nature portfolio

Peer Review File

Irrigation benefits outweigh costs in more US croplands by mid-century

Web links to the author's journal account have been redacted from the decision letters as indicated to maintain confidentiality.

17th Jan

Dear Dr Partridge,

Your manuscript titled "Projecting the value of current and expanded irrigation as a climate adaptation strategy" has now been seen by 3 reviewers, whose comments are appended below. You will see that they find your work of some potential interest. However, they have raised quite substantial concerns that must be addressed. In light of these comments, we cannot accept the manuscript for publication, but would be interested in considering a substantial revised version that fully addresses these serious concerns.

We hope you will find the reviewers' comments useful as you decide how to proceed. Should additional work allow you to

• address these comments (that is, either to incorporate the suggestions or provide a compelling argument why the points made by the reviewers are not valid, or relevant to the editorial threshold as outlined below).

AND

• meet our editorial thresholds as outlined below.

Then we would be happy to look at a substantially revised manuscript. In the following, we list our main editorial concerns.

****

****Editorial threshold 1:

Provide compelling and balanced justification for the assumptions, which need to be robust and appropriate, and explore the potential impacts resulting from the assumptions.

****Editorial threshold 2:

Provide an in-depth balanced discussion of model simulations uncertainties and methods used in this study to provide robust results.

****Editorial threshold 3:

Provide an in-depth discussion of the impacts of interactions between irrigation and climate on the results.

If you choose to take up this option, please either highlight all changes in the manuscript text file, or provide a list of the changes to the manuscript with your responses to the reviewers.

Please bear in mind that we will be reluctant to approach the reviewers again in the absence of substantial revisions.

If the revision process takes significantly longer than three months, we will be happy to reconsider your paper at a later date, as long as nothing similar has been accepted for publication at Communications Earth & Environment or published elsewhere in the meantime.

We understand that due to the current global situation, the time required for revision may be longer than usual. We would appreciate it if you could keep us informed about an estimated timescale for resubmission, to facilitate our planning. Of course, if you are unable to estimate, we are happy to accommodate necessary extensions nevertheless.

We are committed to providing a fair and constructive peer-review process. Please do not hesitate to contact us if you wish to discuss the revision in more detail.

Please use the following link to submit your revised manuscript, point-by-point response to the reviewers' comments with a list of your changes to the manuscript text (which should be in a separate document to any cover letter) and any completed checklist:

https://mts-commsenv.nature.com/cgi-bin/main.plex?el=A3DE3zk6A4IaX2I2A9ftdFmVaXtNUGcyJBYjLpREbLgZ

** This url links to your confidential home page and associated information about manuscripts you may have submitted or be reviewing for us. If you wish to forward this email to co-authors, please delete the link to your homepage first **

Please do not hesitate to contact me if you have any questions or would like to discuss the required revisions further. Thank you for the opportunity to review your work.

Best regards,

Min-Hui Lo

External Editor

Communications Earth & Environment

EDITORIAL POLICIES AND FORMAT

If you decide to resubmit your paper, please ensure that your manuscript complies with our editorial policies and complete and upload the checklist below as a Related Manuscript file type with the revised article:

Editorial Policy Policy requirements (Download the link to your computer as a PDF.)

For your information, you can find some guidance regarding format requirements summarized on the following checklist:(https://www.nature.com/documents/commsj-phys-style-formatting-checklist-article.pdf) and formatting guide (https://www.nature.com/documents/commsj-phys-style-formatting-guide-accept.pdf).

REVIEWER COMMENTS:

Reviewer #1 (Remarks to the Author):

This study quantifies the economic feasibility of sustainable irrigation expansion in the USA. The article builds on recent literature at the global scale that used biophysical models to quantify irrigation expansion potential as an adaptation strategy to climate change. I have minor comment below.

A technical comment:

The authors examine middle and end of the 21st-century conditions under 10 possible future climates, composed of two emission trajectories (ssp245and ssp585) and five GCMs that span the range of future projections. Each climate model reaches a temperature and therefore climate conditions in a different year, by using climate data for 2050 and 2100 from each climate model, you are comparing different climates. For example, a model reaches 3 deg warming in 2040, while another in 2080. The authors should comment on this approach and the uncertainty in the results, the median values used and how these extreme in climate are considered in the assessment.

Minor comments:

Line 39: A recent study examined and reviewed the role of sustainable irrigation expansion to adapt agriculture to climate change: https://iopscience.iop.org/article/10.1088/1748-9326/ac7408/meta

Line 47: See also Rosa et al., 2020, already cited below in the text. This work quantifies the feasibility to expand irrigation considering future water demand and availability under warming scenarios. https://www.pnas.org/doi/10.1073/pnas.2017796117

Line 49: A citation is needed for this statement.

Line 53: A citation is needed for this statement. See for example this recent publication: https://www.nature.com/articles/s43017-022-00368-8#Abs1

Line 72-73: A reference is needed for this statement, see the concept of agricultural economic water scarcity: https://www.science.org/doi/10.1126/sciadv.aaz6031

Line 622: Rosa et al., 2020 not 2021

Reviewer #2 (Remarks to the Author):

This study investigates the net economic value (the irrigation benefit to cost ratio, IrB/C) of the existing and expanded irrigation using the gridded version of the Decision Support System for Agrotechnology Transfer model (pDSSAT) throughout the US under 10 future climates with two emission trajectories and five GCMs. pDSSAT is simulated for historical (1981-2010), mid-century (2036-2065), and end-of-century (2071-2100) conditions under ssp245 and ssp585 and five downscaled CMIP6 GCMs. The results identify the spatial distribution of areas where future crop productivity benefits of irrigation outweigh pumping costs, and the areas that may not be well suited for future irrigation.

This study is an interesting work but accompanies lots of assumptions, which may have critical impacts on the results and conclusions. Without addressing these assumptions and how they will affect the results, it is not possible to have this work published. For example, crops are automatically irrigated with 10 mm of water from unlimited reservoirs on days when plant available water falls below 40% (line 154-155). The irrigation simulations are conducted in the pDSSAT without any justification. Many regions have promoted deficit irrigation, while the improvement on the irrigation strategies is not considered in this study.

More importantly, a critical issue for this study is the the increasing trend of crop yields is also not considered in this study, which is critical for the results analysis. This is a major flaw of the study, as it has been a standard thing to take into account of the crop response under future projects. The increasing trend from genetic development and management improvement should be reflected in the parameters in the pDSSAT model for future simulations.

In addition, there are large uncertainties on the calculation of the irrigation benefits and costs. The marginal yield gain does not consider the fluctuation of crop price. The calculation of costs does not consider the decreasing groundwater table due to irrigation withdrawal. Furthermore, it is unclear on irrigation using surface water, such as the regions where surface water is used for irrigation and its irrigation amount and costs.

Reviewer #3 (Remarks to the Author):

In the paper entitled 'Projecting the value of current and expanded irrigation as a climate adaptation strategy', the authors detect the economic benefit of irrigation and the sustainable irrigation water deficit in three different periods under different scenarios. It was a huge amount of work and I really appreciate the authors' good job! The results of this paper are important for both the science field and its application. The paper is well-written, but there are still some parts which lack clarity. To be published, a minor revision would be necessary. More detailed comments can be found below.

Major comments

Abstract: The abstract is generally good, but I would add one or two sentences to talk about the implications (e.x. for what can the results of this study be used; what is the scientific contribution of this study) of this study.

Results: In the Result section, you repeated something you mentioned in the section Method. For example, the calculation of IrB/C. I would move them all to the section Method and briefly describe them in this section. One thing really confused me is that at L307-L308, the equation for AW does not consider safe environmental flow, but at L618-619, you considered it. Seems that you did an additional simulation but it is not described clearly. Then, to be honest, with most of the colorbars, we cannot easily get the number of different pixels. I would use discrete colorbars for the figures where the values really matter.

Method: As I mentioned before, please move the description of datasets, experiments, and calculation of some metrics to this section. I would also add a subsection 'experimental design' and it would be better if you can add a table to show all your simulations and your extra simulations with their settings. For the model pDSSAT, the input data that pDSSAT needs are not clearly introduced. You only talked about the meteorological forcing data. How about the management, soil and nutrient availability data?

Discussion: One thing you missed is the interaction between irrigation and climate. In your simulations, meteorological data is used as forcing data. However, many studies already showed that irrigation could affect regional climate greatly, especially the temperature. I would include this as a limitation. Another thing is that, in your simulations, you assumed that the cropland will not change under future scenarios. However, there are already some future land use datasets (for example, LUH2). If you also consider future land use, the results can be even more interesting.

Minor comments

L48-49: Please give the source of these numbers.

L123: An SSP585 -> A SSP585 (Check throughout the whole manuscript)

Figure 1: I guess you mean annual total precipitation? Please mention it in the caption or in the figure.

L154-155: is there a water balance in pDSSAT? If so, where is the water for irrigation from?

Figure 2: 'Changes are relative to corresponding average yield from historical simulations' So the results of the rainfed simulation are compared to historical rainfed simulation and results of the irrigated simulation are compared to historical irrigated simulation? Please specify. Figure S15 & S16? I guess you wanted to say Figures S13 & S14? Please check through the whole paper if there is more inconsistency.

L245: I am not sure if you should call it once in 30-year drought.

L457: Please give a brief description of the Livneh dataset.

L460: Please use capital letters for SSP throughout the whole manuscript.

L502-504: It would be great if you can show or share the calibrated SLPF values, which may be useful for other users.

L538: Maybe I missed something, but I guess here should be Figure S1?

L599: Why do you assume the efficiency to be 0.77? Please give the source.

Table 1 -> Table S1 (Check throughout the whole manuscript)

EDITORIAL THRESHOLDS:

****Editorial threshold 1:
Provide compelling and balanced justification for the assumptions, which need to be robust and appropriate, and explore the potential impacts resulting from the assumptions.
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Provide an in-depth balanced discussion of model simulations uncertainties and methods used in this study to provide robust results.
****Editorial threshold 3:
Provide an in-depth discussion of the impacts of interactions between irrigation and climate on the results.

REVIEWER COMMENTS:
Reviewer #1 (Remarks to the Author):

We thank reviewer 1 for their thoughtful comments and suggestions.

This study quantifies the economic feasibility of sustainable irrigation expansion in the USA. The article builds on recent literature at the global scale that used biophysical models to quantify irrigation expansion potential as an adaptation strategy to climate change. I have minor comment below.
A technical comment:
The authors examine middle and end of the 21st-century conditions under 10 possible future climates, composed of two emission trajectories (ssp245and ssp585) and five GCMs that span the range of future projections. Each climate model reaches a temperature and therefore climate conditions in a different year, by using climate data for 2050 and 2100 from each climate model, you are comparing different climates. For example, a model reaches 3 deg warming in 2040, while another in 2080. The authors should comment on this approach and the uncertainty in the results, the median values used and how these extreme in climate are considered in the assessment.

Thank you for this comment. We agree that presenting results by time period (as opposed to temperature change) incorporates the uncertainty associated with the climate sensitivity captured by each GCM. However, doing so was by design as we wanted to explore the crop response across a variety of future climates. This is why we chose GCMs that span the range of climates in CMIP6. We attempted to highlight that range in Figure 1 and Table S1. Presenting future impacts in terms of delta temperature can be more intuitive in certain applications, for example, changes in extreme events. However, as crop productivity is also function of atmospheric CO_2, we feel that the SSP scenario approach (i.e. mid-century and end-of-century) is more intuitive for this application. Given that different models reach thresholds at different times, presenting our results in terms of changes in growing season temperature (or some other metric) would be comparing across atmospheric CO_2 levels, which would make it more difficult to see the value in adopting a lower emissions trajectory. That being said, we agree that this is important to highlight and have added the following text to the manuscript.

> Lines 174-180: “It's important to note that GCMs have varying sensitivity that is reflected in both temperature and precipitation responses to changing greenhouse gas and other external forcings. Our future climate scenarios span a range of potential growing season conditions as illustrated by the timeseries in Figure 1. The yield maps shown in Figure 1 (and Figure S12) represent the average expected response, for our given set of assumptions, under a particular emissions trajectory, not an assigned shift in temperature or precipitation (e.g. a 3°C warmer world).”

Minor comments:
Line 39: A recent study examined and reviewed the role of sustainable irrigation expansion to adapt agriculture to climate change: https://iopscience.iop.org/article/10.1088/1748-9326/ac7408/meta

We have added the linked study to the manuscript on Line 42.

Line 47: See also Rosa et al., 2020, already cited below in the text. This work quantifies the feasibility to expand irrigation considering future water demand and availability under warming scenarios. https://www.pnas.org/doi/10.1073/pnas.2017796117

We have included the citation for Rosa et al., 2020 to the references on line 52.

Line 49: A citation is needed for this statement.

We have added the 2017 USDA Agriculture Census as a reference.

Line 53: A citation is needed for this statement. See for example this recent publication: https://www.nature.com/articles/s43017-022-00368-8#Abs1

We have added examples of existing work to support the claim. The linked study an excellent example of climate impacts on agriculture, but since there is such a rich body of work that directly investigates irrigated agriculture, we’ve decided not to include it here.

> Line 39-42:” To ensure food security while minimizing adverse environmental impacts, it is necessary to understand the potential effects of climate change on agricultural productivity and critically examine adaptation strategies. Especially as some adaptations may be maladaptive for compound extreme events (Lesk et al., 2022).”

Line 72-73: A reference is needed for this statement, see the concept of agricultural economic water scarcity: https://www.science.org/doi/10.1126/sciadv.aaz6031

Thank you for pointing us to this study, we have included it as a reference on line 78.

Line 622: Rosa et al., 2020 not 2021

Fixed. Thanks for catching the mistake.

Reviewer #2 (Remarks to the Author):

We thank reviewer 2 for the thoughtful critiques and encouraging remarks. We agree that there are many assumptions in a study of this kind. While it's unrealistic to eliminate all assumptions, we have attempted to clearly state how our assumptions are grounded and how they could impact our results. We have also listed the major limitations of this work in the new section "4. Assumptions, limitations, and future work"

This study investigates the net economic value (the irrigation benefit to cost ratio, IrB/C) of the existing and expanded irrigation using the gridded version of the Decision Support System for Agrotechnology Transfer model (pDSSAT) throughout the US under 10 future climates with two emission trajectories and five GCMs. pDSSAT is simulated for historical (1981-2010), mid-century (2036-2065), and end-of-century (2071-2100) conditions under ssp245 and ssp585 and five downscaled CMIP6 GCMs. The results identify the spatial distribution of areas where future crop productivity benefits of irrigation outweigh pumping costs, and the areas that may not be well suited for future irrigation.

This study is an interesting work but accompanies lots of assumptions, which may have critical impacts on the results and conclusions. Without addressing these assumptions and how they will affect the results, it is not possible to have this work published. For example, crops are automatically irrigated with 10 mm of water from unlimited reservoirs on days when plant available water falls below 40% (line 154-155). The irrigation simulations are conducted in the pDSSAT without any justification. Many regions have promoted deficit irrigation, while the improvement on the irrigation strategies is not considered in this study.

We agree that not including deficit irrigation is major limitation of the present work and is an area that we would like to explore more in the future. We have added text describing this limitation, as well as others to section 4 in the manuscript.

> Lines 435-442: "Second, we utilized a simplified irrigation scheme within pDSSAT and our $Ir_{B/C}$ analysis. Crops in pDSSAT are irrigated with 10mm of water anytime plant available water falls below 40% throughout the growing season. Many regions have successfully promoted deficit irrigation (a practice of applying less water than is required to meet the full crop evapotranspiration demand) as it has demonstrated to have minimal impact on yields while conserving water use (Rudnick et al., 2019). Simulating future crop productivity under various deficit irrigation strategies could help identify regions, crops, and management strategies that optimize tradeoffs between productivity and water use."

Comparing our results from pDSSAT with those of other crop models would be of great interest. In this work we decided to explore how irrigation requirements could vary across future climate scenarios. Given the number of climate futures we are considering (5 GCMS x 2 SSPs x 2 time periods), adding an additional crop model was outside the scope of this specific project. As such, our results are dependent on the underlying assumptions and biases incorporated within pDSSAT. There are several inter-model comparison projects, and pDSSAT tends to agree with other crop models over the United States. We have added text justifying our selection of pDSSAT and discussing how pDSSAT compares to other gridded crop models.

> Lines 453-459: “Fifth and finally, our results may be dependent on inherent biases and limitations within pDSSAT. As the focus of this work is to explore the potential feasibility of current and expanded irrigation across a range of future climate projections, we opted to use a single crop model over a larger ensemble of climate projections. While we can’t directly evaluate pDSSAT against other crop models, recent crop model intercomparison projects have reported that pDSSAT tends to have the highest skill at simulating maize growth in the U.S. (Franke et al., 2020).”

More importantly, a critical issue for this study is the the increasing trend of crop yields is also not considered in this study, which is critical for the results analysis. This is a major flaw of the study, as it has been a standard thing to take into account of the crop response under future projects. The increasing trend from genetic development and management improvement should be reflected in the parameters in the pDSSAT model for future simulations.

Thank you for this comment. Our analysis does account for increasing yields during the historical period through modifying both crop genetic and management parameters. We agree this was not clear in the initial manuscript and have added the following text.

> Lines144-147: “Simulated yields can be modified through adjusting parameters controlling the planting density of crops as well as physiological parameters such as the number of grain kernels per plant and grain filling rates. We allow these parameters to evolve during the historical period to match yield trends but hold them fixed at contemporary values for future simulations.”

> Lines 577-582: “After estimating maize and soybean phenological parameters, we calibrated simulated yield to observed county yield from NASS by modifying the planting density as well as the maximum kernel number *(g3)* for maize and the cultivar ID for soybean. State level planting densities were acquired from USDA NASS (2017). We linearly increased the kernel number from 730 in 1980 to 790 in 2010 following Lopez et. al., (2022) and soybean cultivar ID numbers were approximated annually based on temperature and photoperiod as described above.”

We spent quite a bit of time discussing how to incorporate simple adaptation measures into our future simulations without introducing too many additional assumptions. Ultimately, we decided to keep plant genetic parameters (i.e. grain filling rates) as well as crop density and fertilizer application rates set at contemporary levels to reduce assumptions about future advancements in crop physiology. While some studies have allowed these parameters to continue increasing in the future, there are biophysical limits and we felt that the assumptions about how these parameters would change in the future are hard to defend. Instead, we projected future shifts in cultivar selection and planting date, as these are relatively easy changes that growers can make and don’t require assumptions about advancements in plant physiology. We also include future simulations using historic maize cultivars as recent work has suggested that climate is only one variable, and perhaps a minor one, in the cultivar selection process. We discuss the difference in our results between the two future cultivar scenarios throughout the manuscript. Given soybeans tolerance to temperature (relative to maize) we decided not to project shifts in future soybean cultivars. We have attempted to justify these assumptions throughout the manuscript and rearranged our methods section to clearly outline historic and future crop parameter assumptions. Please find a few excerpts below:

> Lines 191-192: "Throughout most of the Corn Belt, historically grown maize cultivar yields remain relatively static under a SSP245 midcentury climate and decrease slightly under SSP585."
>
> Line 253: Table 1 – We have included values for the simulations using historic maize cultivars .
>
> Lines 595-599: "Future advancement in plant breeding could lead to increased yield potential for maize and soybean while also increasing their resilience to environmental stress. As projecting these advancements adds additional uncertainty to our analysis, we hold crop physiological parameters static for future periods and allow for relatively simple adaptations in planting date and cultivar selection."

In addition, there are large uncertainties on the calculation of the irrigation benefits and costs. The marginal yield gain does not consider the fluctuation of crop price. The calculation of costs does not consider the decreasing groundwater table due to irrigation withdrawal. Furthermore, it is unclear on irrigation using surface water, such as the regions where surface water is used for irrigation and its irrigation amount and costs.

We agree that these are all major areas of uncertainty in our work and will attempt to address each one that the reviewer brings up below:

Re: crop prices. This is, of course, a major area of uncertainty and we have attempted to design our analysis in a way that reduces this uncertainty as much as possible. Fluctuations in crop and energy prices are difficult to predict 1-2 years out, and projections beyond that become unreliable. Instead of presenting results in terms of net profit (or net cost) we chose to keep crop and energy market prices constant (set at present levels) and present our results in terms of changes to the Irrigation benefit to cost ratio. This, of course, assumes that crop and energy prices will fluctuate by similar amounts in the future, but we feel that assumption is easier to justify than to project trends on crop and energy prices.

> Lines 214-219: "As projected changes in future crop market and energy prices become unreliable after a few years, we hold crop and energy prices constant for future periods and report the economic benefit of irrigating as the irrigation benefit to cost ratio ($Ir_{B/C}$) for each grid cell and growing season. This assumes that crop and energy prices will fluctuate at roughly concurrent rates and that the modern ratio is a reasonable analog for the future."

Re: changing costs due to groundwater depletion: We agree that this is a limitation of this study. We do not explicitly account for decreasing groundwater due to future withdrawals. Doing so would require not only the inclusion of a more sophisticated groundwater model, but also further assumptions about socioeconomic trajectories (e.g. shifts in land use, cultivated area, crop selection, etc.) that we felt added too much complexity. As such, our calculation of costs is likely overly conservative if unsustainable withdrawal rates persist. We have attempted to emphasize this throughout the manuscript and highlighted it in the Limitations section.

> Lines 424-431: "First, we do not account for changes in depth to groundwater due to shifting withdrawal rates. Simulated recharge rates within pDSSAT do account for changes to precipitation and evapotranspiration, but those changes are small relative to the potential impact of increased (or decreased) withdrawals. As such, our results reflect the isolated climatological impact on maize and soybean irrigation profitability and sustainability under present groundwater availability. Developing future CONUS scale groundwater availability scenarios with evolving land use and withdrawal rates would be a significant contribution to evaluating future water availability."

Re: Surface water vs. groundwater. Thank you for pointing this out. We agree that the original manuscript wasn't as clear as it could be. This work primarily focuses on groundwater and we have removed the discussion of surface water as we felt our analysis is too simplistic to accurately account for current and future surface water diversions. We have tried to more explicit that we are focused on groundwater throughout the manuscript and modified the title to highlight that.

> Lines 232-234: "For completion we show $Ir_{B/C}$ values for all simulated grid cells. There are many areas throughout the U.S. that irrigate primarily with surface water and estimated pumping costs over these areas may be artificially high."

Reviewer #3 (Remarks to the Author):

Thank you for the encouraging remarks, we appreciate your thoughtful critiques and have attempted to address each one below.

In the paper entitled 'Projecting the value of current and expanded irrigation as a climate adaptation strategy', the authors detect the economic benefit of irrigation and the sustainable irrigation water deficit in three different periods under different scenarios. It was a huge amount of work and I really appreciate the authors' good job! The results of this paper are important for both the science field and its application. The paper is well-written, but there are still some parts which lack clarity. To be published, a minor revision would be necessary. More detailed comments can be found below.

Major comments
Abstract: The abstract is generally good, but I would add one or two sentences to talk about the implications (e.x. for what can the results of this study be used; what is the scientific contribution of this study) of this study.

We have added the following text to the abstract:

> Lines 29-32:” Shifting incentives for installing and maintaining irrigation equipment could place additional challenges on resource availability. It will be important for decision makers throughout the U.S. to understand and account for local water demand and availability when developing policies guiding irrigation installation and use.”

Results: In the Result section, you repeated something you mentioned in the section Method. For example, the calculation of IrB/C. I would move them all to the section Method and briefly describe them in this section. One thing really confused me is that at L307-L308, the equation for AW does not consider safe environmental flow, but at L618-619, you considered it. Seems that you did an additional simulation but it is not described clearly. Then, to be honest, with most of the colorbars, we cannot easily get the number of different pixels. I would use discrete colorbars for the figures where the values really matter.

Thanks for mentioning this. We have tried to move as much text as possible to the methods section. The original manuscript has separate calculations of available water, one that included surface water and one that only included groundwater. We agree that it was confusing and have removed the analysis that included surface water from the manuscript.

Re: colorbars, we have adjusted all the figures to use discrete colorbars.

Method: As I mentioned before, please move the description of datasets, experiments, and calculation of some metrics to this section. I would also add a subsection ‘experimental design’ and it would be better if you can add a table to show all your simulations and your extra simulations with their settings. For the model pDSSAT, the input data that pDSSAT needs are not clearly introduced. You only talked about the meteorological forcing data. How about the management, soil and nutrient availability data?

We have moved most of the discussion of datasets, experiments, and calculations to the methods section. However we have left some brief discussion in the intro and results to provide context and improve readability as the methods section is included at the end of the manuscript in *Communications Earth & Environment*

We have added an Experimental Design section to our methods and included a table of the datasets we used for forcing, calibrating, and evaluating pDSSAT. We’ve included an additional table on Line 540.

Line 540:
Table 2: Data used to run pDSSAT simulations, estimate and evaluate maize and soybean growth parameters, and calculate the $Ir_{B/C}$ and irrigation water deficit values.

Data Type	Data	Source
pDSSAT inp	Daily meteorological forcing data	Livneh et al., (2015)
	Future climate projections	CNRM-CM6: Voldoire (2019)

		CanESM5: Swart et. al., (2019) HadGEM3-GC31-LL: Good (2019) MPI-ESM1-2-LR: Wieners et. al., (2019) NESM3: Cao, Jian (2019)
	Gridded soil textures	Shangguan et al., (2014)
	Global atmospheric CO2	Meinshausen et al.(2020)
	Fertilization rates	Lopez et al., (2022)
	U.S. cultivated area	Boryan et al., (2012)
pDSSAT calibration and evaluation	Irrigated Area	Pervez & Brown (2010)
	County crop yield	USDA NASS
	County crop progress dates	USDA NASS
	State planting density	USDA NASS
	Irrigation application rates and pumping costs	2013 USDA Farm and Ranch Irrigation Survey
	Groundwater recharge rates	Reitz et. al., (2017)
$Ir_{B/C}$ and water deficit calculation	Depth to groundwater and transmissivity	Zell & Sanford, (2020)
	Energy costs	U.S. Energy Information Association
	Irrigation ownership and maintenance costs	See Table S2
	Irrigation application and pump efficiency	McCarthy et al. (2020); New (1988)
	Industrial and municipal water use	Dieter et al. (2018)

Discussion: One thing you missed is the interaction between irrigation and climate. In your simulations, meteorological data is used as forcing data. However, many studies already showed that irrigation could affect regional climate greatly, especially the temperature. I would include this as a limitation. Another thing is that, in your simulations, you assumed that the cropland will not change under future scenarios. However, there are already some future land use datasets (for example, LUH2). If you also consider future land use, the results can be even more interesting.

We agree that the feedbacks between irrigation and climate are of great interest, and this work actually spun off from a project thinking about how those interactions may evolve in the future. While this effect is important to consider, we do feel that it is likely a secondary effect given the projected shifts in growing season temperature imposed by climate change. We have added additional text to the discussion describing irrigation induced cooling, it's potential implications for this study, and highlighting the need for future work to consider these interactions.

> Lines 448-453: "Fourth, our modeling exercise does not account for the influence of irrigation on local and regional climate, which has been shown to be significant throughout regions of the U.S. (D. Lobell et al., 2009; Pei et al., 2016). While irrigation induced changes to local and regional climate are likely secondary to climate change effects, future work exploring the land-atmosphere feedbacks between future changes in irrigated agriculture (and other agricultural management practices) could help constrain regional climate projections."

Re: Changes in cropland: Correct, we hold cultivated land static and simulate maize and soybean across all presently cultivated land. This was an exploration into the feasibility of future irrigation to identify regions where irrigated maize and soybean may be possible (and profitable) as well as those where it isn't. We agree that comparing our results to future land use datasets would be of great interest, but feel that it would add an additional analysis that is outside the scope of this study. However, we have included text describing this as a potential future research avenue.

> Lines 431-435: "Further, our results could influence existing land use projections such as those from the Land Use Harmonization project (Hurtt et al., 2020). A comparison of land use projections with water availability and agricultural productivity could inform land use optimization for agriculture, renewable energy development, residential use, and other development."

Minor comments
L48-49: Please give the source of these numbers.

Fixed.

L123: An SSP585 -> A SSP585 (Check throughout the whole manuscript)

Fixed, thanks for catching.

Figure 1: I guess you mean annual total precipitation? Please mention it in the caption or in the figure.

Fixed

L154-155: is there a water balance in pDSSAT? If so, where is the water for irrigation from?

Yes, but it's not realistic for the irrigated simulations because the water used for irrigation comes from an unlimited reservoir and is then traced throughout the simulation (e.g. ET and recharge rates could be artificially high under irrigated cells). As such, when we calculate the irrigation water deficit we use recharge rates from the rainfed simulations.

> Lines 297-299: "Recharge rates are simulated directly in rainfed pDSSAT simulations (irrigated simulations don't have a closed water budget) and other uses consist of consumptive uses from industrial and residential sources at the county level (Dieter et al., 2018a)."

Figure 2: 'Changes are relative to corresponding average yield from historical simulations' So the results of the rainfed simulation are compared to historical rainfed simulation and results of the irrigated simulation are compared to historical irrigated simulation? Please specify.

Correct. We've added text explaining the figure.

> Lines 200-202: "Changes are relative to corresponding average yield (i.e. rainfed or irrigated) from historical (1981-2010) simulations which are shown Figures S15 & S16."

Figure S15 & S16? I guess you wanted to say Figures S13 & S14? Please check through the whole paper if there is more inconsistency.

L245: I am not sure if you should call it once in 30-year drought.

Fair point. That phrasing seems to imply a recurrence interval. We've adjusted the text to:

> Line 249: "$Ir_{B/C}$ during the driest year exceeds ~1.5 for nearly all currently irrigated cropland..."

L457: Please give a brief description of the Livneh dataset.

> Lines 530-533: "We utilize daily meteorological data from the Livneh dataset, which assimilated data from roughly 20,000 weather stations into the Variable Infiltration Capacity Hydrologic model to provide daily gridded hydrometeorological data at a 1/16° horizontal resolution for the CONUS, Mexico and southern Canada (Livneh et al., 2013, 2015)."

L460: Please use capital letters for SSP throughout the whole manuscript.

Fixed.

L502-504: It would be great if you can show or share the calibrated SLPF values, which may be useful for other users.

Great idea. We spent quite a bit of effort calculating them, and hope they might be of use to others. We will make the netcdf files publicly available upon publication here: https://doi.org/10.5281/zenodo.7747561.

> Lines 732-734:
> **Data Availability**
> Model inputs are available from the sources listed in Table 2. Crop model output and campaign files are publicly available at https://doi.org/10.5281/zenodo.7747561.

L538: Maybe I missed something, but I guess here should be Figure S1?

Yes, good catch! Thank you.

L599: Why do you assume the efficiency to be 0.77? Please give the source.

Thanks for catching this. The 77% efficiency comes from an extension document that we have cited in the manuscript and included in the new Table 2.

Lines 691-692: "ε_P is the pumping efficiency which we assume to be 0.77, the typical efficiency suggested by (New, 1988),"

Table 1 -> Table S1 (Check throughout the whole manuscript)

Fixed, thanks!

26th May

Dear Dr Partridge,

Your manuscript titled "Projecting the value of current and expanded irrigation from groundwater as a climate adaptation strategy" has now been seen by our reviewers, whose comments appear below. In light of their advice I am delighted to say that we are happy, in principle, to publish a suitably revised version in Communications Earth & Environment under the open access CC BY license (Creative Commons Attribution v4.0 International License).

We therefore invite you to revise your paper one last time to address the remaining concerns of our reviewers. Specifically, please discuss the variation in groundwater pumping costs (as requested by reviewer 2) in the limitations section.

At the same time we ask that you edit your manuscript to comply with our format requirements and to maximise the accessibility and therefore the impact of your work.

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We hope to hear from you within two weeks; please let us know if you need more time.

Best regards,

Min-Hui Lo, PhD

Editorial Board Member

Communications Earth & Environment

Heike Langenberg, PhD

Chief Editor

Communications Earth & Environment

On Twitter: @CommsEarth

REVIEWERS' COMMENTS:

Reviewer #1 (Remarks to the Author):

Thank you to the Authors for their careful and balanced response to my comments. I am pleased to recommend acceptance of your paper. Well done!

Reviewer #2 (Remarks to the Author):

Thanks for the authors' efforts to revise the manuscript based on the comments. They have provided careful responses and discussion for the comments, and have made detailed revision in the manuscript. The replies on two issues of "Crop prices" and "Surface water vs. Groundwater" are reasonable. However, I still have some concerns on the variations of pumping costs due to groundwater level change. The authors did not discuss the feasibility of the assumption, but using the difficulty of considering other socioeconomic factors compared with this. As this study mainly aims to investigate the economic value of irrigation from groundwater, necessitating a comprehensive consideration of groundwater. I suggest the authors to add some discussion or investigation on this assumption.

Reviewer #3 (Remarks to the Author):

I have no more comments for this paper. I appreciate the authors' efforts to address our comments in the last round. Before being published, some small issues need to be fixed, like:

P3 L41: '. Especially' -> ', especially' and

Remember to change the number of subsections in Section 6

Reviewer #1 (Remarks to the Author):

Thank you to the Authors for their careful and balanced response to my comments. I am pleased to recommend acceptance of your paper. Well done!

Thank you for your thoughtful feedback, it has improved the quality of our paper.

Reviewer #2 (Remarks to the Author):

Thanks for the authors' efforts to revise the manuscript based on the comments. They have provided careful responses and discussion for the comments, and have made detailed revision in the manuscript. The replies on two issues of "Crop prices" and "Surface water vs. Groundwater" are reasonable. However, I still have some concerns on the variations of pumping costs due to groundwater level change. The authors did not discuss the feasibility of the assumption, but using the difficulty of considering other socioeconomic factors compared with this. As this study mainly aims to investigate the economic value of irrigation from groundwater, necessitating a comprehensive consideration of groundwater. I suggest the authors to add some discussion or investigation on this assumption.

Thank you for your kind remarks and thoughtful feedback. I'm not sure I totally understand your concerns on the variations of pumping costs due to groundwater change. We've added the following text to the manuscript to clearly state our assumptions:

Lines 194-199:" Future groundwater availability will depend on withdrawal rates and climate. Due to the challenges associated with projecting future withdrawal rates, we hold future depth to groundwater at contemporary levels for the start of each growing season. The variability in future pumping costs is a function of climate driven crop water requirements and the within growing season drawdown associated with pumping groundwater to meet those requirements."

We have also included a supplemental figure exploring the sensitivity of our results to a theoretical increase in the depth to groundwater.

Lines 363-371: "First, we do not account for changes in depth to groundwater due to shifting withdrawal rates. Simulated recharge rates within pDSSAT do account for changes to precipitation and evapotranspiration, but those changes are small relative to the potential impact of increasing (or decreasing) withdrawals. As such, our results reflect the isolated climatological impact on maize and soybean irrigation profitability and sustainability under present groundwater availability. A theoretical 20% increase in the depth to groundwater has minimal impact on the spatial pattern of $Ir_{B/C}$ values (Supplementary Figure 32). Developing future CONUS scale groundwater availability scenarios with evolving land use and withdrawal rates would be a substantial contribution to evaluating future water availability."

Reviewer #3 (Remarks to the Author):

I have no more comments for this paper. I appreciate the authors' efforts to address our comments in the last round. Before being published, some small issues need to be fixed, like:
P3 L41: ‘. Especially’ -> ‘, especially’
and
Remember to change the number of subsections in Section 6

Thank you for your thoughtful comments. We have attempted to address the minor typos and issues on resubmission.