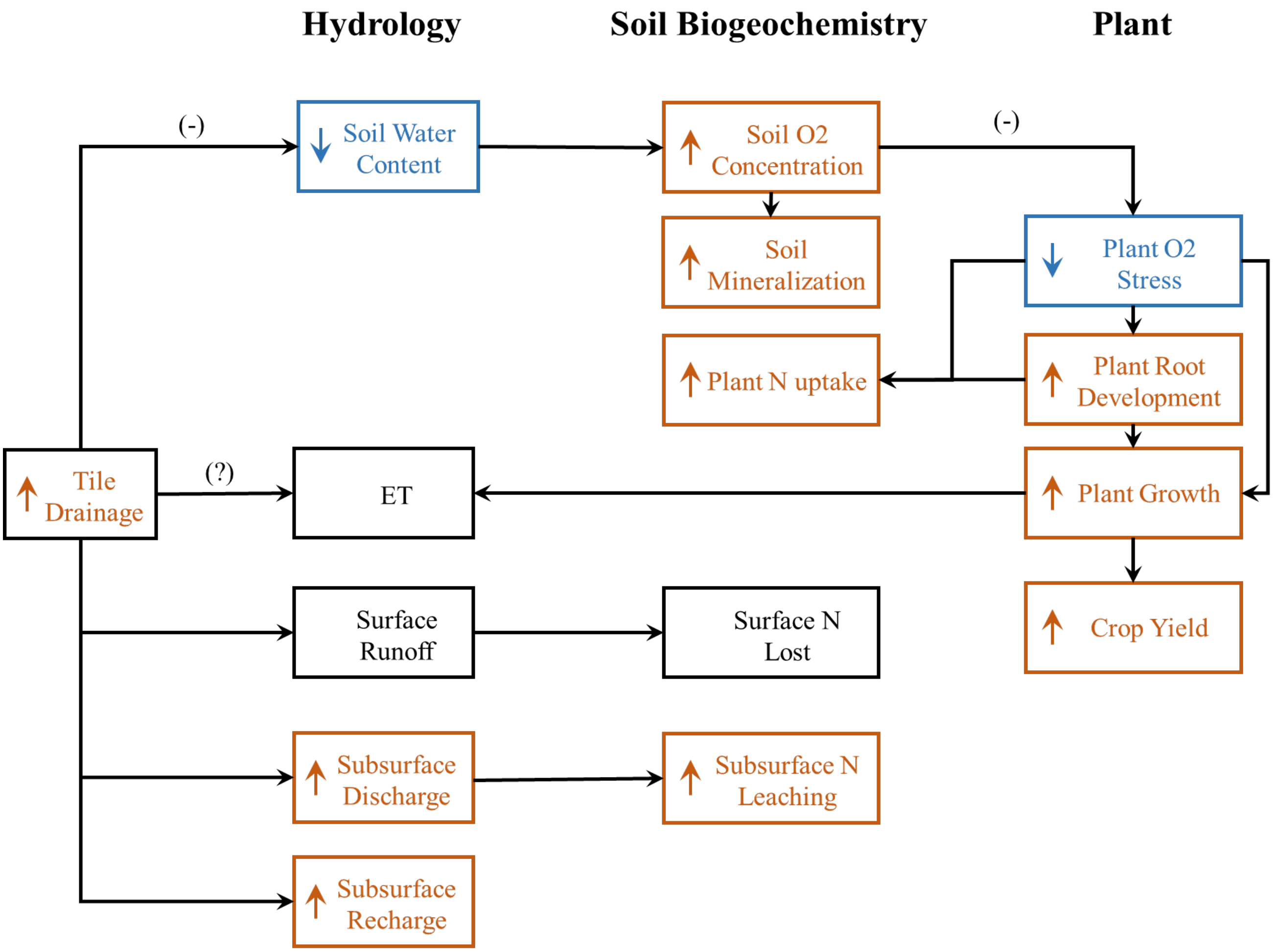

**Figure 13: Schematic of the impact of tile drainage on hydrology, soil biogeochemistry, and crops for the U.S. Midwest agroecosystems with sufficient precipitation in the spring.**

## 4.2 The impact of tile drainage on hydrology

Our results demonstrate that tile drainage has a pronounced impact on field hydrology cycles, influencing both water storage and water fluxes (Fig. 13). 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. 6). 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. 6), and tile drainage has a limited impact on surface runoff at our study sites (Fig. 6).

This can be partially attributed to the soil type in the selected field, which consists of Taintor and Kalona soil with low permeability. Those soils are classified as poorly drained (Helmers et al., 2012). The low soil permeability might be a key factor that determines precipitation partitioning, and infiltration-excess runoff might dominate the surface runoff generation processes, which limits the impacts of tile drainage on surface runoff (Blann et al., 2009). We acknowledge that we currently do not consider the macropores that directly connect tile pipes 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, as tile drainage did not significantly change crop growth, similar to some previous studies (Khand et al., 2017; Yang et al., 2017).

The impact of tile drainage on the hydrology 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. 5 and 7). In summer, crops actively draw water from soils, which reduces soil water content. High ET, coupled with reduced soil water storage under tile conditions, results in an increase in subsurface recharge (Fig. 7). 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).

### 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. 13). 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 leaching by 28.5%, accompanied by a 29.6% increase of subsurface discharge in water partitioning at the study site (Fig. 6 and 8). Furthermore, the impact of tile drainage on nitrogen leaching 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. 5 and 8) (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. 9c). 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. 9a). The increased net mineralization compensates for the decreased soil inorganic nitrogen through subsurface leaching.

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### 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. 10). The increased leaching by tile drainage reduces the soil inorganic nitrogen content, while the increased net mineralization, contradictorily, increases the soil inorganic nitrogen content (Fig. 8 and 9). 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 themselves 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 its 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. In wet springs, tile drainage alleviates crop oxygen stress by reducing soil water content and elevating soil oxygen concentration (Fig. 10 and 12), which guarantees the early growth of both the root system and the above-ground part of the crop under excessive precipitation. Deeper and more dense root systems are observed under tile drainage conditions (Fig. 10), 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. 10f-j). The lower oxygen stress and developed root system together benefit crop growth (Fig. 13).

In summary, our study reveals that tile drainage significantly enhances the production of both corn and soybean 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. 10 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. 10). Lastly, our hypothetical numerical experiments indicate that the yield benefit of tile drainage amplifies with increasing precipitation across various amounts (Fig. 11).

### 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. 10, 11, 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 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. 10) (Zhou et al., 2022b).

However, tile drainage also poses threats to downstream water quality under climate change. Tile drainage increases the nitrogen leaching 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, and woodchip bioreactors) (Mitchell et al., 2023; USDA NRCS, 2017, 2023). While many studies suggest promising outcomes of these conservation practices in terms of reducing nitrogen leaching 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 leaching and potentially provide yield benefits under dry conditions (Delbecq et al., 2012; Ghane et al., 2012; Singh and Nelson, 2021; Youssef et al., 2023). The results at our study site indicate that 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. 10 and S13). 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 in observed tile pipes 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.

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## 5. Conclusions

In this study, we used a process-based model to evaluate the impact of tile drainage on hydrology, biogeochemistry, crop growth, and their connections in the central U.S. Midwest agroecosystem. The model's unique ability to explicitly simulate soil oxygen dynamics and crop oxygen uptake with first-principal mechanisms enabled a nuanced understanding of the interconnectedness of these impacts. The model performance is validated with field crop yield data and tile flow observation. We systematically compared model simulations under both tile-drained and non-tile-drained conditions to quantitatively evaluate the influence of tile drainage on hydrology, biogeochemistry, and plant growth of the agroecosystem. Using the process-based model, we also reveal the interconnections of tile drainage's impacts on these critical components. 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 tile drainage firstly modifies the hydrology 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 discharge, 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.

Our study provides a systematic assessment of the tile drainage's impact on hydrology, biogeochemistry, and crop growth, and 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.

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