In the following responses, reviewers' comments are reproduced in their entirety in black, and the authors' responses are noted in blue. The text that appeared in the manuscript is indented.

Reply to Referee 1

Reply to Referee 2

Reply to Referee 1:

In the following responses, reviewers' comments are reproduced in their entirety in black, and the authors' responses are noted in blue. The text that appeared in the manuscript is indented.

General Comments

1. Research question on modeling impacts of tile drainage on hydrology and crop yield using ecosys model is new and worthy contribution to the literature.
2. Predicting crop yield using O2 modeling is novel
3. The manuscript could be significantly strengthened with additional details on the methods and a greater emphasis on novel results fo the work.

Response: Thanks for the positive feedback and the suggestion to improve the manuscript with more clearly modeled illustrations and emphasizing the novelty of the paper. Please see the point-to-point response below.

Suggest that the authors consider the following points regarding their methods:

1. General observations:

1.1. Use the past tense when referring to methods and results

Response: Thanks for the suggestions! We have revised the methods and results section accordingly.

1.2. Model setup:

- Hydrological processes lack clarity and better description of terms and more consistent useage of terms is needed: In Fig S1, terms used are surface leaching, runoff, infiltration, discharge, subsurface leaching. What is meant by surface/subsurface leaching?
- No subsurface recharge is shown in Fig S1, but it is discussed in results. What is this?
- "Subsurface discharge" used in results. Please define.
- "Subsurface recharge" used in results. Please define.

Response: Thanks for the comments and suggestions. We have revised Fig. S1-3 and added a more detailed description to define those fluxes in the main text.

> **Line 266-276**: "2.1.4 Water balance
>
> The water balance in the simulated field is given by,
>
> $$\Delta S_i = P_i - Q_i - R_i - ET_i \qquad (13)$$
>
> 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 the 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. "

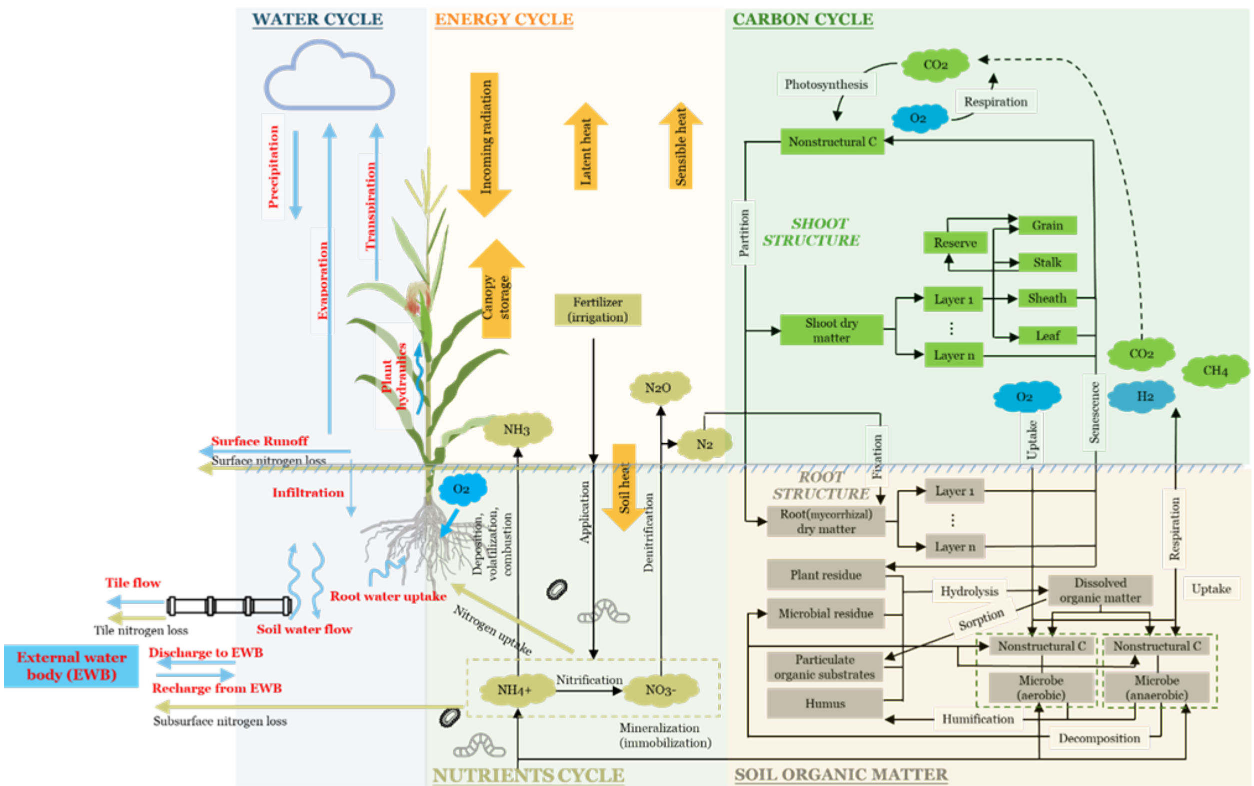

Figure S1. Schematic of the processes in *ecosys*. Hydrological processes are highlighted with **bold red** fonts.

1.3 What is the scale of the model, and what are the boundaries of the setup?

Response: Thank you for your valuable feedback and the supplementary materials. In the revised manuscript, we have clarified that ecosys is a 3D ecosystem model, typically configured as a 1D model for field-scale studies. This study specifically utilizes the 1D configuration to perform a diagnostic analysis at an experimental site located at the Iowa State University Southeast Research and Demonstration Farm in Washington County.

> **Line 137-145**: “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; 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, and the 1D configuration also ensures a greater numerical stability.”

We have revised the figure to show the location and scale of the experiment site from the supplementary to the main text as Fig. 4 now.

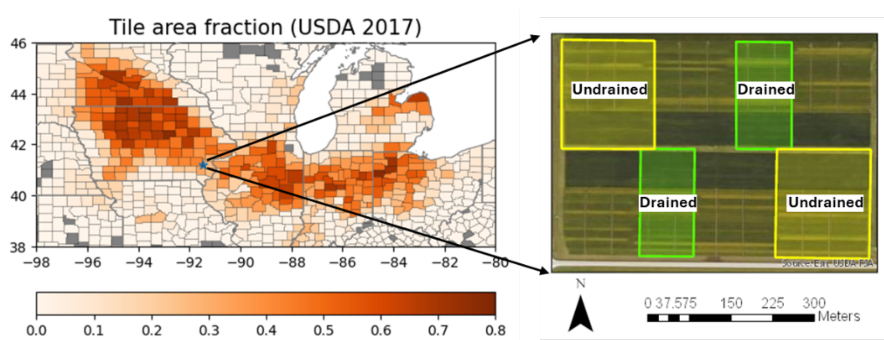

Figure 4: Tile fractions over the U.S. Midwest region, and the location and layout of the selected experiment field. The yellow boxes represent sub-fields without tile drainage, and the green boxes represent sub-fields with conventional drainage.

1.4 Calibration/Validation:

1.4.1 More detail is needed here. Why use undrained for calibration and drained for validation? State reasons for doing so.

Response: Thanks for the comment and suggestion. There are three reasons we are doing so: 1) To extend the validation and calibration period length. There are only 11-year yield observations with corn-soybean rotation (2007-2017). If we split the calibration and validation in the time domain, the calibration period and validation period would be too short, for instance, 6 years (3 corn years and 3 soybean years) for calibration and 5 years (2 corn years and 3 soybean years) for validation. By splitting the calibration and validation on the tile-drained and no-drained field, we have 11 years in total for validation and calibration. 2) to keep parameters the same for the tile-drained field and the undrained field. Except for tile drainage settings, we do not expect to see other differences between tile-drained fields and undrained fields. 3) To ensure the model correctly captures the impact of tile drainage on crop yield. As we only calibrate the related parameters in the undrained condition, we could validate whether the model could capture the impact of tile drainage on crop yield. We have briefly stated that in the main text now:

> **Line 339-340**: "*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."

1.4.2 List all parameters used in calibration, along with beginning and final values

Response: Thanks for the suggestion. We have updated Table S1 with calibration range and final values in the revised paper.

Table S1. Calibrated plant parameters in *ecosys*

Crop	Parameters	Explanation	Range	calibrated values
Corn	GroupX	Plant maturity group: Node number required to start floral initiation (-)	[13,17]	15
	Chl4	Fraction of leaf protein in mesophyll chlorophyll for C4 plants (-)	[0.015,0.055]	0.025
	Gfill	Maximum rate of kernel filling (g seed-1 h-1)	[0.0004, 0.0008]	0.0004
	RCS	Shape parameter for stomatal resistance vs leaf turgor potential (-)	[4, 8]	6
	XKCO2	Rate constant for Rubisco Carboxylation (uM)	[20, 30, 40]	40
soybean	GroupX	Plant maturity group: Node number required to start floral initiation (-)	[13, 19]	17
	VCMX	Specific rubisco carboxylase activity (umol g-1 s-1)	[35 ,50]	45
	Gfill	Maximum rate of kernel filling (g seed-1 h-1)	[0.0002, 0.0006]	0.0006
	RCS	Shape parameter for stomatal resistance vs leaf turgor potential (-)	[-8,4]	-5
	XKCO2	Rate constant for Rubisco Carboxylation (uM)	[8, 16]	12.5

1.4.3 Why is precipitation different in tile vs no-tile treatments (Fig. 6)?

Response: Sorry for the confusion. The precipitation under tile and no tile conditions is the same. We have updated the figure to avoid the confusion as follows (Figure 7).

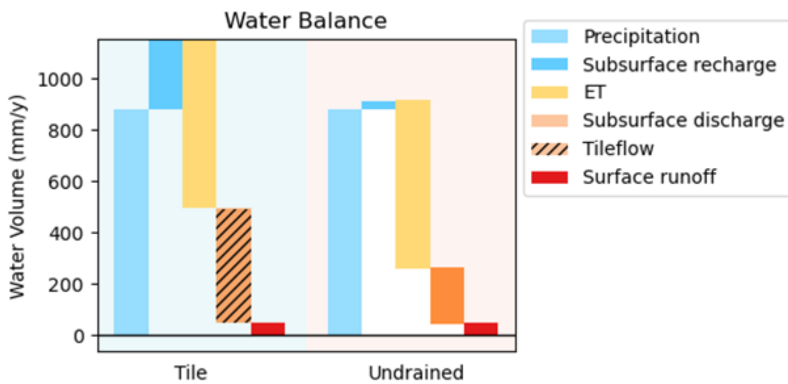

Figure 7: Ecosys-simulated annual water balance under tile and undrained conditions. Overall, tile drainage increases both subsurface discharge (water coming out of the field) and subsurface recharge (water going into the field), and ET and surface runoff are similar under tile and undrained conditions.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

1.5 Increased precipitation experiment:

1.5.1 Why stop at 30% increased precipitation? Why not go further?

Response: A 30% increase is already a large change. Based on the National Climate Assessment, the mean precipitation in the winter and spring may increase around 10% by the end of the century in the U.S. Midwest region (Assessment, 2018), and the IPCC estimates a 7% increase in precipitation for each degree of warming (Predictions of future global climate, 2025). Thus, varying precipitation for -10% to 30% should capture those cases.

1.5.2 How was additional precipitation distributed? The seasonal/daily/hourly distribution of rainfall is important. Please comment on this.

Response: We appreciate the reviewer's insightful comment. We recognize that the allocation of additional rainfall across seasons, days, or hours can significantly impact flood dynamics and, subsequently, crop responses. In our experimental design, we maintained the original seasonality and the intra-daily/hourly structure of precipitation. Instead, we applied a uniform scaling factor to each time step of the original precipitation record, thereby increasing the total seasonal (or annual) rainfall by the specified amount while preserving the relative variability across all timescales, as illustrated in Figure S7. While an increase in extreme rainfall frequency is projected for the future, a standardized method for distributing additional precipitation remains elusive. Furthermore, the uncertainty inherent in distributing additional precipitation could potentially overshadow the signal we aim to investigate. To enhance clarity and prevent misinterpretation, we have incorporated the following description into the main text.

Line 354-363: “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),

$$P = (p_1, p_2, \cdots, p_n)$$

$$P_\lambda = (\lambda p_1, \lambda p_2, \cdots, \lambda p_n)$$

where P is the original precipitation time series that drives the model, and p_i is the precipitation at i-th time step [mm]. P_λ 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."

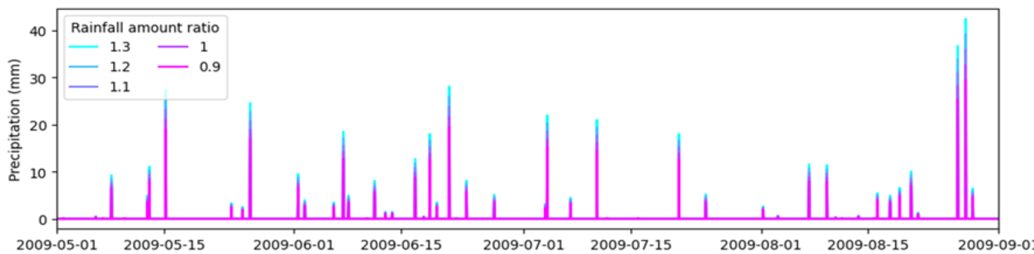

Figure S7. Example of precipitation inputs in the numerical experiments. Basically, we changed the precipitation on each time step with a scaling factor (i.e., 0.9, 1, 1.1, 1.2, and 1.3) to account for the increased rainfall amount.

2. Results:

2.1 Predicted *no impact* or *increase* of surface runoff in the tiled scenario (Fig S10 and line 385)—what is the explanation for this unusual result (normally, surface runoff decreases with tile drainage)?

Response: Thank you for your valuable feedback. We have thoroughly examined our model configurations and pinpointed the elements influencing simulated runoff. Our analysis indicates that surface runoff primarily arises during substantial rainfall, suggesting that an infiltration-excessive mechanism is the dominant factor in its generation. While tile drainage generally reduces soil water content, its impact is more noticeable in deeper soil profiles (Figure S13). The similar soil water content observed in the topsoil layer may result in comparable infiltration rates under both tiled and undrained conditions. Our simplified 1-D column representation of the field restricts surface water holding capacity, which consequently reduces the perceived role of tile drainage in surface water. This rapid removal of surface water likely leads to an underestimation of tile drainage's influence on surface runoff regulation, potentially explaining the absence of observed impact in this scenario. It is also important to note that soil water flow, such as interflow, significantly contributes to observed river discharge and can be challenging to differentiate from surface runoff in observations, potentially being misidentified as such.

Upon reviewing the model's internal processes, we also identified potential numerical inconsistencies. The Richards equation is highly nonlinear, and both the characteristic curve and hydraulic conductance exhibit nonlinear changes with soil water content. The model's internal results suggest that higher water content under undrained conditions leads to a higher infiltration rate, possibly due to elevated hydraulic conductivity (Figure S30). Although the infiltration rate under tiled conditions exceeds that in undrained conditions, surface water is removed by surface runoff due to the reduced surface water residence time in the 1-D column representation. This ultimately leads to a slight increase in surface runoff as total infiltration decreases. Addressing this issue will require additional observations for model calibration or the identification of a more appropriate soil characteristics curve. We have included those figures and the discussion in the supplementary and clearly cite them in the main text.

> **Line 579-581:** "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."

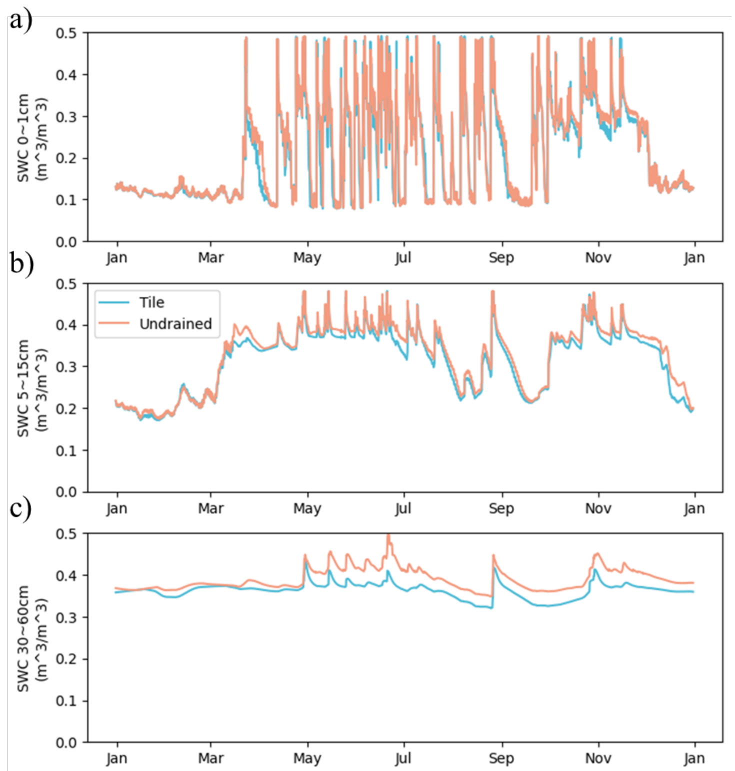

Figure S13. Ecosys-simulated soil water content (SWC) in 2009. Soil water content in a) 0~1 cm soil layer, b) 5~15 cm soil layer, c) 30~60 cm soil layer.

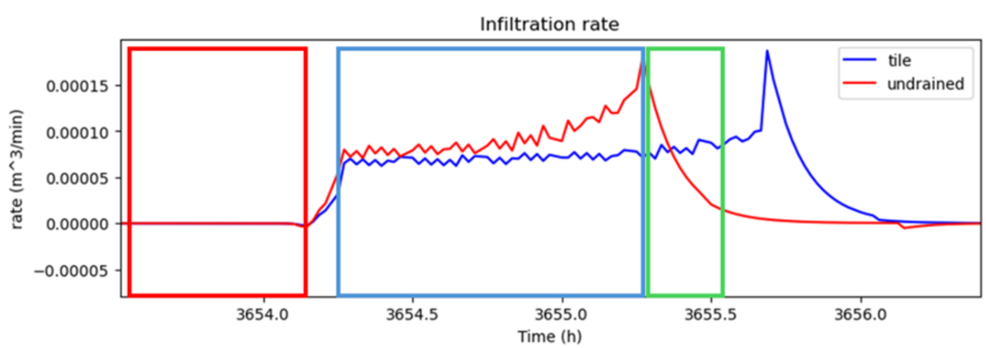

Figure S30. Diagnostic checking for infiltration timeseries during a rainfall event. Though the model drives with hourly inputs, the water fluxes were calculated on a minute time step to ensure numerical stability. The figure shows different stages before and during a rainfall event. In the red rectangular region, no infiltration happens. The soil water content is controlled by gravimetric force and capillary force, affected by soil pores and surface litter. In the blue rectangular region, water infiltrates into the soil. The infiltration rate increases with soil water content, as hydraulic conductivity increases with the increase of soil water content. In the green rectangle, the infiltration rate decreases as soil water increases due to the nonlinearity of the soil characteristic curve (Figure S31). In this process, the water content reaches the air-entry pressure, and infiltration is estimated with saturated hydraulic conductivity, though it is not saturated. This also led to a jump in the figure.

To summarize, the model's internal results suggest that higher water content under undrained conditions leads to a higher infiltration rate, possibly due to elevated hydraulic conductivity (Figure S30). Although the infiltration rate under tiled conditions exceeds that in undrained conditions, surface water is removed by surface runoff due to the reduced surface water residence time in the 1-D column representation. This ultimately leads to a slight increase in surface runoff as total infiltration decreases. Addressing this issue will require additional observations for model calibration or the identification of a more appropriate soil characteristics curve.

The soil water content (θ) based on Richards' equation,

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial t}\left(\frac{K(\theta)}{C(\theta)}\frac{\partial \theta}{\partial t}\right) + \frac{\partial K}{\partial z}$$

$$C(\theta) = \frac{\partial \theta}{\partial h}$$

where θ is the soil water content [m^3 m^(-3)], K is the hydraulic conductivity [m/h]. h is the pressure head given θ [m], and it is highly non-linear, which leads to the quick reduction in the blue rectangular, that is, a small soil water content change will lead to a large potential reduction.

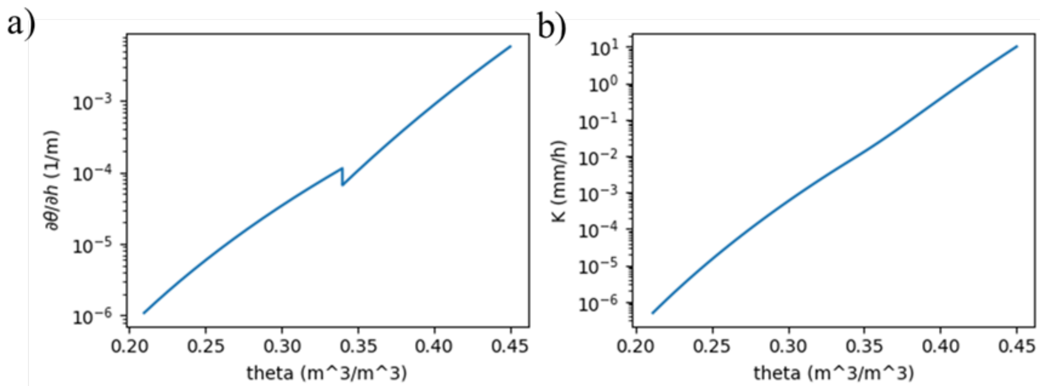

Figure S31. Soil characteristics curve used in *ecosys*. a) the partial derivative of soil water content with respect to soil potential against soil water content, b) the change of soil water content with respect to soil water content.

2.2 What is the mechanism for tile drainage increasing ET in the summer months?

Response: We hypothesized that tile drainage increases ET in the summer months through promoting crop transpiration via stronger roots developed in the early growing season. Figure 11h-j shows the modeled profile of soil water, soil oxygen concentration, and root density on August 15th, 2013 (a dry summer). The results indicate that tile drainage reduces soil water content while promoting root growth. Though the reduced soil water content might expose the crop more to water stress, the developed root offsets the water stress induced by reduced soil water content in our case, which ultimately increases crop evaporation (Figure 11m-n).

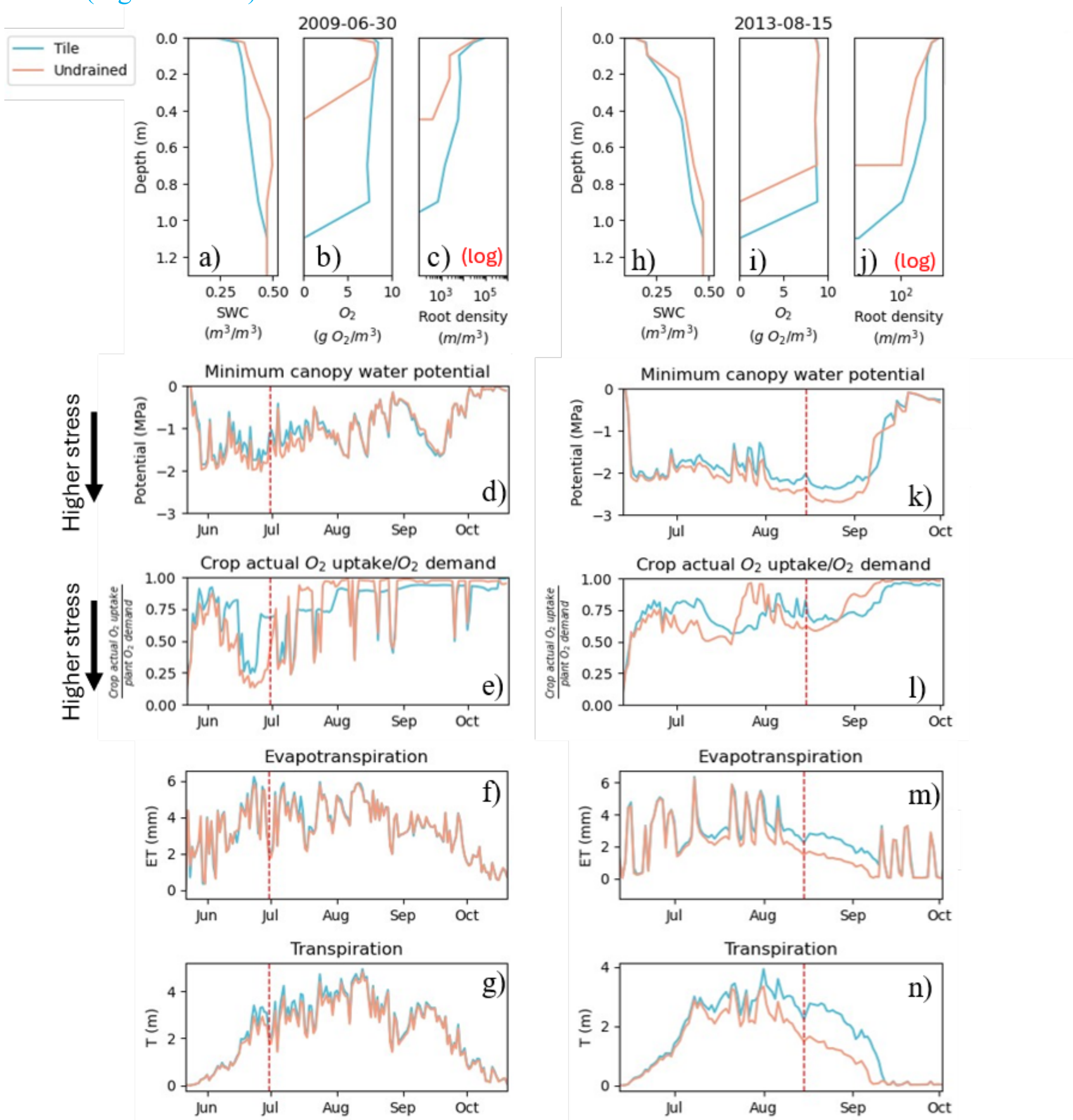

Figure 11: Ecosys-simulated soil profile and time series of water and oxygen stress in typical wet and dry soybean years. The profile of a) Soil water content, b) soil O_2 concentration, and c) root density profiles in the soil column on June 30th, 2009. Time series of d) minimum canopy water potential and e) crop actual O_2 uptake rate/O_2 demand (potential O_2 uptake rate under non-limiting O_2 conditions) 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 O_2 concentration, and j)

root density profiles in the soil column on June 30th, 2013. Time series of k) minimum canopy water potential and l) crop actual O_2 uptake rate/O_2 demand (potential O_2 uptake rate under non-limiting O_2 condition), f) evapotranspiration, g) crop transpiration in the 2013 growing season (a typical year with wet spring and dry summer for soybean). The x axis of c) and j) is in log-scale, see Fig. S29 for the plots showing root density in the linear scale.

2.3 Fig 6 - keep tile drainage volume separate.

Response: Thanks for the comments. We have updated the figure in the revised paper, see Figure 7 in reply to comment 1.4.3.

2.4 Fig 6 - Is subsurface recharge ("water going into the field") flow from adjacent fields? Please define this parameter?

Response: Sorry for the confusion. The surface recharge in the model is the water going into the field across the subsurface boundary. In reality, this should be the water flow from the surrounding environment, including the adjacent field.

It is not intuitive, and we confirmed recharge does exist through a simple mass balance analysis, as shown in Figure S21. The amount of precipitation (observation) is smaller than the sum of the field evapotranspiration (simulation) and tile flow (observation), and additional water fluxes from the surrounding environment, including the adjacent field, are required. Note that even though the ET is simulated by ecosys, we confirm that the annual mean ET (659 mm) is typical in a corn/soybean field.

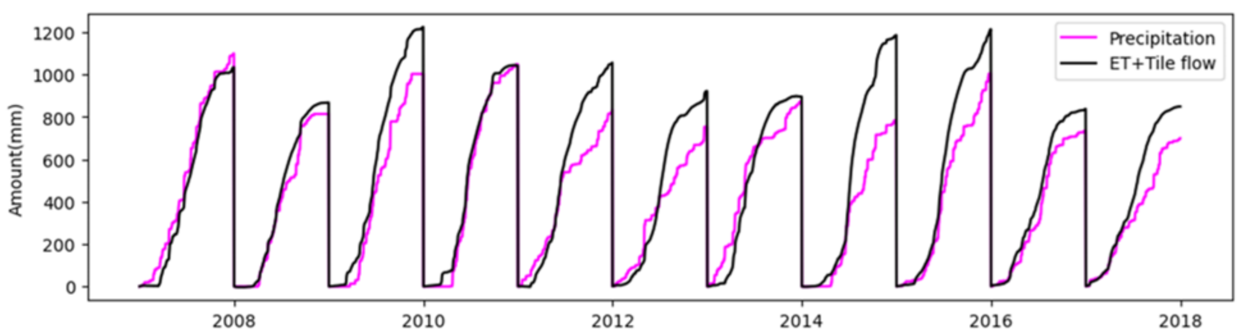

Figure S21. Cumulative precipitation and cumulative *ecosys*-simulated ET+observed tile flow. The results suggested that the precipitation can't sustain both tile flow and field evapotranspiration, and recharge from an external source is required to close the system water balance.

3 Conclusions

3.1 Conclusions drawn by the authors do not really challenge or go beyond what we already know about the impacts of tile drainage on soils and crop growth--but I think there is a potential to do so. This seems like a missed opportunity with the novel approach taken by this study. Recommend reevaluating the discussion and conclusions to focus on unique aspects of this study.

Response: We appreciate the comments and suggestions. We acknowledge the extensive existing literature on the impacts of tile drainage on hydrology and crop growth. We assert that this study is distinguished by two key aspects. Firstly, we adopt an integrated systems perspective, examining the complex interactions and feedbacks among natural/climatic/hydrological, ecological and agricultural, and social processes within the tile drainage system, including soil oxygen dynamics simulation. Secondly, we move beyond a black-box approach by employing the Ecosys model, which captures critical ecological and biogeochemical processes. Unlike previous studies, our model explicitly simulates oxygen dynamics and the root system, thereby enhancing our understanding of the tile drainage system. The incorporation of plant hydraulics representation (Zhang et al., 2021) further allows us to evaluate the system under intricate scenarios, such as the combined occurrence of a wet spring followed by a dry summer. Consequently, this study represents a distinct and comprehensive examination of the effects of tile drains, diverging significantly from prior research. The insights derived from this investigation can inform the development of simplified, coupled models tailored to this specific region. We have revised the discussion and conclusion accordingly to bring out those innovations.

> **Line 23-44 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 is 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."

> **Line 526-544 Discussion Section 4.1**: "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)"

Line 688-700 Conclusion: "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:"

4. Other comments in the supplement files

Response: Many thanks for the detailed checking of our manuscript. I have corrected the specific grammar issues and did not list those comments here

4.1. Line 25, “in the U.S. Midwest”. Tile drainage is not only used in the U.S. Midwest but also throughout the world.

Response: Thanks for the correction. We have revised it.

4.2 Line 27, “their connections are poorly understood and highly uncertain”. This is not the case, so further justification and reference are needed for the authors to make this assertion.

Response: Thanks for the comment. We have revised it and changed the statement as follows:

> **Line 24-27:** “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 is critical to unravelling these interactions and has been ignored or oversimplified in existing models.”

4.3 Line 35, “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.” These impacts are well-known. Perhaps the authors can make a more specific statement that alludes to the unique findings of this work.

Response: Thanks for the comments. We have revised the abstract, and stress the novelty of this work as 1). using a model with first-principle mechanisms to reveal the impacts of tile drainage on the hydrology-biogeochemistry-crop system. 2) Our work reveals the underlying causal mechanisms that drive agroecosystem response to drainage on hydrology, biogeochemistry, crop growth, and their interconnections. Please see the reply for comment 3.1.

4.4 Line 41, “The model reveals the inherent connections of tile drainage’s impacts on hydrology, soil biogeochemistry, and plant growth.” Same comments as before--well-understood effects of tile drainage

Response: Thanks for the comments. Similarly, we have revised the abstract accordingly to bring out the innovation of our study. Please see the reply for comment 3.1.

4.5 Line53-56, Recommend finishing this thought by saying that the practice of tile drainage will become even more important and thus, understanding the impacts .....

Response: Thanks for the correction. We have revised accordingly.

> **Line 55-59:** “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., 2022). Thus, understanding the tile drainage impacts and managing the hydrological condition over the Midwestern agroecosystem are critically needed.”

4.6 Line64, “These local-scale changes additionally alter watershed hydrology”. Need a reference.

Response: Thanks for the correction. We have added citations to show the tile drainage across different scales.

Example of the impact of tile drainage at the field scale: (Woo and Kumar, 2019)
Example of the impact of tile drainage at a relatively small scale: (Hansen et al., 2013)
Example of the impact of tile drainage at the regional scale: (Miller and Lyon, 2021)

4.7 Line 83, "The development of tile drainage modules has recently attracted lots of", These have been developed over the last 50 years!

Response: Thanks for the correction. We have corrected it in the revised paper. The idea here is that the development of the tile drainage module is still active in the hydrology and land surface model.

> **Line 84-85:** "Tile drainage modelling has a long history and has recently gained attention for its integration into comprehensive hydrology and land surface models. "

4.8 Line 118-121, "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." Suggest proposing more specific hypotheses. These hypotheses are already well-proven--no need for additional research to address them. Perhaps reword the hypothesis to address your approach of looking at O2.

Response: Thanks for the comments and suggestions. We have revised the hypotheses accordingly to stress the novelty of involving oxygen dynamics to link the impacts of tile drainage on hydrology, soil biogeochemistry, and crop yield.

> **Line 120-127:** "... 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."

4.9 Line 137, Please mention whether Ecosys is a 1- 2- or 3-dimentional model.

Response: We have specified its dimension and the dimension in this study.

> **Line 138-146**: "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; 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, and the 1D configuration also ensures a greater numerical stability."

4.10 Line 266, "Tile flow only occurs in soil layers above the tile pipes". Please provide more detail here. When saturation above the depth of the drains occurs, flow is present both above and below the drains (the flow field involves saturated zone both above, and below the tile). The authors' statement seems to not recognize this. Also, use "tile drains" instead of "tile pipes".

Response: As mentioned before, we have added details about how the model simulates soil water. We acknowledge that both the soil above and below the tile pipe could be drained through tile drains. However, in our model framework, the tile flow is regarded as a horizontal flow in model simulation, similar to the Dupuit–Forchheimer assumption. In this case, tile flow is only calculated in the soil layer above the tile pipes. The vertical soil water movement is governed by the Richards equation. Besides, solute nutrients could move vertically along with vertical water fluxes governed by the Richards equation and through the diffusion process.

We have changed "tile pipes" to "tile drains" all over the paper.

4.11 In Figure 3, What are the black vertical dots representing in the figure?

Response: Sorry for the confusion. We have revised the paper and noted that the dots represent omitted soil layers.

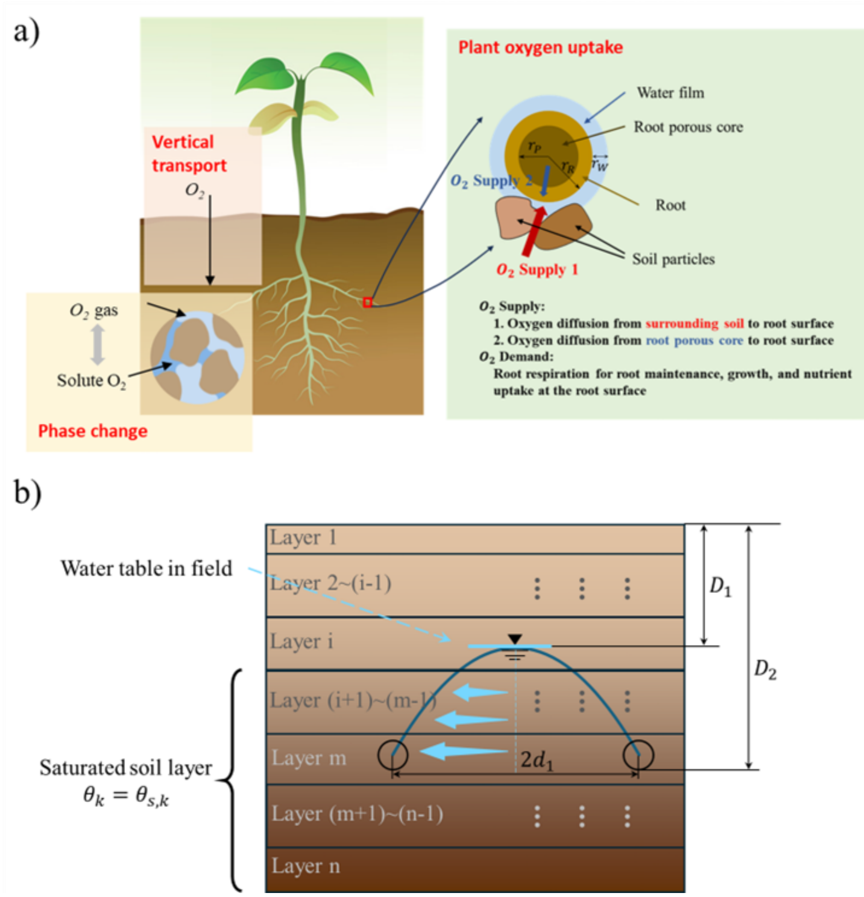

Figure 3: Representation of a) oxygen dynamics and root oxygen uptake, and b) subsurface tile flow in the ecosys model. r_R is root radius $[m]$; r_W is the thickness of the water film $[m]$; r_P is the radius of the root porous core $[m]$. D_1: Water table depth in the field $[m]$; D_2: Tile depth $[m]$;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

4.12 Line 279, I think you are hinting at spatial scale here, but not stating it, specifically. What is your spatial scale--the entire US Midwest? If so, what are the boundaries of your system?

Response: This paper performs a diagnostic analysis at an experimental site in the Iowa State University Southeast Research and Demonstration Farm in Washington County (Figure 4). To avoid the confusion, I have removed this related statement.

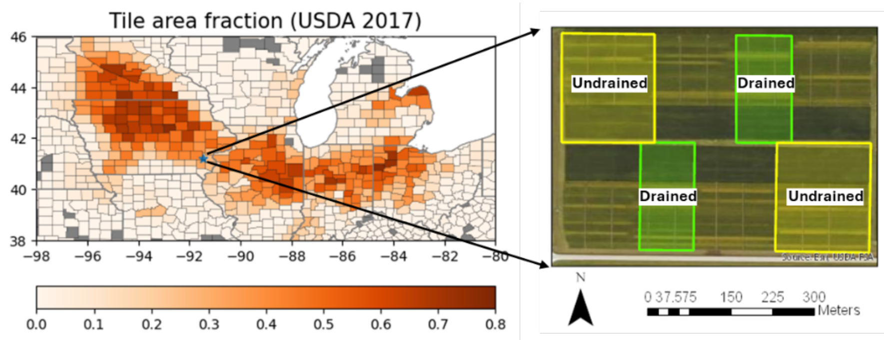

Figure 4: Tile fractions over the U.S. Midwest region, and the location and layout of the selected experiment field. The yellow boxes represent sub-fields without tile drainage, and the green boxes represent sub-fields with conventional drainage.

4.13 Line 288, this figure (Fig S5) should be improved and placed in the main paper. There is no scale or dimensions and the text in the figure is not very clear. As this is key to the calibration & validation, it should be described more clearly.

Response: We have revised the figure and moved it into the main text (Figure 4).

4.14 Line 290, Provide more detail on these soils--at least giving the soil types. Even better to show soil properties with depth.

Response: We have provided the details of the layered soil information in Table S2.

> **Line 307**: "The major soil types in this site are Tanitor and Kalona soils (silty clay loam soil)... 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."

Table S2. Layered soil information for model setup from gSSURGO dataset.

hzname (-)	layer top (cm)	layer bottom (cm)	Bulk density (g/cm3)	Sand (%)	Silt (%)	Field Capacity (m3/m3)	Wilting Point (m3/m3)	Ksat (mm/h)	Organic Matter (gC/kg)	PH (-)	CEC (cmol+/kg)
Ap	0	23	1.35	2	68	0.335	0.21	10.80	23.2	6.5	24.6
A1	23	41	1.35	2	64	0.34	0.219	10.80	17.4	6	27.1
A2	41	51	1.35	2	61	0.345	0.229	2.52	14.5	6	29
Btg1	51	61	1.38	2	57	0.31	0.226	0.32	2.9	6	30
Btg2	61	71	1.38	2	58	0.307	0.221	0.32	2.9	6	29.4
Btg3	71	91	1.38	2	62	0.332	0.205	2.52	2.9	6	26.9
Btg4	91	117	1.45	2	65	0.328	0.198	10.80	2.9	6.4	24.9
Cg	117	152	1.45	2	70	0.31	0.169	10.80	2.9	6.9	21.6

4.15 Line 295, use "cm" or "mm".

Response: Thanks for the correction. We will correct it in the revised paper.

4.16 Line 305, “we simply assumed that precipitation is uniformly distributed over two distinct hours”. Why do this, when other techniques for distributing rainfall, exist?

Response: Thanks for the comment. Although techniques exist to downscale precipitation, these approaches primarily rely on the probability distribution of known high-resolution precipitation information, such as the AWE-GEN method. It lacks the reference at the study site, and it also introduces uncertainty by referring to other stations far from the study site. We think the current downscaling method could satisfy our needs to reveal the mechanisms of how tile drainage affects the system. We have added information in the main text.

> **Line 324-328:** “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.”

4.17 Line 306, “The soil information was obtained from The Gridded Soil Survey Geographic Database”. The research site did not have soil characterization data? Explain why gSSURGO data was used instead of site data.

Response: The research site has some measured soil data. However, not all the soil data required to drive the model is provided. Thus, we used gSSURGO to drive the model.

4.18 Line 307, “External water table depth”. Please explain what "external water table depth" is, and how it is used.

Response: As stated above, we have added a subsection (Section 2.1.4) to define the relevant terms and provided a detailed description in the supplementary materials.

.

> “Text S2. Subsurface water fluxes
>
> The soil water flow in ecosys is governed by Richards’ equation,
>
> $$\frac{\partial \theta_w}{\partial t} = \frac{\partial}{\partial z}\left(K(\theta_w)\left(\frac{\partial h}{\partial z} + 1\right)\right) - S \qquad (S7)$$
>
> where θ_w is the soil water content $[m^3\ m^{-3}]$; $K(\theta_w)$ is the soil hydraulic conductance at θ_w $[m/h]$. S is soil water sink term $[m^3\ m^{-3}\ h^{-1}]$, including plant and mycorrhizal water uptake, lateral water exchange, and discharge to tile drainage. The lateral water exchange is controlled by lateral subsurface boundary condition, with a specific external water table depth and a specific lateral distance over which lateral subsurface water flow occurs.

Lateral water exchange and discharge to tile drainage are simulated with Darcy's flow in saturated soil,

$$v = \frac{K\Delta D}{d} \qquad (S8)$$

where v is the flow velocity $[m/h]$; K is the saturated hydraulic conductance $[m/h]$; ΔD is the pressure drop $[m]$ over a distance d $[m]$. The lateral water exchange is controlled by lateral subsurface boundary conditions, 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. In the calculation of the lateral water exchange with the external water table, the pressure drop is defined as the difference between the internal water table depth and the external water table depth $(D_3 - D_1)$, and the distance is then defined as the distance to the external water table (d_2). A positive velocity indicates water leaving the field to the external water table, and a negative velocity indicates water entering the field from the external water table. For the tile flow, the pressure drop is defined as the difference between the internal water table depth and tile depth $(D_2 - D_1)$, and the distance is then defined as half of the tile space (d_2). 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,

$$D_1 = \left(d_s - \frac{L_i\theta_i}{\theta_{i,s}}\right) \qquad (S9)$$

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 $[m^3/m^3]$.

"

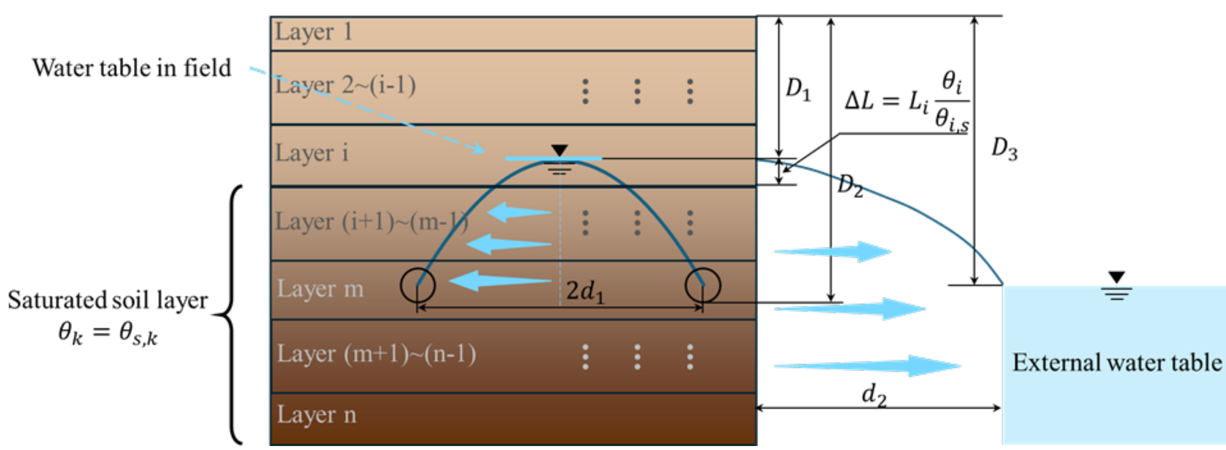

Figure S4. Representation of subsurface water flow. D_1: Water table depth in the field $[m]$; D_2: Tile depth $[m]$; D_3: External water table depth $[m]$; d_1: Distance to the external water table

$[m]$; $2d_2$: Tile spacing $[m]$; θ_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: The thickness of the i-th soil layer $[m]$

4.19 Line 310, "Half of 310 the tile spacing is 9.15 m." Preferable to list the tile spacing.

Response: Thanks for the suggestion. We have revised it.

4.20 Line 315, Need to provide details on precisely what parameters were used for calibration and the range of values used.

Response: Thanks for the suggestion. We have listed the parameters, their definition, ranges, and final values in Table S1.

Table S1. Calibrated plant parameters in *ecosys*

Crop	Parameters	Explanation	Range	calibrated values
Corn	GroupX	Plant maturity group: Node number required to start floral initiation (-)	[13,17]	15
	Chl4	Fraction of leaf protein in mesophyll chlorophyll for C4 plants (-)	[0.015,0.055]	0.025
	Gfill	Maximum rate of kernel filling (g seed-1 h-1)	[0.0004, 0.0008]	0.0004
	RCS	Shape parameter for stomatal resistance vs leaf turgor potential (-)	[4, 8]	6
	XKCO2	Rate constant for Rubisco Carboxylation (uM)	[20, 30, 40]	40
soybean	GroupX	Plant maturity group: Node number required to start floral initiation (-)	[13, 19]	17
	VCMX	Specific rubisco carboxylase activity (umol g-1 s-1)	[35 ,50]	45
	Gfill	Maximum rate of kernel filling (g seed-1 h-1)	[0.0002, 0.0006]	0.0006
	RCS	Shape parameter for stomatal resistance vs leaf turgor potential (-)	[-8,4]	-5
	XKCO2	Rate constant for Rubisco Carboxylation (uM)	[8, 16]	12.5

4.21 Line 335, "We found that ecosys is promising in estimating both crop yield and tile drained flow in the tile." You are stating results before you have presented any results. Please present results first, discuss them, and then make conclusions later.

Response: Thanks for the suggestion. We have revised the statement accordingly.

Line 366: "The *ecosys* model's crop yield simulations were evaluated against field observations (Fig. 4 and Table 3). Overall, the Pearson coefficient r …"

4.22 Line 340, use Metric units!

Response: Thanks for the correction. We revised the units here and all over the manuscript.

4.23 Table 2, label the calibration and validation

Response: Thanks for the correction. We have updated the table.

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 (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

4.24 Line 397, "the annual mean total inorganic nitrogen (IN) loss from surface runoff and subsurface discharge is 2.72 $gg\ NNmm{-}2$ and 1.89 $gg\ NNmm{-}2$ for tile and no-tile". Fig 8 does not show annual mean. Please add to figure.

Response: Thanks for the suggestions. We have added the boxplot at the annual scale in the revised paper.

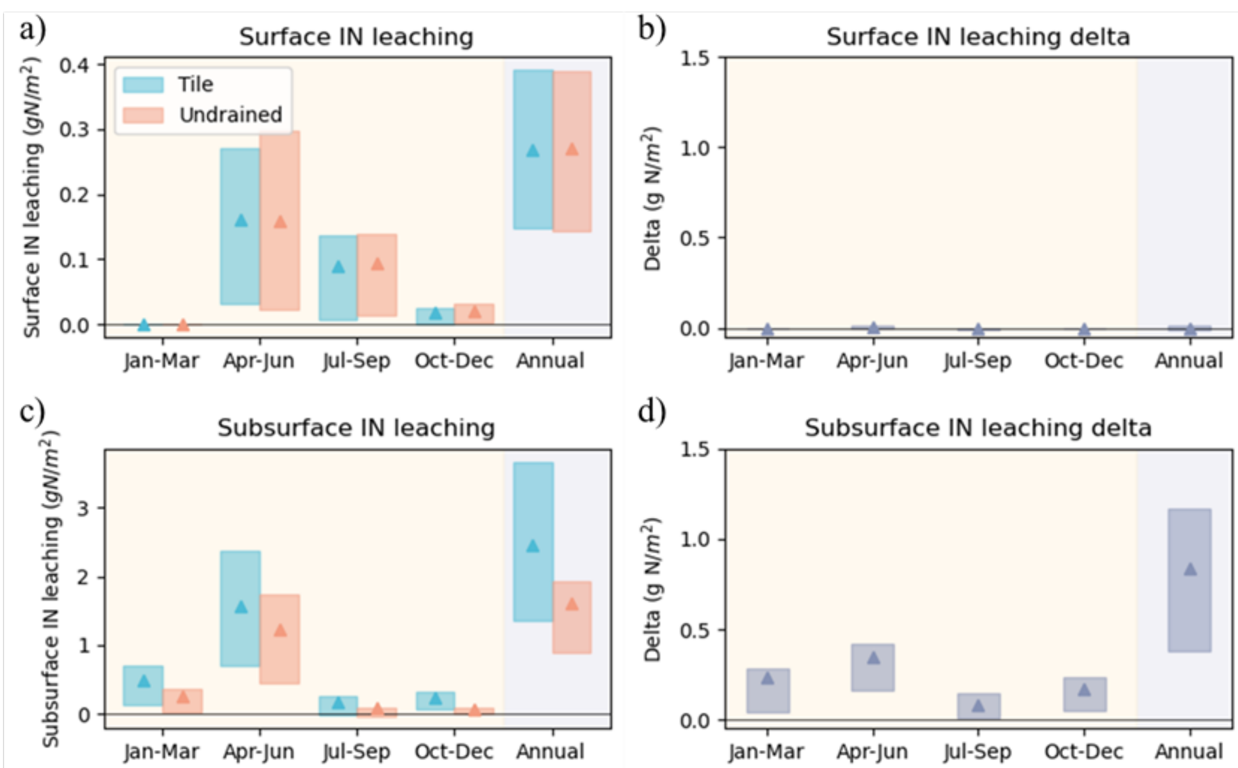

Figure 9: *Ecosys*-simulated inorganic nitrogen (IN) lost under tile and undrained conditions from 2007 to 2017. a) Boxplot of the quarterly and annual subsurface inorganic nitrogen discharge, b) Boxplot of difference of the quarterly and annual subsurface inorganic nitrogen loss between tile and undrained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

4.25 Line 399, "Tile drainage primarily increases subsurface inorganic nitrogen leaching," The word "leaching" is a poor choice. Surface losses are not typically referred to as "leaching" and subsurface losses are either losses, or transport of N. If deep percolation to groundwater is mentioned, then the term "leaching" is appropriate, in this instance.

Response: Thanks for the correction. We have corrected the usage all over the manuscript.

4.27 Line 407, "Furthermore, model results show that nitrogen leaching increases with the total precipitation (Fig. S12)." Why not plot annual N loss vs precipitation?

Response: Thanks for the suggestion, we have added the scatter plots to show nitrogen loss against mean annual precipitation under the hypothetical rainfall amount test.

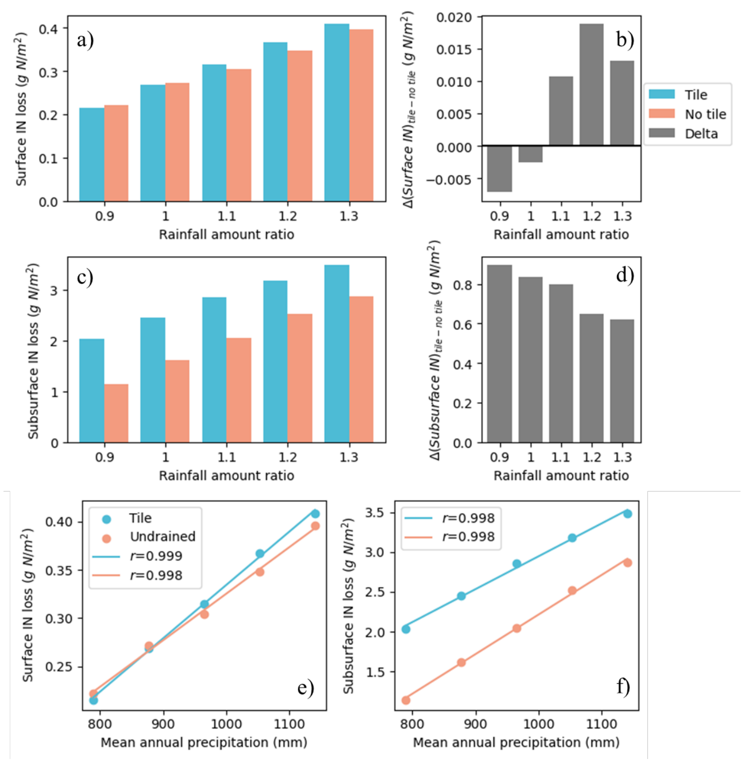

Figure S12. *ecosys*-simulated inorganic nitrogen (IN) leaching in the hypothetical numerical experiment under different precipitation. a) Multiyear mean surface IN loss under tile and undrained conditions**. b)** The tile-induced surface IN loss increase (surface IN loss difference between tile and undrained conditions)**. c)** Multiyear mean subsurface IN loss under tile and undrained conditions**. d)** The tile-induced subsurface IN loss increase (subsurface IN loss difference between tile and undrained conditions). **e**) Scatter plot of multiyear mean surface IN leaching against multiyear mean precipitation. **f**) Scatter plot of multiyear mean subsurface IN loss against multiyear mean precipitation.

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Reply to Referee 2:

In the following responses, reviewers' comments are reproduced in their entirety in black, and the authors' responses are noted in blue. The text that appeared in the manuscript is indented.

1. The manuscript presents a modeling assessment of the impact of tile drainage on hydrology, biogeochemistry, and crop growth at a representative US Midwest agroecosystem. Using the model ecosys, the work reveals the interconnected processes that lead to increased subsurface discharge, subsurface nitrogen leaching, soil oxygen content, net mineralization, crop growth, and resilience to precipitation variability. Overall, the manuscript presents comprehensive and solid analysis that contributes to advancing the current understanding of drainage-managed agroecosystems and supporting agricultural management. Below are specific comments aiming to help enhance the clarity and interpretation of the findings.

Response: Thanks for your positive comments! Please see the point-by-point response below.

2. The work leverages the detailed mechanistic description of root-zone processes in ecosys, which offers the unique opportunity to diagnose interactive hydrological, biogeochemical, and ecophysiological processes. As pointed out multiple times in the manuscript, the root distribution, particularly rooting depth, is a critical factor that drives the benefits of tile drainage for yield, including enhanced nutrient and oxygen supply and access to deeper moisture in summer. Are there data or relevant work supporting deeper roots in tile drainage settings? It would also help to include explicit quantification or discussion on how the uncertainty of model-simulated rooting depth might affect the robustness of the findings, e.g., on yield and plant water stress.

Response: Thanks for the suggestions to enhance the validity by including explicit quantification or discussion on the uncertainty in the root depths simulation. It is a good point to strengthen the model results. However, some of the variables illustrated in this work are hard to measure (e.g., root distribution, soil oxygen concentration, etc.), especially in the field. We looked into the literature and did not find an available site with root depth measurement under tile and no-tile conditions. However, many studies show that a high water table reduces root depths, and roots are less developed under waterlogging. For instance, Ordóñez et al (2018) analyzed the maximum root depth in six field traits over the U.S. Midwest and found that root maximum depth decreased with water table depth increase for both corn and soybean. (Ordóñez et al. 2018). Follett et al (1974) also illustrated that root depth and density decreased with water table depth increase in a control experiment at a single site (Follett, Allmaras, and Reichman 1974). Ren et al. (2016) performed soil columns in the lab to investigate the effect of waterlogging on corn roots developed at different growth stages, and showed that waterlogging reduced corn root depth and density and corn is more susceptible to waterlogging at the early growth stage (V3 in their work) (Ren et al. 2016). We have added the following discussion in the main text,

> **Line 554-559: Section 4.1:** "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. "

Line 632-635: Section 4.4: "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."

3. Model validation & Fig. 4: Based on the description of available site data, the crop yield record includes the typical wet and dry years presented in Fig. 10. Can the validation be shown in a time series so that it illustrates whether field data supports the advantages of tile drainage in extreme (wet and dry) years (Fig. S13), apart from the long-term averages presented in Table 3? The comparison could also help gauge the confidence in the benefits of yield resilience to precipitation variability derived from simulations (Fig.S18).

Response: Thanks for the suggestion. We have updated the figure. We now display time series of simulated and observed crop yield as c panel in Figure 5. In general, the time series shows that tile drainage benefits crop yield in both wet and dry years.

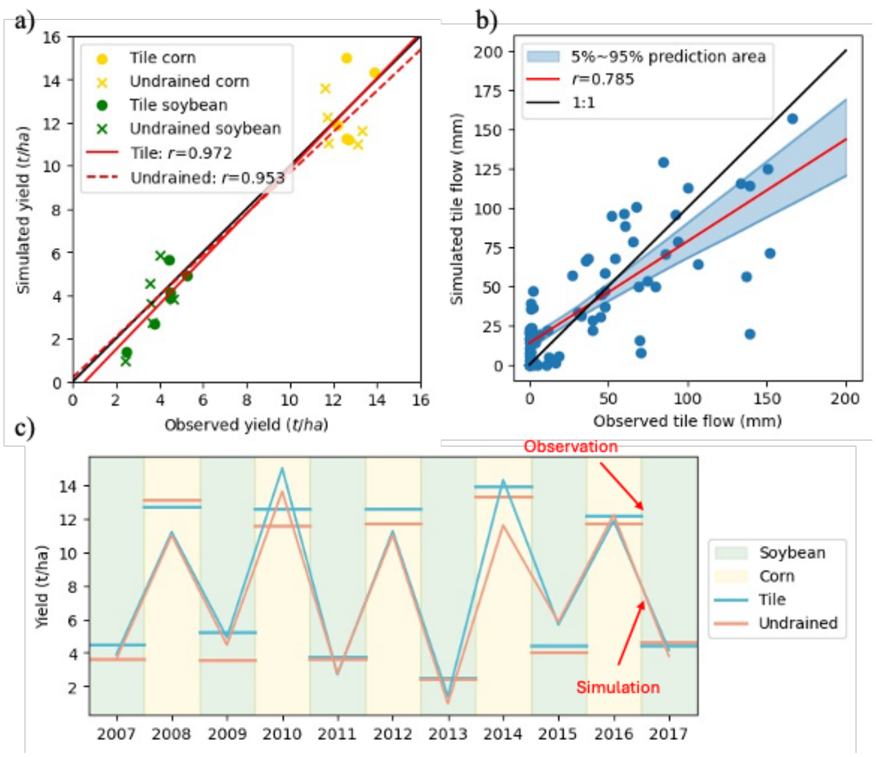

Figure 5: Validation for crop yield and tile flow. Comparison of *ecosys*-simulated and ground-measured **a**) maize (15 % moisture) and soybean (13 % moisture) grain yield, and **b**) monthly tile flow in the growing season (April to October). **c**) Time series of simulated and observed yield. Corn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

4. Section 2.2.1 Field Data: It would help to describe the distance between the two sites, tile and no tile, and if there are additional differences in site characteristics such as slope, soil texture etc. The distance

between the two sites might be relevant as the precipitation amount for the two sites is not trivial (Fig. 6). Why is this the case?

Response: Sorry for the misunderstanding. The experimental fields are close to each other. Except for tile drainage settings, there is no other difference between the tile-drained and undrained conditions. In the revised manuscript, we have included Figure 4 to show the geological location of the two sites. Figure 7 (previously Figure 6) has been revised to avoid the confusion about the precipitation settings. Also, the soil information and soil map in the study site are shown in Figure

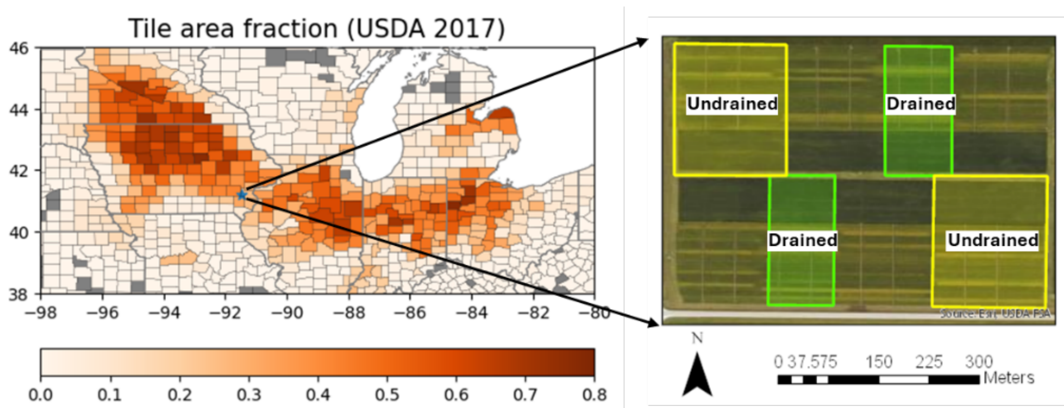

Figure 4: Tile fractions over the U.S. Midwest region, and the location and layout of the selected experiment field. The yellow boxes represent sub-fields without tile drainage, and the green boxes represent sub-fields with conventional drainage.

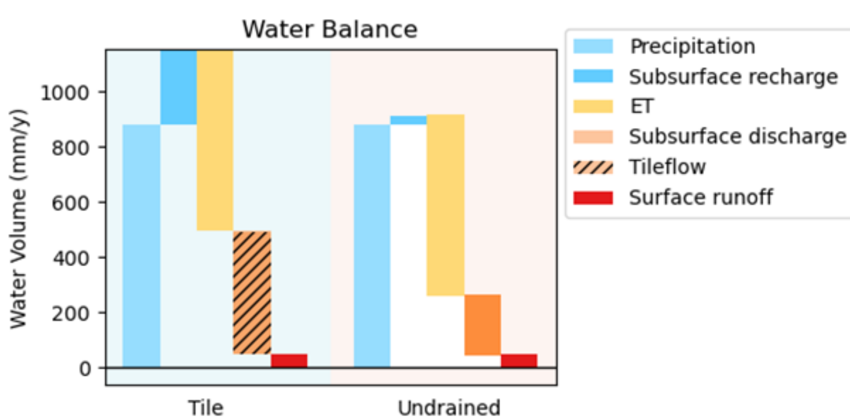

Figure 7: Ecosys-simulated annual water balance under tile and undrained conditions. Overall, tile drainage increases both subsurface discharge (water coming out of the field) and subsurface recharge (water going into the field), and ET and surface runoff are similar under tile and undrained conditions.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

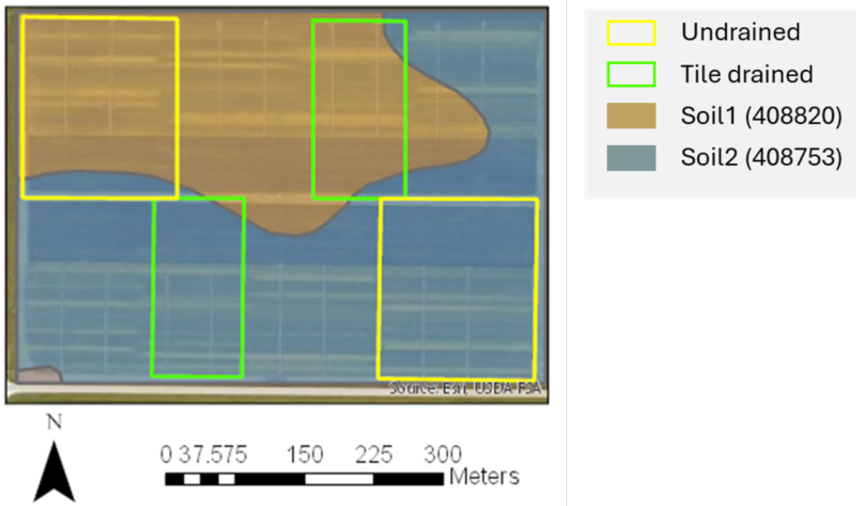

Figure S6. Soil type in the targeted field from the gSSURGO soil type. Soil 1 is the Kalona silty clay loam soil with MUKEY of 408820; Soil 2 is the Taintor silty clay loam soil, with MUKEY of 408753. Both soils have high silt and clay content.

Table S2. Layered soil information for model setup from gSSURGO dataset.

hzname (-)	layer top (cm)	layer bottom (cm)	Bulk density (g/cm3)	Sand (%)	Silt (%)	Field Capacity (m3/m3)	Wilting Point (m3/m3)	Ksat (mm/h)	Organic Matter (gC/kg)	PH (-)	CEC (cmol+/kg)
Ap	0	23	1.35	2	68	0.335	0.21	10.80	23.2	6.5	24.6
A1	23	41	1.35	2	64	0.34	0.219	10.80	17.4	6	27.1
A2	41	51	1.35	2	61	0.345	0.229	2.52	14.5	6	29
Btg1	51	61	1.38	2	57	0.31	0.226	0.32	2.9	6	30
Btg2	61	71	1.38	2	58	0.307	0.221	0.32	2.9	6	29.4
Btg3	71	91	1.38	2	62	0.332	0.205	2.52	2.9	6	26.9
Btg4	91	117	1.45	2	65	0.328	0.198	10.80	2.9	6.4	24.9
Cg	117	152	1.45	2	70	0.31	0.169	10.80	2.9	6.9	21.6

5. Fig. 6: Related to the above, the differences in hydrological budget between the tile and no tile sites seem comparable or smaller than the difference in precipitation. How do the confounding factors, including precipitation and possibly other site characteristics, affect the interpretation of differences in hydrological budgets?

Response: Sorry for the misunderstanding. Except for tile drainage settings, there is no other difference between the tile-drained and undrained conditions. We have revised this figure to avoid confusion (see the updated Figure 7 above).

6. The results and discussion on tile-induced ET change could be clearer. It is unclear how the moisture profile and plant water stress affect ET in wet and dry years, which can be improved by including subpanels showing ET time series in Fig. 10. The discussion in L554-565 makes it difficult to draw the message clearly, and separate between findings here and in the previous studies.

Response: Thanks for the suggestion. We have revised and updated the figure (Figure 11). In 2009, the model suggested that the tile drainage promoted crop transpiration during the early growing season. In 2013, the role of tile drainage was more pronounced during the dry summer. Given less soil water as shown in Figure 11h, the crop under the tile conditions was predicted with higher transpiration, which evidenced that the more developed root system helped crops access soil water in deeper soil.

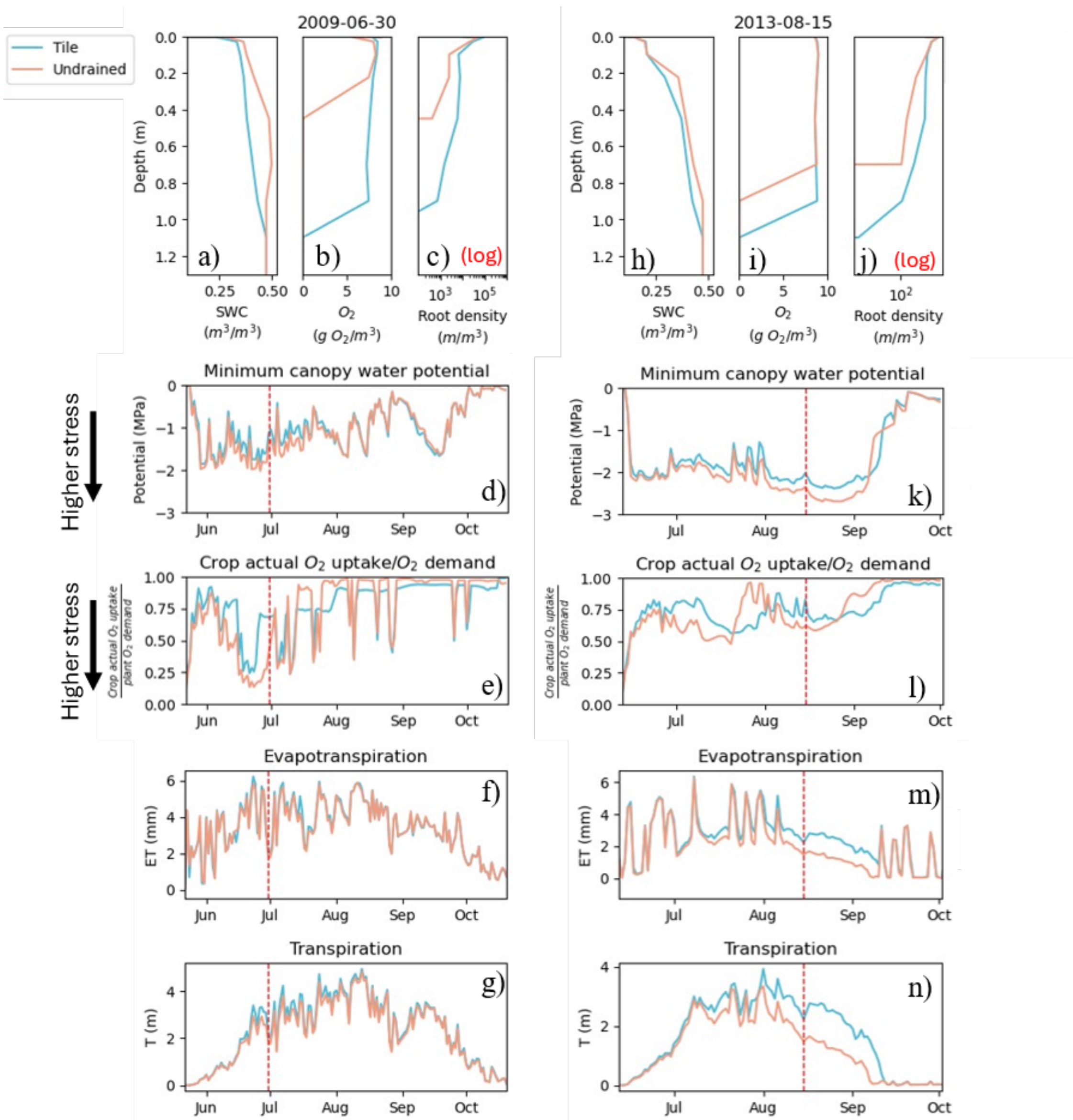

Figure 11: Ecosys-simulated soil profile and time series of water and oxygen stress in typical wet and dry soybean years. The profile of a) Soil water content, b) soil O_2 concentration, and c) root density profiles in the soil column on June 30th, 2009. Time series of d) minimum canopy water potential and e) crop actual O_2 uptake rate/O_2 demand (potential O_2 uptake rate under non-

limiting O_2 conditions) 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 O_2 concentration, and j) root density profiles in the soil column on June 30th, 2013. Time series of k) minimum canopy water potential and l) crop actual O_2 uptake rate/O_2 demand (potential O_2 uptake rate under non-limiting O_2 condition), f) evapotranspiration, g) crop transpiration in the 2013 growing season (a typical year with wet spring and dry summer for soybean). The x axis of c) and j) is in log-scale, see Fig. S29 for the plots showing root density in the linear scale.

.

7. Fig. 10: It could help to compare the profiles shown in panels f-h but on the driest days in August to understand drought-induced stresses.

Response: Thanks for the suggestions. We have revised the figure and shown the soil profile on August 15th now (Figure 11, see above).

Crop suffers high water stress at this day, as indicated by a large absolute canopy water potential (Figure 11i). The results show that the soil water content under the tile condition is smaller, which might put more water stress on the crop. However, the root under tile conditions is more developed, and the developed root ultimately increases the ET in June and August. In this case, the benefit of tile drainage overcomes its negative impacts in our model.

8. Fig. 11 & L460-464: Should the low variability of yield to precipitation increase be interpreted by high resilience or low sensitivity to precipitation rather than high resilience? Also, while the Midwest is projected with increasing average precipitation, the variability is also increasing. How does tile drainage impact yield in droughts, e.g., when the rainfall amount ratio falls below 0.9? Quantification or discussion on this aspect could help clarify the interpretation of the impact of tile drainage. Also, should "1.3 times greater than" in the legend of Fig. 11 be "1.3 times of"?

Response: Thanks for the comments. We suppose those are two perspectives to see the system. Tile drainage increases the drainage ability and makes the crop less sensitive to the increase in precipitation, and this is equivalent to the system having a high resilience to precipitation increase. For instance, the IPCC defines resilience as "The capacity of interconnected social, economic and ecological systems to cope with a hazardous event, trend or disturbance, responding or reorganising in ways that maintain their essential function, identity and structure" (Writing Team et al., 2023).

We acknowledge that, except for the rainfall amount, the precipitation variability is also a concern under climate change, which might lie on two sides: 1) imbalanced precipitation distribution, with more precipitation in the winter and spring and less precipitation in the summer; 2) more frequent extreme precipitation (Ford et al., 2021; Zhou et al., 2022). In our work, we discussed the role of tile drainage under two cases: 1) varying precipitation with a scalar directly applied to the input precipitation time series to mimic the increased rainfall amount. This also sheds insights on how the system responds to more intensive precipitation, as the scalar larger than 1 results in more intensified precipitation. 2) showing a case study on a wet spring and dry summer to account for the imbalanced precipitation distribution.

In terms of investigating the role of tile drainage in droughts, we tend to limit the discussion to the specific case in 2013. The scenarios under various precipitation mainly target at understanding the system's response to wetter conditions, rather than drought conditions, as precipitation might not be a key control factor in crop productivity. Some studies have shown that temperature, controlling VPD, might be more important. We have clarified this in the main text. After consideration, we also tuned down the tone to state the benefit of tile under drought conditions, given that significant yield reduction is observed even under tile conditions (Figure S18).

> **Line 354-363:** "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),
>
> $$P = (p_1, p_2, \cdots, p_n)$$
>
> $$P_\lambda = (\lambda p_1, \lambda p_2, \cdots, \lambda p_n)$$
>
> where P is the original precipitation time series that drives the model, and p_i is the precipitation at i-th time step [mm]. P_λ 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."
>
> **Line 651- 656:** "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. 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 (Singh et al., 2022; Youssef et al., 2023)."

The detailed results to verify the tile drainage benefits crop growth in the 2013 dry summer can be found in Text S9. To ensure the model correctly reflects drought stress, we performed a numerical experiment. We replace the climate drivers (i.e., precipitation) from June to August in 2013 with those in 2008, and run the model without tile drainage, named "no tile (normal)" (Figure S15). The precipitation from June to August in 2008 is close to the average precipitation. We assume the crop will not suffer drought stress in this hypothetical experiment. The simulated results showed that crop yield under the "no tile (normal)" is higher than that in the tile-drained and undrained cases, driven by actual climate forcings (Figure S16). The absolute minimum canopy water potential under the "undrained (normal)" is the smallest, indicating the crop suffers less water stress (Figure S17a). Through this hypothetical experiment, we could confirm 1) the crop suffers from water stress under both tile drainage conditions and undrained conditions; 2) the developed root helps to mitigate drought under tile drainage conditions.

We acknowledge that tile might lead to higher drought stress. However, it's a balance between the promoted root depth and reduced soil water content, and our simulation results show that the tile benefits the crop in summer drought under excessive water in the early growing period. Due to the limitations of the paper, we could not show all the results of the hypothetical experiment and might leave them in the supplementary.

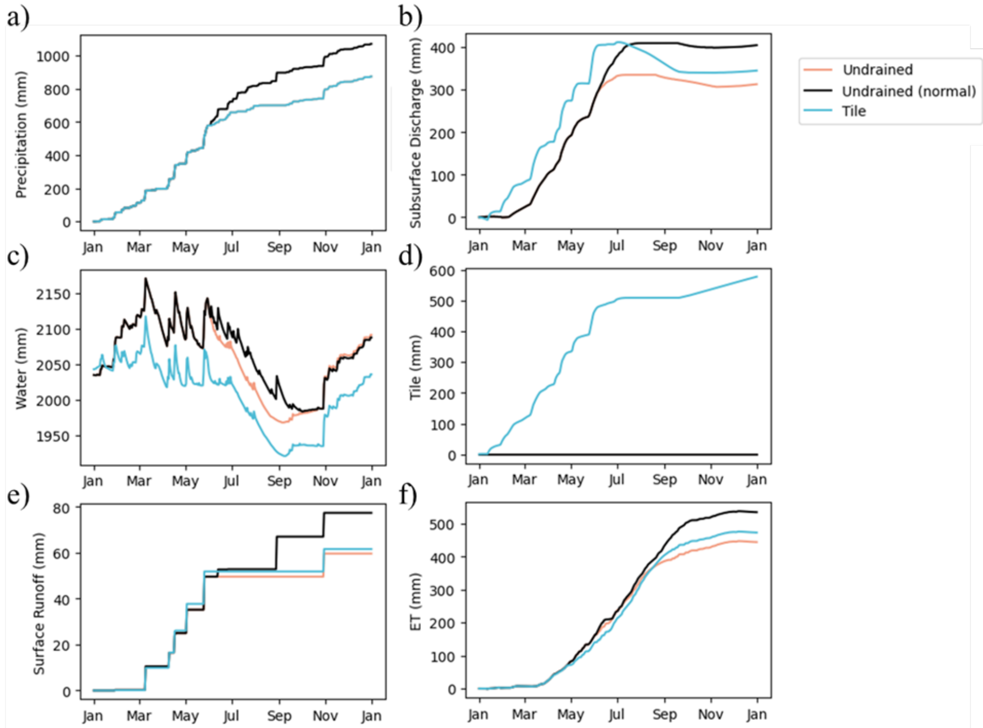

Figure S15. *Ecosys*-simulated water fluxes in 2013. a) Accumulate precipitation. b) Accumulate net subsurface discharge. c) Total soil water content. d) Accumulate tile flow. e) Accumulate surface runoff. f) Accumulated evapotranspiration (ET). The *tile* and *no tile* conditions are driven by the actual climate data from the NLDAS2 dataset and in-situ measurements. The climate forcings in June, July, and August are replaced with those in 2008 under the *no tile (normal)* conditions.

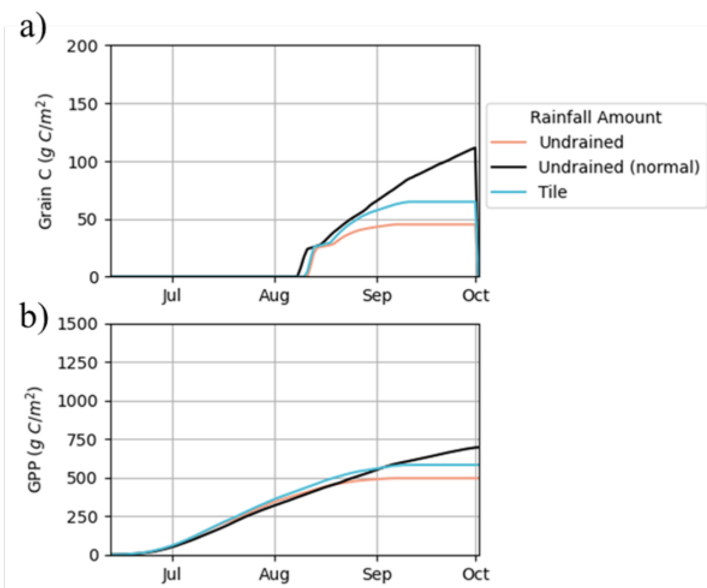

Figure S16. *Ecosys*-simulated a) grain carbon and b) gross primary productivity (GPP) in 2013. The *tile* and *no tile* conditions are driven by the actual climate data from the NLDAS2 dataset and in-situ measurements. The climate forcings in June, July, and August are replaced with those in 2008 under the *undrained (normal)* conditions

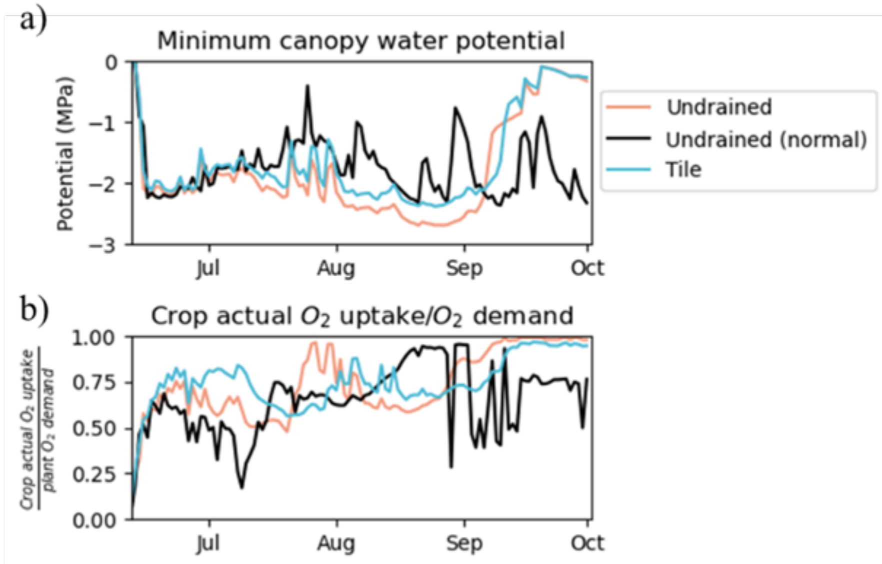

Figure S17. ***Ecosys*-simulated time series of water and oxygen stress in 2013. a**) minimum canopy water potential and **b**) crop actual O2 uptake rate/O2 demand (potential O2 uptake rate under non-limiting O2 conditions) in 2009. The *tile* and *undrained* conditions are driven by the actual climate data from the NLDAS2 dataset and in situ measurements. The climate forcings in June, July, and August are replaced with those in 2008 under the *undrained (normal)* conditions.

9. Line 595-599 & L617: Related to the above, deeper roots allow access to deeper water but might also expose the roots to low soil water potential in thicker dry soils in extreme droughts. Would it induce a potential risk of tile drainage?

Response: We appreciate your feedback and acknowledge this as a potential risk. Our model results and observations indicate that crops experience drought stress during dry summers under both tile-drained and undrained conditions. Generally, tile drainage benefits crop growth. However, in our studies and other peer-reviewed publications, we did not observe tile drainage leading to greater yield reduction, despite some arguments found online. We have incorporated additional references in the main text to highlight studies demonstrating that sub-irrigation systems or controlled drainage can increase crop yield compared to conventional drainage systems, see the citation in the next reply.

10. L 628: Regarding controlled drainage, does the finding here offer implications on optimal schedules of controlled drainage for yield depending on the interplay of seasonality of coupled processes? A brief discussion on the potential or future work might help.

Response: Thanks for the question and suggestion. The finding in the paper provides insights on controlled drainage on two folds, 1) reducing drought stress in dry summer. Although our results show that tile drainage overall increases crop yield under wet spring and dry summer, the model also indicates the crop suffers drought stress, which necessitates the need for controlled drainage in dry summer. 2)

Reducing nitrogen loss in non-growing seasons. Our results show that tile drainage increases nitrogen loss, and it would be helpful to use a control structure to reduce nitrogen loss, especially in the spring. We have added brief discussions about this in the main text,

> **Line 592-699 Section 4.2**: "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 non-growing season in controlled drainage (Helmers et al., 2022). With a subirrigation system, the removed water can be cycled and irrigate the field crop in summers with less precipitation (Singh et al., 2022)."

> **Line 670-677 Section 4.5:** "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)."

11. The growing season was considered from April to October (L345). Did the model account for different planting schedules across the years?

Response: Yes, the planting dates and harvesting dates are two input parameters in the model, and we used the reported values in this work to drive the model. We have included the planting data and harvest data information in the supplementary material in the revised paper (Table S3). The growing and harvest dates vary in different years. To ensure fair comparisons with the same length, we consider the growing season from April to October, which covers the actual growing seasons for each year.

Table S3. Planting date and harverst data

Year	Crop	Planting date	Harvest date
2007	Soybean	2007-06-02	2007-10-11
2008	Corn	2008-05-09	2008-11-05
2009	Soybean	2009-05-22	2009-10-20
2010	Corn	2010-04-15	2010-09-30
2011	Soybean	2011-05-11	2011-10-03
2012	Corn	2012-04-18	2012-09-20
2013	Soybean	2013-06-12	2013-10-02
2014	Corn	2014-05-06	2014-11-07
2015	Soybean	2015-05-02	2015-10-07
2016	Corn	2016-05-13	2016-10-03
2017	Soybean	2017-05-17	2017-10-02

12. Equations 1-5: The definition of D_{d,O_2} in Eq. 1 is missing. Mathematical syntaxes in Equations 2-5 are inconsistent with those in the text. Examples include Q_{a,O_2}, C_{a,O_2}, D_{a,O_2}, and D'_{a,O_2}.

Response: Thanks for the correction. We have corrected them.

> **Line 189-198:** "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 $[g\ m^{-3}]$. "

13. Fig. S13 needs a more complete caption, e.g., stating the difference between green & yellow lines and the black & red lines.

Response: Sorry for the confusion. We have removed Figure S13, and moved and modified the original panel into Figure 5 in the main text, see the reply to comment 3 above.

14. Fig. 12 and 13 summarize the key mechanisms nicely. In Fig. 13, should there be downward arrows in the boxes of surface runoff and surface N loss?

Response: Thanks for checking. We tentatively left black there. As in our case, we did not observe a significant change in surface runoff and surface nitrogen leaching. We carefully examined the model setup and model results, and identified several potential reasons: Our analysis shows that surface runoff predominantly occurs during significant rainfall events, suggesting that the infiltration-excessive mechanism is the primary driver of surface generation (Figure R2). While tile drainage generally reduces soil water content, its effect is more pronounced in deeper soil layers. The similar soil water content in the top soil layer might lead to similar infiltration rates under tile and undrained conditions. Our simplified 1-D column representation of the field limits surface water holding capacity, which in turn diminishes the perceived role of tile drainage in managing surface water. This rapid removal of surface water likely leads to an underestimation of tile drainage's influence on surface runoff regulation, potentially explaining the lack of impact observed in this scenario. It is noteworthy that soil water flow (e.g., interflow) also contributes significantly to observed river discharge, making it difficult to distinguish from surface runoff in observations, and might be recognized as surface runoff.

Line 575-581: "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."

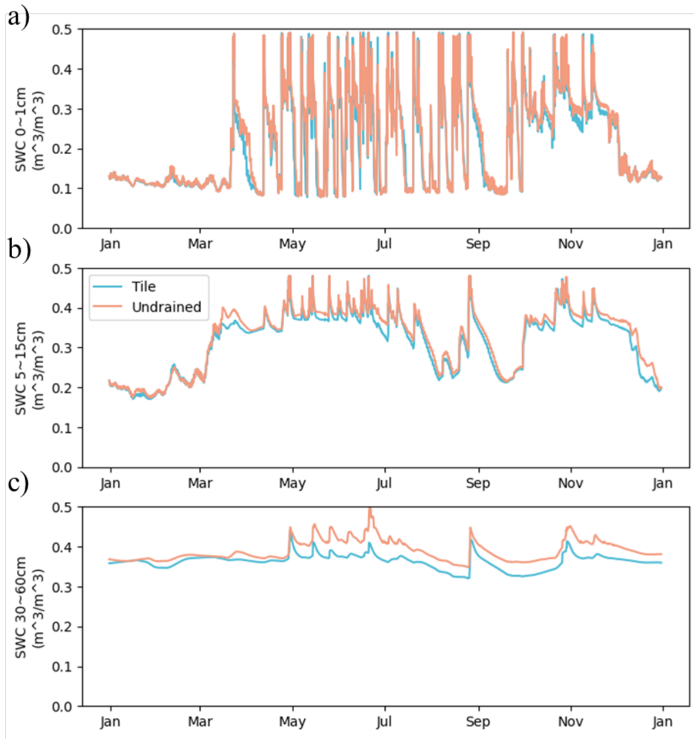

Figure S13. Ecosys-simulated soil water content (SWC) in 2009. Soil water content in a) 0~1 cm soil layer, b) 5~15 cm soil layer, c) 30~60 cm soil layer.

15. L554: The statement needs rephrasing. As of now, "tile drainage did not significantly change crop growth" seems contradictory to the findings and the summary in Fig. 13.

Response: Thanks for pointing this out. We have removed the statement to avoid confusion.

16. L659: There are two repetitive phrases of "subsurface discharge"

Response: Thanks for the correction. We have corrected it.

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