Dear Prof. McCabe,

We would like to thank you and the two reviewers for your time and excellent comments regarding our manuscript, titled “A case study of field-scale maize irrigation patterns in Western Nebraska: Implications to water managers and recommendations for hyper-resolution land surface modelling”. After careful analysis of all the comments, we have made extensive revisions to our manuscript. You can find our detailed responses to the reviewers’ comments (shown in red italics) and the changes we made to the manuscript in the following sections. We have also included a marked up version of the original manuscript.

On the behalf of all coauthors, I hope that this revised version would meet the publication standard of Hydrology and Earth System Sciences (HESS) and inclusion in the Eric F. Wood special issue. Please let us know if there are more questions and comments about the manuscript.

Sincerely,

Justin Gibson

School of Natural Resources

University of Nebraska-Lincoln, USA

Comments to the Author:
Dear Justin.

Thank you for your manuscript, submitted to HESS as part of the Special Issue on "Observations and modeling of land surface water and energy exchanges across scales". After reviewing your contribution and the comments from the two referees, I am requesting that you provide some additional details and revisions so that I can further assess it for publication. I am optimistic that these revisions should be fairly straightforward to implement, as they are mostly structural or require additional paragraphs for analysis or interpretation. I have detailed some of the more critical suggestions below, but draw your attention to the detailed comments provided by each of the referees in their respective reports. I encourage you to carefully consider these in your revised version, providing details on where the manuscript has been updated in your response.

1. In line with RC1, I agree that a time series/sub-annual breakdowns would be very useful, but also appreciate the data limitations. Refined temporal analysis would be especially important for active management of irrigation systems, as well as for the LSM community in better representing such systems in modeling approaches. Where possible, try to expand upon the temporal aspect, either explicitly in the results or more generally in the discussion sections.

Section 3.7 was added to discuss the sub-seasonal irrigation time series. Figure 8 presents the results.

L376-382: 3.7 Simulated Growing Season Irrigation Application

Daily time series of simulated irrigation application can be seen in Fig. 8. Data for observed sub-growing season irrigation application is unavailable. Irrigation application tends to begin later in the growing season for the two routines that consider soil (CM and H). This is likely due to the routines first allowing soil moisture to be depleted before irrigation is triggered. The amount of soil moisture storage is typically near field capacity but in exceptionally dry years (2012) this storage is reduced and thus will lead to less of a delay.

2. Both reviewers identify the need for some discussion on the broader application of these schemes, both in terms of their generality beyond this specific location, as well as their potential integration into "hyper-resolution" type schemes. Section 4.4 is an obvious area where these concepts could be expanded upon. I understand that an actual example may not be feasible, but you can certainly identify some of the challenges and opportunities that such a scheme may present.

We have expanded this section as requested. We also note 2 followup papers are in preparation that explore this topic (Gibson et al. 2017, Ag water management, and Lawston et al. 2017 HESS)

L461: The four irrigation routines although biased, capture year-to-year variation in irrigation in Western Nebraska. Given the widespread use of center-pivots we expect the irrigation routines *to be appropriate for the HPA and into parts of the eastern USA. Gibson (2016) provides a fuller assessment of irrigation behavior throughout central Nebraska. We note that it is unclear how these routines would behave in areas with center-pivot outside the USA (i.e. Brazil, South Africa, Australia), where energy costs for pumping may be more restricting and drive human-decisions on irrigation. Assessment of these routines in those areas would require further validation.*

We believe the routines combined with a reasonable bias correction could be easily incorporated into future hyper-resolution LSMs with the above routine descriptions and readily available LSM model output or datasets (see Table 1). Clearly accurate and local precipitation is critical in driving these irrigation routines and capturing producer behavior. This topic deserves more research, particularly and the opportunity to combine low cost in-situ gages with radar and remote sensing products. Additionally, we note the four routines could be run offline in order to provide reasonable guesses of applied irrigation for a given irrigation season. This may be beneficial in representing processes not explicitly considered in LSMs (Kumar et al. 2015), or making future assessments and recommendations about water availability for managers. Finally, the four routines provide reasonable irrigation bounds and more importantly predictions about decreases in irrigation as technology is introduced and adopted in novel areas.

3. An additional section (or combined within Section 4.4) focusing on possible implementation requirements or issues may also be useful: this may go some way to addressing both referee comments on the feasibility of the approach for broader scale application.

Table 1 is provided that summarizes the inputs and tunable parameters needed for each routine. In addition Lawston 2017 HESS explores the role of irrigation physics in the NOAH LSM.

4. In addition to summarizing key results, the conclusions can synthesize some of these discussions to provide a broader scale context for the work.

The conclusions were modified to include the key future direction we recommend for understanding irrigation behavior in this area and the HPA in general. That is providing realtime local precipitation to producers. This is a hot topic being actively pursued by private industry as well. The ability to merge low cost sensor networks with radar and satellite products would be a huge benefit to producers and water managers alike.

L482: In this work we describe four plausible and relatively simple irrigation routines that could be coupled to the next generation of hyper-resolution LSMs operating at scales of 1 km or less. The crop model irrigation outputs reproduce the year-to-year variability of the observed irrigation amounts with a low bias of 80 mm yr-1. Predictions from the vadose zone model indicate potential irrigation savings of up to 120 mm yr-1 for maize. In addition, daily precipitation variability across the study area was found to introduce significant variability in *daily irrigation decision making depending on which value was considered. Future work could focus on providing accurate realtime 1 km daily precipitation products through a combination of in-situ low cost gages, radar, and satellite remote sensing. Accurate and realtime precipitation remains a critical weakness in these rural and vast landscapes. Given the clustering of irrigation fields in Western Nebraska, the number of in-situ gages needed could be significantly reduced to provide high density networks in key areas. Findings from the work may be useful to local water managers and stakeholders in evaluating potential water saving technologies. In addition, the simple routines could be coupled to future hyper-resolution land surface models that seek to understand the degree of land surface atmospheric coupling and consequences to operational forecasts. This understanding is essential as society continually recognizes the importance of human activities on the global water cycle and invests more resources to understand the water-food-energy nexus.*

5. Carefully review language and grammar: I'm not sure you mean "predications" on Line 449?

Thank you we have made the change.

Overall, I believe that the manuscript will benefit from a focused revision, addressing these and the specific referee comments: I look forward to receiving an updated version.

Best wishes,
Matt

Reviewer 1:

Overall Comments:

Overall, this is a well-written manuscript describing 4 new ways to account for irrigation that could be used by managers and modelers alike. This type of work is much needed, as the human element/drivers of new LSM physics remain a challenge in how to account for them and prescribe them accurately. This is also a novel dataset put to good use. The schemes use sound assumptions and represent an array of complexities. The paper is a worthwhile contribution, but becomes a bit thin in the results section and a few of the major limitations are glossed over and require further discussion. As a result, I recommend major revisions in order to help the manuscript become more impactful and useful for irrigation-related studies. In addition, I strongly recommend that, if possible, the results/analysis be extended to time series and sub-annual breakdowns of irrigation water vs. precipitation (and variability) for each of these schemes. Much of the utility for managers and more so for modelers will be on the diurnal and sub-seasonal scales, in which they need to obtain the water balance, soil moisture, and fluxes correct in order to couple to the atmosphere and represent the precipitation connection more accurately (i.e coupling). Also missing is the broader applicability of these schemes outside of this unique, well-instrumented and reported-on field/domain. Other locations with less decision-making data points or coarser precipitation will no doubt find greater challenges.

Thank you for the thoughtful comments. We will do our best to address your main concerns. We have added a section (3.7) of daily dynamics of each of the irrigation schemes in a wet and dry year. It is clear the water savings are due to starting irrigation later in the season by better harvesting available soil water storage. Without monitoring or modeling this the producer is left with a tough decision on when best to irrigate. In addition, we are working with a cost sharing program to bring useful technologies to this area and is the focus of J. Gibson's PhD. Initial discussions with water managers and producers indicate a real desire to increase monitoring (rainfall in particular) with realtime decisions through pivot telemetry. This work will serve as a key study to continue to build these relationships and make lastly changes in the real world to conserve water and sustain critical livelihoods.

Specific Comments:

L24: What is difference between a conservative and water savings routine? Sounds similar if you do not know the terminology. This is explained better in the paper itself, but maybe a word or two in the abstract could help better clarify what is meant by each.

Updated abstract to:

L24: Here we find the most yield-conservative irrigation routine (crop model).

L29: Is the actual transition of information and decision making part of this paper? Or is it suggested that it would be valuable in the future for managers? If the latter (which according to the paper itself there is no transition or decision making taking place (yet!), then please clarify this here to suggest it may be useful in the future (not that it already has been useful).

Agreed, we will update to make more explicit that it could be useful in the <u>future</u>. Text updated to:

L29: The results from the various irrigation routines and associated yield penalties will be valuable for future consideration by local water managers to be informed by the potential value of water savings technologies and irrigation practices.

L52: might want to mention that the impact of SM on these is really modulated by the flux contribution to the atmosphere (SHF, LHF, or evap fraction, or just ET). So getting the SM-Flux relationship correct is critical, and i.e irrigation is essential as a component of that.

Indeed, the presence of irrigation doesn't necessarily impact the flux rates – we will update to include the SM-Flux relationship. Update text to:

L52: Although the presence of irrigation doesn't necessarily impact soil moisture contribution to the atmosphere, the soil moisture-flux relationship is critical to surface energy balance and atmospheric dynamics.

L58: Which are the 'both' here?

Both are affected by both. Changed sentence for clarity.

Both the risk-aversion side of decision making and from biophysical requirements. Gibson, 2015 identified that the majority of irrigated fields were irrigated approximately 50mm more that crop water demand.

Gibson, K.E.B: More Crop per Drop: Benchmarking On-Farm Irrigation Water Use for Crop Production. Master's Thesis, 2016.

L58: More complicating is that both irrigation timing and volumes are based on human decision making processes and biophysical requirements (Gibson, 2016).

L59: Is there a predictive nature to irrigation decision making? Do Calendars vs. Consultants vs. Probe percentages change over time due to other factors (technology, financial, drought, etc.)? Are consultant-based decisions consistent (is the advice consistent) over time?

K. Gibson (2016) found only 45% of irrigation volumes can be explained by biophysical factors. The remaining variation is likely due to human decision making. Seems to be a challenging social ecological system to understand, particularly for prediction.

L99: Not clear what is meant by 'irrigation triggering regimes'? Earlier (abstract) they were referred to as 'routines' that could be incorporated into LSMs. Regimes suggest something different?

We will update to keep routine consistent throughout the manuscript.

Replaced all "regimes" with "routine"

L122: What is the native resolution of SSURGO relative to the study area and field scale?

Greater than field scale but still does well for in- field observations.

L125: Same for SPNRD.

Data is on the field scale, total volume pumped for irrigated area.

Section 2.2: Based on the descriptions of these, are this ranging from the most simple to most complex (in order)?

Yes, simplest to most complex. We will clarify.

L144: Moreover, the four routines can be easily coupled or implemented into LSMs where PD is the simplest routine, and H the most complex.

For H, would it be possible that the minimal yield loss could be set so high as to represent larger irrigation than in CM?

Not possible within the constraints of irrigation depths and frequency (3 days for the lateral to move 360 degrees). The CM is triggered with no constraint on irrigation frequency.

L168: 'amount of water'

Updated to clarify the depth of water.

L166-168: Irrigation depth is determined by the deficit of soil moisture defined by the current moisture level subtracted from 95% of field capacity.

L179: Has this approach been used in the past? There are no references, and based on interviews and expert knowledge. How did you come up with 6.5 exactly? If the ultimate goal is to have this in an LSM, I can envision that it might be very sensitive to this 6.5 number and thus overly simplistic. Are there any other knobs to turn?

The SPNRD recommends a total amount of P+I of 650 mm within the growing season. In other areas this could be informed by growing season ET totals. The irrigation season is approximately 100 days long based on typical irrigation patterns. So 650mm/100 days is 6.5 mm/day in the absence of rainfall to meet this demand. The work of Sharma and Irmak 2012 quantify net irrigation requirement around NE. This same type of procedure could be extended across the HPA to determine daily irrigation intensity.

Sharma, V. and Irmak, S.: Mapping spatially interpolated precipitation, reference evapotranspiration, actual crop evapotranspiration, and net irrigation requirements in Nebraska: Part II Actual evapotranspiration and net irrigation requirements, Trans. ASABE (American Soc. Agric. Biol. Eng., 55(3), 923–936, doi:10.13031/2013.41524, 2012.

L185: This sounds reasonable as first order approximations for extreme rainfall. What about the low-intermediate rainfall conditions and the speed of drainage? Should the delay estimates be constant regardless of the soil type (conductivity), land cover, and precipitation rate?

Low rainfall rates (<6.5 mm/day) will not lead to a delay in irrigation application and this is consistent with discussions with producers in the area. Significant drainage is not expected within the growing season due to ET demand. Highly conductive soils would require a shorter delay, however maize is not typically produced in such soils. Land cover will change but these algorithms are specific to maize.

L243: What is meant by seasonal dynamic?

Updated to daily time series.

L255-256: For each year's growing season we simulated a daily LAI time series using HM.

L280: All assumptions embedded in these approaches have been explained and seem reasonable. The proof is in the pudding, of course, and the results will bear that out. However, it might be useful to summarize what the input requirements and the assumed/tunable parameters are for each approach as well, if they are to be used in LSMs. An example here is the date ranges that are used. 6.5 is another as is -500cm, and the depths of the soil pressure.

Yes, Table 1 provided a summary of key inputs and tunable parameters for each routine.

L284: Where are they located with respect to the study site and the fields? Should some kind of interpolation (or average) be used as well?

The average of the 7 gauges was used. It is clear that local rainfall data is needed for optimal irrigation management and a focus of future work.

L293: Mean ETc?

We had only 1 ETc estimate.

L294: Totals of what?

Will update to precipitation totals.

L305-306: In general, as precipitation totals increased, the range of seasonal precipitation totals observed by the 7 gauges increased as well (slope = 0.246 mm yr^{-1}*,* $R^2 = 0.38$*).*

L297: This is critical. The 4 schemes rely on P as the most important input (right?). Forcing for LSMs comes from satellite and gauge-based datasets, likely much coarser (e.g. .125-deg) than the <1km field scale. How will this be addressed? How can we capture the irrigation variability without knowing that of Precip?

Indeed, P is the most important input in both the routines and in the field. Decision making occurs from both radar estimations and in-field gauge readings. On shorter timescales (day to weekly), rainfall variability tends to be large. However, on the monthly to seasonal scale, variability tends to decrease. This is in part why we have focused on seasonal totals. Future work with this area will include the development and installation of a low cost met. station network delivered in realtime to producers. We added reference to Gibson 2016 which tackles this issue in more depth in central Neb.

L325: I think a lot more could be said - this is the critical result/figure from this paper. There is a lot of error bar info on there and other aspects that could be discussed. The low bias stands out and is significant.

Yes, the low bias motivates the recommendation of 50-75 mm reduction in irrigation application. The fact that irrigation application is in excess of crop water demand is in line with Gibson, 2015.

L328: ‘Regimes’ again.

Will update to routine.

L338: See earlier comment. This is a major limitation to all of these approaches and modeling irrigation at this scale.

See comment above (L325). Indeed we need the local P data. We hope the new NASA GPM 4 km product will be useful here.

L356: What does this imply about the assumed yield-irrigated amount relationship? That they underestimate and still didn’t impact yield is even more surprising. There must be a lot of leeway (i.e. overwatering?).

This is the motivation and focus of the ongoing cost-share program funded by Coca-Cola within the study area. This will be the focus of Gibson’s PhD looking at corporate supply chain *sustainability and scientifically sound water savings numbers. More to come over the next few years.*

L373: You are saying that, based on these models, you can get away with much less water and still produce the same yield, correct? Isn't that something that should have been quantified in the past (or known by the farmers)? Or is this still largely unknown?
How certain are we that the models are correct and that the yield will still be met?

See comment above (L356).

L384: Supports the need for a bit further analysis/figures looking into the time series of the results.

We have added a section of the daily time series of each model (Figure 8 and section 3.7).

L392: This was alluded to in an earlier comment: How can we know that prior decision making holds in the future or during other conditions not in the recent historical record?

We can only hypothesize about future conditions. Continued monitoring of irrigation application will be important with the continued trend of irrigation technology adoption.

L404: Why? Is it because soil types here are so are similar, with slowly varying properties?

Measurement of the soil properties is currently in progress. This was a surprising result indeed! Gibson 2016 also explored this and found soils had minimal impact on explaining irrigation amounts. Seems about 30% of irrigation variability in central NE can be explained by available water holding capacity. More to come on this for Gibson (2016 in review) and work with this project.

L433: How about a controlled experiment/field to test sensitivity and realism of these schemes and resultant quantities? Is that reasonable in the future?

Integration of these considerations within a producer's operation may be feasible and is indeed the focus of current work. However, the suggestion of a producer strictly following these mechanistic routines and abandoning their own "know-how" is unlikely to be well received other than at research and extension centers with more control. Producers are unlikely to make decisions that will affect their economics. Perhaps a program where we compensate the producer for yield losses could be implemented in the future. Some existing literature on this is from the Nebraska Water Balance Alliance.

L443: Any predictive capabilities?

Not sure.

Section 4: This discussion section was welcome - lot of areas that need study but this is a good start.

L453: 'may be useful'?

Updated.

Section 5: The conclusions are a bit thin, and perhaps should focus on some of the limiting factors and broader/future applicability (precip forcing, decision making, soil properties).

We added a few sentences about providing better rainfall products, which is the lowest hanging fruit in our opinion.

L477: Future work could focus on providing accurate realtime 1 km daily precipitation products through a combination of in-situ low cost gages, radar, and satellite remote sensing. Accurate and realtime precipitation remains a critical weakness in these rural and vast landscapes. Given the clustering of irrigation fields in Western Nebraska, the number of in-situ gages needed could be significantly reduced to provide high density networks in key areas.

Fig. 1: Hard to tell exactly where these fields are as this box points to a point on the corner of CO and NE.

Fig. 1: Might be interesting to overlay a 1km model grid on these to see what we are dealing with when trying to resolve individual fields.

We have added a 1 km grid to the figure.

Fig. 2 (Caption): Is this from STATSGO or from individual field samples?

SSURGO data downloaded from web soil survey and parsed via the NRCS toolkit. Changed caption.

Fig. 3 (Caption): Inferring that heavier precip is more localized?

Thank you for the suggestion.

Fig. 4 (Caption): depths across all sites?

Changed caption to all sites.

Fig. 5: Hard to see the error bars (busy plot already) - are they important or can they be conveyed in a sentence or two (general trends of increasing w/irrigation amount?).

After consideration we left error bars on plot for completeness of illustrating the mean and its uncertainty. Felt visual was stronger message than describing values in text.

Fig. 5: They are all underestimating the reported totals, though the slopes are consistent mostly weighted by the very high anchor points (600mm). Very mixed bag at lower values (300mm).

Yes, clearly risk aversion behavior compared to modeled needs.

Fig. 6 (Caption): Is this P+I from observations, or output from the schemes?

From observations, updated caption.

Fig. 7: What is going on in 2008?

Not totally sure, perhaps forcing data was off?

I'm a big disappointed in the analysis/figures. Would have been nice to see some time series of how these schemes are all working over time and in response to precip and precip variability.

To this end, it will be important for LSMs to get the seasonal and sub-seasonal cycle right (including the exact timing of irrigation) if they are to be used for coupled modeling and initialization. So the long-term or annual totals do not tell the whole story.

We will investigate this but are somewhat limited by the data only being at annual totals. We are working on a followup paper using energy use as a proxy to estimate subdaily irrigation rates in the area.

Section 3.7 was added to discuss the sub-seasonal irrigation time series. Figure 8 presents the results.

L373-379: 3.7 Simulated Growing Season Irrigation Application

Daily time series of simulated irrigation application can be seen in Fig. 8. Data for observed sub-growing season irrigation application is unavailable. Irrigation application tends to begin later in the growing season for the two routines that consider soil (CM and H). This is likely due to the routines first allowing soil moisture to be depleted before irrigation is triggered. The amount of soil moisture storage is typically near field capacity but in exceptionally dry years (2012) this storage is reduced and thus will lead to less of a delay.

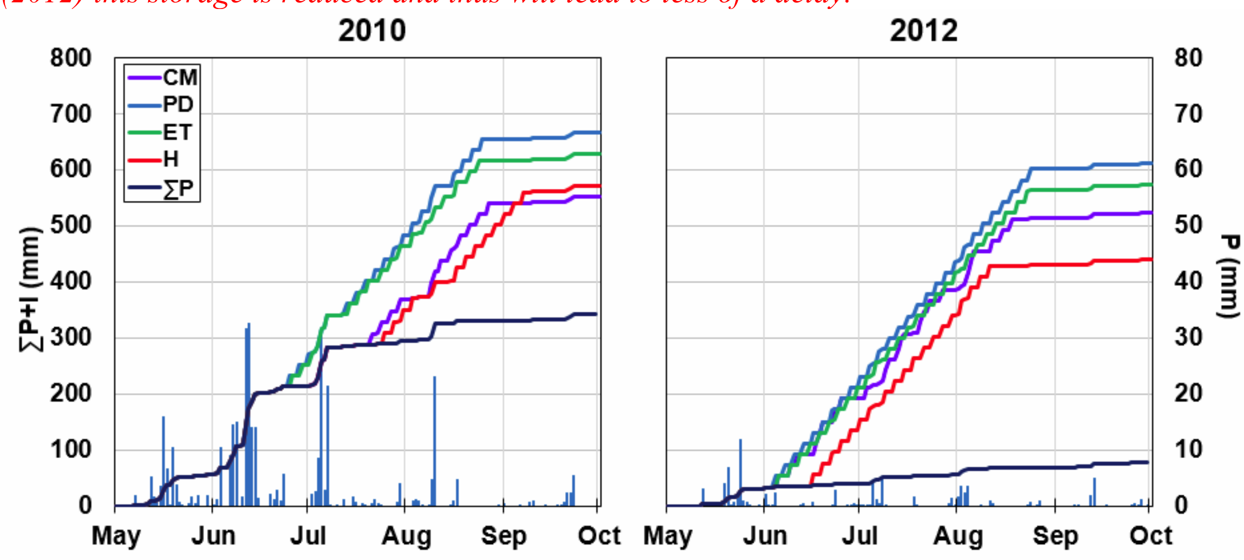

Fig. 8: Simulated growing season cumulative P and P+I with daily P values plotted on secondary y-axis for the 4 irrigation routines. Irrigation starts later for routines that track soil moisture.

Reviewer 2:

I find the study interesting and relevant. A better account of irrigation impact and dynamics in LSM is definitely an area that needs investigation. I do miss more specific information on the actual linkage between the described irrigation routines and the so-called hyper-resolution LSM. An actual example on this would have been a particularly strong additional element. As a minimum, a more detailed description on the potential integration should be provided along with its feasibility (i.e., input requirements and sources, crop-specific calibrations, limitations etc) for largescale application. In addition some clarifications to the methodology and findings are needed as detailed below.

Thank you for the thoughtful review. An example LSM routine (NOAH) is currently the focus of a paper in preparation by P. Lawston that should be submitted to HESS by the end of the year. We refer the reviewer to that study. We have added Table 1, which summarizes the needed inputs for each irrigation routine. Given access to those data we anticipate this scheme would be reasonable for the HPA and eastern USA where center-pivots are in operation.

Specific Comments:

1) Hyper-resolution needs to be properly defined. For me hyper-resolution intuitively refers to something that is very fine and very well resolved (i.e. at the meter scale) but that is obviously not the case here.

For better of worse, we adopted the language from Wood et al. 2011.

2) L136 – 66: I think that the points made in these sections are valid but I do think that framing would benefit from a slightly more streamlined and ordered structure, if possible.

Thank you for the suggestion. We have made some alterations. In addition we added larger context of the importance of irrigation to global food production: L101

L101: We note that irrigation is a key component of global food security, accounting for ~40% of global food production and ~20% of all arable land (Molden, 2007; Schultz et al., 2005). No doubt irrigation will continue to expand in the future.

3) L67-68: How was the critical field scale established?

We updated the text to:

L71-72: This critical scale is defined as where human-water decisions are made at due to the history of land partitioning and the inherent geometry is dictated by this landscape.

4) L91: Not sure what is referred to here in terms of the critical LSM scale.

See comment above.

5) L94-95: I would hope you could be a little more specific when talking about the next generation of hyper-resolution LSM and operational weather forecast models; what those this statement imply?

I guess it is simply the inclusion of better irrigation physics in LSM schemes and coupling to atmospheric models like NLDAS. We added the citation to Kumar et al. 2015.

6) L100-102: I would save the specifics of the irrigation routines to the method section.

We felt a brief description was helpful to introduce the overall framework of the paper.

7) L113: I find Fig. 1 pretty poor and not that informative. As a minimum, you will need a meaningful background image for the field boundary overlay.

Thank you for the suggestion. We updated with a 1 km grid along with a more meaningful background image.

8) L117: Why the reference to alfalfa here the entire area in under maize production?

Updated to maize referenced ET

L124-125: The study area is semi-arid where annual crop referenced (maize) evapotranspiration (ET_c) is significantly higher than precipitation (P) (HPRCC, 2016). The 7-year (2008-2014) average annual P is 440 mm/yr and average annual ET_c is 820 (mm/yr), as measured by the High Plains Regional Climate Center weather station (HPRCC, 2016) located within 10 km of the study area near Brule, NE.

9) L125-130: I think that you need to be more specific on the actual datasets used in this study. I see no description of the meteorological forcing data used.

We update the section with a description of the meteorological forcing data. HESS now requires a data availability section we included.

10) L134: The full names of the irrigation schemes should be given here as well.

Updated the text to:

L140-142: In the following sections we will describe four identified irrigation triggering routines, including crop model (CM), precipitation delayed (PD), evapotranspiration replacement (ET), and Hydrus 1-D (H).

11) L135: Why is "(CM)" given here? Same issue with "(H)" in next sentence. The reference/link is not evident from the text.

This is the abbreviation for the irrigation routine.

12) Section 2.2.1: I'm a little confused about the differentiation between CM and HM. HM also seems to be linked to Hydrus but not CM? May need a separate description of HM if that is the case or use CM consistently throughout.

CM and HM are linked. Hydrus uses the outputs from HM.

13) L150-151: The inputs (e.g., meteorological data, crop biophysical parameters) to the model are not well described here or in Section 2.1.

We added Table 1 and a data availability section to the manuscript.

14) L195: "was triggered"

Corrected

L207: triggered

15) L208: How was daily ETr determined?

From the HPRCC meteorological dataset.

16) L222: HM or CM? See previous comment.

CM and HM are linked. Hydrus uses the outputs from HM.

17) L243: So are you saying that you used a nondynamic (i.e., the same) LAI time-series for all years? Why not consider inter-annual variations in phenology? Does these descriptions of HM also apply to CM?

No, just a single LAI time series for all irrigation routines. The LAI time series is on the daily time step and varies from year-to-year. The description will clarified to:

L255-256: For each year's growing season we simulated a daily LAI time series using HM.

18) L244 and L250: The sentence "In addition, HM...." is repeated here.

Updated and removed the repetition.

19) L307: There's an issue with the figure numberings. Fig. 5 referred to here is Fig. 6.

Yes, updated the figure number.

20) L317: This is not Fig. 6 but Fig. 5.

Yes, updated the figure number.

21) L317-323: I'm confused about these numbers, which seem somewhat conflicting. It is stated that both CM and PD are near the historical average. But then it is mentioned that CM is 80 mm lower, the same as ET. In addition, the percentages differ. I also find it difficult to verify these numbers based on the figure. These issues will need to be clarified.

Agreed, this does need clarification. The slopes are similar but with an offset. The percentages were clarified.

L331-332: Both the CM and PD routines reproduce the trend of the historical irrigation amounts but with a low offset (similar slopes).

22) L323: Fig. 5?

Yes, will update the figure number.

23) Section 3.5: Why is ET and PD not mentioned here?

The don't have a soil consideration within the routine and so soil texture will not have an impact on their numbers. This will be mentioned in the text.

L357: Both ET and PD do not have a soil component considered in their routine and as such are not impacted by soil texture.

24) Section 3.6: In Fig. 7, the CM and ET colors can't be distinguished.

We will update both colors and line weights for clarity.

25) L353-354: The historically reported yield should also be plotted on the figure for comparison.

We only have historical yield for years prior to the study.

26) L371: Was the 30% reduced irrigation need described/mentioned in the results?

Updated to up to 115 mm or 30%.

27) L401-413: This section is a little hard to follow and should be rewritten for better clarity.

We have made edits for clarity.

L426: With regard to soil texture differences in the study area, observed irrigation data indicated no difference between fields in these two texture classes. Similar behavior was seen from the irrigation routine simulations that showed 10% difference for H and 1% difference for CM. We note that given the similar soil texture classes (and thus soil hydraulic parameters) this result is not unexpected. In practice, we are finding that producers are being to adopt precision irrigation techniques (Hedley and Yule, 2009; Hedley et al., 2013). Here, small scale features within a field (e.g. sandy or gravelly areas, underperforming parts of the field, water ways, pivot roads, etc.) can be better managed with the new technology. Therefore, managing fields following 1 dominant soil type (i.e. irrigation-pressure trigger point) may be highly inefficient (Kranz et al., 2014). More refined and consistent soil texture data across arbitrary political boundaries (Chaney et al., 2016) are needed to better account for differences in irrigation water application on the sub-field scale, especially in areas with increasing adoption of precision agriculture technology.

28) Section 4.4: This section is very brief and would benefit from a much more substantial and elaborate description of the feasibility and limitations associated with the integration of the routines in the LSMs.

We have expanded this section as requested.

L461: The four irrigation routines although biased, capture year-to-year variation in irrigation in Western Nebraska. Given the widespread use of center-pivots we expect the irrigation routines to be appropriate for the HPA and into parts of the eastern USA. Gibson (2016) provides a fuller assessment of irrigation behavior throughout central Nebraska. We note that it is unclear how these routines would behave in areas with center-pivot outside the USA (i.e. Brazil, South Africa, Australia), where energy costs for pumping may be more restricting and drive human-decisions on irrigation. Assessment of these routines in those areas would require further validation.

We believe the routines combined with a reasonable bias correction could be easily incorporated into future hyper-resolution LSMs with the above routine descriptions and readily available LSM model output or datasets (see Table 1). Clearly accurate and local precipitation is critical in driving these irrigation routines and capturing producer behavior. This topic deserves more research, particularly and the opportunity to combine low cost in-situ gages with radar and remote sensing products. Additionally, we note the four routines could be run offline in order to provide reasonable guesses of applied irrigation for a given irrigation season. This may be beneficial in representing processes not explicitly considered in LSMs (Kumar et al. 2015), or making future assessments and recommendations about water availability for managers. Finally, the four routines provide reasonable irrigation bounds and more importantly predictions about decreases in irrigation as technology is introduced and adopted in novel areas.

29) L447: Isn't the 1 km scale often too coarse to resolve field-specific irrigation dynamics?

Not necessarily for this landscape. The land is partitioned into 0.8 km sections. Often irrigation decisions are made for uniform conditions. Some sub field decisions using precision agriculture are now available but not widely used yet.

A case study of field-scale maize irrigation patterns in Western Nebraska: Implications to water managers and recommendations for hyper-resolution land surface modelling

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Abstract

In many agricultural regions the human use of water from irrigation is often ignored or poorly represented in land surface models and operational forecasts. Because irrigation increases soil moisture, the feedbacks to surface energy balance, rainfall recycling, and atmospheric dynamics are not represented and may lead to reduced model skill. In this work, we describe four plausible and relatively simple irrigation routines that can be coupled to the next generation of hyper-resolution LSMs operating at scales of 1 km or less. The irrigation output from the four routines (crop model, precipitation delayed, evapotranspiration replacement, and vadose zone model irrigation based) are compared against a historical field scale irrigation database (2008-2014) from a 35 km^2 study area under maize production and center pivot irrigation in western Nebraska (USA). Here we find the most yield-conservative irrigation routine (crop model) produces seasonal totals of irrigation that compare well against the observed irrigation amounts across a range of wet and dry years but with a low bias of 80 mm yr^{-1}. The most aggressive irrigation savings irrigation routine (vadose zone model) indicates a potential irrigation savings of 120 mm yr^{-1} and yield losses of less than 3% against the crop model benchmark and historical averages. The results from the various irrigation routines and associated yield penalties will be valuable for future consideration by local water managers to be informed by the potential value of irrigation savings technologies and irrigation practices. Moreover, the routines offer the hyper-resolution LSM community a range of irrigation routines to better constrain irrigation decision making at critical temporal (daily) and spatial scales (<1 km).

Keywords: Crop model; Irrigation; Irrigation savings technology; Maize; Hydrus

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1. Introduction

Regional land surface models (LSM) often ignore or do a poor job of representing irrigation physics (Kumar et al., 2015). This is in part due to the difficulty of validating irrigation amount estimates as irrigation datasets are rare, in formats that are difficult to work with on a regional scale (e.g., different reporting formats from one agency to another or in paper records), and have a latency period of months to years making them impractical to use in operational forecasts. The USDA produced Farm and Ranch Irrigation Survey (USDA, 2014) contains survey data on the county level, however data are only reported every five years and irrigation data are given on a pumping volume basis instead of depth per irrigated area as needed by LSMs (Siebert et al., 2010). Another well-known irrigation database, AQUASTAT (FAO, 2008), contains irrigation data at a spatial scale too coarse for investigating important feedbacks like land-atmospheric coupling and lacks information for Europe and North America. There are only a few studies that have used field-level irrigation databases (c.f. Grassini et al. 2011, 2014, 2015), mostly focusing on benchmarking on-farm irrigation in relation to crop production.

With the continual refinement in the spatial resolution of LSMs down to <1 km (Wood et al., 2011) and the coupling to crop models (Kucharik, 2003), reliable irrigation data needs to be incorporated in the calibration and validation of LSMs. Although the presence of irrigation doesn't necessarily impact soil moisture contribution to the atmosphere, the soil moisture-flux relationship is critical to surface energy balance and atmospheric dynamics. One area of particular importance is the impact of soil moisture on atmospheric processes, such as rainfall recycling (Findell and Eltahir, 1997), the strength of atmospheric coupling (Koster et al., 2004), and planetary boundary layer dynamics (Santanello et al., 2011), all of which impact the skill in operational forecast models. More complicating is that both irrigation timing and volumes are

Deleted: , and irrigation is an important component of that relationship based on human decision making processes and biophysical requirements (Gibson, 2016). For example, the USDA found 24% of producers relied on crop calendars, 16% on crop consultants, and 23% on in-situ probe technology (USDA, 2014). Because irrigation decisions are dependent on both processes, reliable historical irrigation data are critical to understand why and how decisions were made in order to accurately represent the physics in hyper-resolution LSMs and operational forecast models. In the absence of irrigation data, LSMs have typically relied on mass balance approaches (Döll and Siebert, 2002; Wada et al., 2012) where irrigation amounts close the water balance. While a reasonable first approach, this methodology may introduce additional uncertainty into LSMs due to the complexity of representing the human decision making process on water use. The uncertain irrigation schemes affect the time history of soil moisture and thus our ability to properly assess the impacts of human water use on coupled land-atmospheric model physics.

The focus of this study was to investigate historical irrigation use at the critical field scale (~0.8 by 0.8 km) in a study area of 3500 ha in western Nebraska, which resides on the edge of the USA Corn Belt. This critical scale is defined as where human-water decisions are made due to the history of land partitioning and the inherent geometry dictated by this landscape. While a relatively small area, the study site is an ideal location for assessing the sustainability of groundwater pumping for irrigation of crops. The study area is a microcosm of many areas across the globe, where humans rely on groundwater withdrawals for their livelihoods (Mekonnen and Hoekstra, 2011). The study area is at a critical location as it is on the boundary where irrigation supply volumes can no longer economically compensate for the deficit between potential evapotranspiration (ET_p) and precipitation (P). Of particular concern to impacts on both human and natural ecosystems are the resultant declines in the local water table due to irrigation

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(Young et al., 2014). For example, the southern portion of the High Plains Aquifer (HPA) has had significant groundwater depletion over the last 80 years, with up to 50% losses of saturated thickness (Scanlon et al., 2012). In the Northern HPA (Butler et al., 2016), where this study area is located, intense irrigation pumping has led to localized water table declines (specifically in Box Butte County, and widespread throughout the neighboring Upper Republican Natural Resources District) but has yet to be widespread across the region (Young et al., 2013). Given low recharge (Szilagyi and Jozsa, 2013; Gibson, 2015; Wang et al. 2016) relative to irrigation pumping, rising global food and water demands (FAO, 2009), and concomitant effects of climate change (Kumar, 2012), the sustainability of this study area and the overall HPA system in support of long-term irrigation agriculture is uncertain (Butler et al., 2016). The study presented here is an important first step in assessing water saving technologies to continue to make irrigation agriculture sustainable for its critical need in meeting rising global food demands.

Here, we benchmark relatively long-term (2008-2014) and field-specific flow-meter measured irrigation amounts within the study area against a range of irrigation strategies. The data includes information on 55 fields (~65 ha) producing maize under center pivot irrigation. Datasets at this critical LSM scale are rare due to privacy concerns and as a result are often aggregated to county and seasonal totals (USDA, 2014; USDA-NASS, 2014) making assessment of the irrigation depths over a given area difficult to ascertain. This study therefore fills a critical data need in the development and testing of the next generation of hyper-resolution LSMs and operational weather forecast models (Kumar et al., 2015). The next generation of LSMs will be essential for better assessing the impacts of irrigation on the surface energy balance as well as evaluating the long-term sustainability of groundwater resources in agricultural areas. We note that irrigation is a key component of global food security, accounting for ~40% of global food production and ~20% of all arable land (Molden, 2007; Schultz et al., 2005). No doubt irrigation will continue to expand in the future.

The primary objective of this study is to benchmark historical irrigation amounts in the study area using different plausible physically based irrigation triggering routines. In the methods sections we will summarize the four identified irrigation triggering routines- 1. crop model (CM), 2. Precipitation delayed (PD), 3. Evapotranspiration replacement (ET), and 4. Vadose zone model where irrigation is triggered by simulated pressure head (H). In the results section we will assess the impacts of annual variations in precipitation on irrigation, and soil texture differences in the study area. In the discussion, we will provide a general framework for including plausible irrigation schemes in LSMs, as well as discuss any expected changes in irrigation behaviors as producers adopt various technologies into practice. The framework and irrigation schemes provide LSMs a practical guideline for estimating irrigation depths and timing as well as a strategy for investigating technology adoption scenarios.

2. Methods

2.1 Description of Study Area and Historical Data

The study area is located in western Nebraska where the South Platte River enters the state (Fig. 1). The site encompasses 55 fields with an average area of 65 ha under irrigated maize production (3500 ha total area). Overhead sprinkler irrigation from center-pivots using water from the underlying HPA is the most common form of irrigation in this area as well as throughout Nebraska, and the USA, as it is a cost effective and more efficient option than flood irrigation. The study area is semi-arid where annual crop referenced (maize) evapotranspiration (*ET_c*) is significantly higher than precipitation (*P*) (HPRCC, 2016). The 7-year (2008-2014)

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average annual P is 440 mm/yr and average annual ET_c is 820 (mm/yr), as measured by the High Plains Regional Climate Center weather station (HPRCC, 2016) located within 10 km of the study area near Brule, NE.

Data obtained from SSURGO (Soil Survey Staff, 2016) indicates that soil texture in the area falls within 2 USDA textural classes: sandy loam and loam (Fig. 2). Historical land management data for the area are available from the South Platte Natural Resource District (SPNRD, 2015). The SPNRD dataset includes field-specific information from the period of 2008-2014 on crop type, irrigation pumping volumes, and irrigated area. Detailed descriptions and quality control of NRD databases can be found in Grassini et al. (2014) and Farmaha et al. (2016). The above datasets provide the needed meteorological forcing, model parameters, and calibration datasets for running and evaluating the suite of irrigation modeling routines described below.

2.2 Irrigation Modeling Routines

In the following sections we will describe four identified irrigation triggering routines, including crop model (CM), precipitation delayed (PD), evapotranspiration replacement (ET), and Hydrus 1-D (H). The four irrigation triggering routines represent the upper limit of irrigation requirements in which no plant water stress occurs (CM), and the lower irrigation limit needed to ensure minimal yield loss against a crop model benchmark (H). Moreover, the four routines can be easily coupled or implemented into LSMs where PD is the simplest routine, and H the most complex. We also note the difference between the historical irrigation practices and lower bound of simulated irrigation provides a potential irrigation savings value in the study area. This irrigation savings value will be important for evaluating the economics of new irrigation

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technologies as well as providing critical information to policy makers and local stakeholders on the sustainable management of the HPA (Butler et al., 2016). Table 1 provides of summary of key needed inputs and list of tunable parameters for each routine.

2.2.1 Crop Model Irrigation (CM)

A crop model, Hybrid Maize (HM) (Yang et al., 2013) was utilized to estimate irrigation requirements and yield potential under an idealized scenario of crop growth with no water stress. Model performance has been extensively validated against measured yield in crops that received near-optimal management across the Corn Belt (Grassini et al, 2009, 2011). However, it has not been rigorously tested for seasonal irrigation totals, which is one key outcome of this study. Details on the model can be found in Yang et al. (2013) and a brief description of the model is given here. Inputs to this model include meteorological data, soil texture, crop biophysical parameters, sowing date, and plant density. The datasets are described above in section 2.1. Soil water dynamics over the root zone are simulated through a bucket model approach with 10 cm thick layers. Drainage between soil layers occurs when soil moisture exceeds field capacity. Irrigation application is triggered when actual ET (ET_a) is less than crop referenced potential evapotranspiration (ET_c), ensuring no water stress occurs throughout the entire growing season. Irrigation depth is determined by the deficit of soil moisture defined by the current moisture level subtracted from 95% of field capacity within the managed root zone. Maximum water application per irrigation event was set to 19.5 mm. When the depth-weighted unsaturated hydraulic conductivity (K_r) of the root zone is greater than or equal to ET_c, ET_a is equal to ET_c. Otherwise ET_a is equal to depth-weighted K_r of the root zone.

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2.2.2 Precipitation Delayed Irrigation (PD)

Water application in an idealized land management operation would consider all components of the water balance within the decision making process. However, in practice, precipitation is often the only component considered due to 1) the difficulty of accurately measuring the other water balance components and 2) the relative economic return is minimal when considering the perceived potential of crop yield loss versus savings due to reduced pumping/irrigation. With this in mind, producers often develop "rules of thumb" to irrigate up to a target total amount water equal to irrigation plus in-season rainfall (in the study area, 1 May to 30 September). Using these basic rules of thumb and local crop calendar requirements, we suggest the following routine based off of precipitation data alone. However, we note that this is not a recommendation for producer adoption, but instead represents a simplified method of irrigation management for modeling purposes. In addition, the applicability of this method to other regions should be possible with complimentarily datasets (i.e. *P* and ET_c). Recommendations obtained from the SPNRD indicate that maize requires approximately 650 mm of total water (precipitation plus irrigation, *P*+*I*) per growing season (http://www.spnrd.org/index.html). Field observations indicate that irrigation often starts around mid-June and concludes around mid-September, leading to a 100-day irrigation season. Average irrigation application in the absence of precipitation would be 6.5 mm/day or 19.5 mm per 3 day period. This irrigation depth is consistent with producer interviews and local expert knowledge. Three day periods are critical to consider as this is often the time required to perform a single 360^o rotation of a center-pivot (i.e. dictated by soil infiltration rates and well pumping capacity). In this routine, if rainfall is greater than 6.5 mm/day, then irrigation for one day is met, and thus a 1 day delay is set. Likewise, for a rainfall event of 13 mm/day, then two days of irrigation are

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met and irrigation is delayed 2 days, and so on for larger rain events. For simplicity, rain events and irrigation delays are rounded to the nearest day and up to a maximum of 7 days' delay. For rainfall events greater than 45.5 mm/day, we assume a maximum delay of 7 days due to deep drainage and runoff losses incurring during the event.

2.2.3 ET Replacement Irrigation (ET)

The primary purpose of irrigation is to ensure ET_a is able to adequately keep up with ET_c over the growing season as ET_a is linearly correlated with yield (Passioura, 1977). Proper management allows a deficit between applied water and ET_a in order to allow for adequate infiltration after rainfall. This deficit was assumed to be 6.5 mm for this routine based on the average daily crop water requirement discussed above. In this algorithm whenever the deficit was greater than 6.5 mm during the irrigation season (15 June to 30 September) an irrigation event of 19.5 mm was triggered for the next day. Again, an irrigation event of 19.5 mm was used as it represents a 3 day period, over which the center-pivot operates.

Estimating ET_c is necessary in order to track the deficit between applied water and ET_a. While estimating ET_c is complex given the variability of micrometeorological variables from one field to another, in practical applications, crop coefficients are often used to surmise the differences in crop biophysical relationships and the effect of soil (Shuttleworth, 1993). These coefficients are often published from local services like the state climate office or HPRCC in Nebraska.

Here, ET_c (mm/day) was estimated following the single crop coefficient method outlined in Allen et al. (1998):

$$ET_c = ET_r K_c \quad (1)$$

where ET_r (mm/day) is reference crop ET_p calculated from micro-meteorological variables, and K_c is a dimensionless empirical constant that encompasses crop development as well as the average effect of soil on evaporation rates. Daily ET_r data were determined from the HPRCC weather station data. K_c values were calculated as a function of growing degree day accumulation (*GDD*) from the HPRCC data (HPRCC, 2016). A single day calculation of growing degrees (GDD_{daily}) is defined as:

$$GDD_{\mathrm{daily}} = \frac{T_{\max} + T_{\min}}{2} - T_{base} \qquad (2)$$

where $T_{\max}$ is the daily maximum temperature (°C) (with a maximum of 30°C), $T_{\min}$ is the daily minimum temperature (°C), and T_{base} is 10°C. The *GDD* method is preferred as it more accurately represents a proxy for crop development, as opposed to a fixed number of days after sowing.

2.2.4 Hydrus-1D Irrigation (H)

A physically based vadose zone model, HYDRUS-1D (H1D) (Šimůnek et al., 2013) was used to simulate irrigation requirements based on predefined soil pressure head trigger points in the root zone. In order to carry out necessary seasonal dynamics for annual crops (i.e. dynamic root growth, root distribution), we coupled the HM and H1D models using Matlab. We note that soil pressure triggered irrigation events based on more than one soil pressure value, flexible irrigation timeframes, and dynamic root growth with a specified distribution are unavailable in the standard H1D code. Here we use Matlab to link together a series of one day simulations (totaling 7 years), where model outputs (pressure head at depth, flux rates, actual evapotranspiration, etc.) at the end of the day were used to make a decision about irrigation for the following day.

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H1D simulates soil water dynamics and water flow by a numerical approximation to the 1D Richards equation:

$$\frac{\partial \theta}{\partial t} = \left(\frac{\partial}{\partial z}\right)\left[K(\theta)\left(\frac{\partial h}{\partial z}+1\right)\right] - S \qquad (3)$$

where θ is volumetric water content (cm^3/cm^3), t is time (day), z is the spatial location (cm), $K(h)$ is unsaturated hydraulic conductivity (cm/day), h is pressure head (cm), and S is a sink term describing evapotranspiration (1/day). The soil profile simulated is 6 m deep with 1 cm node discretization. Free drainage is set for the lower boundary condition, as local depth to groundwater is on average 15 m (Korus et al., 2013)

The H1D model requires ET_c be partitioned into potential evaporation and potential transpiration. This is accomplished using Beer's law:

$$T_p = ET_c\left(1 - e^{-k*LAI}\right) \qquad (4)$$

$$E_p = ET_c - T_p \qquad (5)$$

where T_p is potential transpiration (cm/day), E_p is potential evaporation (cm/day), k is the light extinction coefficient (set here to 0.55 (Yang et al., 2013)), and LAI (m^2/m^2) is the leaf area index. For each year's growing season we simulated a daily *LAI* time series using HM. This same seasonal dynamic was used for all simulations. In addition, HM was used to estimate date of silking for each simulated year. Water stress is minimized during silking periods as this is the most critical grain filling period for yield. Most producers will heavily water in this period to ensure yield. In order to accurately represent the irrigation behavior, we forced irrigation events every three days, one week before and after the silking date. In the case where a simulated day occurred during the growing season, root depth (*Zr,* cm) and root distribution (*Zr_{RD}*, dimensionless) parameters were calculated on a daily basis based off of a pre-determined *GDD*

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accumulation after planting date for each growing season. This process was carried out following the equations outlined in the HM user manual (Yang et al., 2013):

$$Zr = \frac{GDD}{GDD_{\mathrm{Silking}}} Zr_{\max} \quad (6)$$

$$Zr_{RD} = \exp(-VDC\, Z_L / Zr) \quad (7)$$

where $GDD_{silking}$ is growing degree days at silking, ZR_{max} is a biophysical parameter representing the maximum depth the root zone can reach (cm) and set to 150 cm here (Yang et al., 2013), VDC is a vertical distribution coefficient set to 3 here, and Z_L is the current depth in the root zone (cm).

Irrigation events and depths for the following day were calculated by investigating the average soil pressure heads at 30, 60, and 90 cm during the historical irrigation period from June 15 through September 30. Prior to the silking date, the average soil pressure head at 30 and 60 cm is computed and compared against a preset irrigation trigger value set to -500 cm based off of the dominant soil types in the area (Fig. 2). Following the silking date, the average soil pressure is computed at 30, 60, and 90 cm with the same trigger point of -500 cm of pressure. This algorithm is based on best practice irrigation recommendations summarized in Irmak et al. (2014). In practice, producers vary the irrigation pressure trigger point based upon farmer risk aversion and soil type. Given that yield is the primary economic driver over energy costs for pumping water, this trigger point is often set at conservative values. When the pressure head at the considered depths exceeds the trigger point, an irrigation event of 19.5 mm is set for the following day. The irrigation event is added to any precipitation that may arrive randomly on that day as well.

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In order to numerically advance the models through time, we set up a series of 1 day simulations and logical statements. If the model date occurred outside of the growing season (October 1 to April 30), no changes were made to precipitation and bare surface was simulated. If the model day was after planting (1 May) and before the start of the historical irrigation season (15 June), only the root zone depth and root distribution parameters were updated. For model dates during the irrigation season (15 June to 30 September), the root zone depth, root distribution, and irrigation amounts were changed for the following day. Using this routine, the model was run continuously at 1 day intervals for the entire study period (1 January 2008 to 31 December 2014).

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2.3 Rainfall Variability Across the Study Site

Daily precipitation data for the years 2008-2014 were available from 7 gauges within a radius of 35 km of the study site. In order to help assess the effect of precipitation variability on irrigation application, all 7 time series along with the average precipitation time series were used within the four irrigation routines described above. In addition, all irrigation routines that considered soil type were repeated for the two dominant soil types in the study area, i.e., sandy-loam and loam.

3. Results

3.1 Precipitation Variability and ET_c

As expected, significant gauge-to-gauge variability was observed within the 7 rain gauge time series within each growing season with a mean of 320 mm and a CV of 35% (Fig. 3). In general, as precipitation totals increased, the range of seasonal precipitation totals observed by

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the 7 gauges increased as well (slope = 0.246 mm yr^{-1}, $R^2 = 0.38$). There was no consistent year-to-year spatial precipitation gradient, and no gauge consistently reported high or low totals. We hypothesize that this natural variability in rainfall is a large contributor of the irrigation variability we see at the field level. This hypothesis was beyond the scope of the current paper but suggest future research in this area (c.f. Gibson 2016). In terms of growing season ET_c, the HPRCC reported an average of 815 mm, and was within 10% of county-level values estimated by Sharma and Irmak (2012).

3.2 Historical Field Scale Irrigation

Average seasonal irrigation over the 2008-2014 period was 380 mm with a CV of 23%. Distributions of irrigation amounts are provided in the box and whisker plots given in Fig. 4. Normal distributions and non-normal distributions with both negative and positive skewing were observed (D'Agostino-Pearson test, $p<0.05$). Growing season precipitation plus irrigation averaged 700 mm (Fig. 5) with a CV of 5%. The highest seasonal irrigation average occurred during the growing season of 2012 (580 mm) due to an extremely dry growing season with only 80 mm of rainfall. We found that soil texture was not a significant factor affecting irrigation application at the field scale in this region. This finding was consistent with results from central Nebraska (Gibson 2016). After grouping the fields by soil type (loam and sandy-loam), we found that the mean irrigation for all years were not statistically different from each other (Student's t-test, $p = 0.73$). This indicates that soil type did not factor into the irrigation decision making process.

3.3 Comparison of Historical Seasonal Irrigation Amounts with Four Irrigation Routines

Results of the comparison between the historical irrigation (2008-2014) and the four irrigation routines are summarized in Fig. 5. Both the CM and PD routines reproduce the trend of the historical irrigation amounts but with a low offset (similar slopes). CM irrigation water requirements were on average, 80 mm lower (20% of total) relative to historical irrigation. For PD, the average seasonal difference was 40 mm lower (10% of total). For ET and H, simulated irrigation amounts were 80 mm (20% of total) and 120 mm (30% of total) lower than the historical average, respectively. We also note the slopes of the observed irrigations and the CM and PD for the given years were in general similar. However, it is obvious from Fig. 5 that the slopes of ET and H were different from the observations, which results in larger deviations in drier years and thus a potential for greater irrigation savings. The implications to water management will discussed in the next section.

3.4 Irrigation Sensitivity to Rainfall

All irrigation routines responded to differences in the eight rainfall time series, and this response is represented as vertical error bars in Fig 5. The difference between the highest and lowest irrigation amount for each growing season was on average 75 mm, or 20% of average irrigation totals. The largest difference in irrigation totals occurred in 2008 for all irrigation routines with an average of 130 mm between all 4 routines, and the smallest difference occurred in 2012 at an average of 27 mm due to uniformly low precipitation. The analysis illustrates the variation in irrigation amounts depends on which rainfall gauge is used to make a decision. Given that producers often have fields distributed across a region the uncertainty in local rainfall directly propagates into variations in irrigation amounts (Gibson 2016). Future research efforts

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should investigate the effect of spatial rainfall variability on producer decision making but this was beyond the scope of the current study.

3.5 Soil Texture Impact on Irrigation Routines

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We found that the two dominant soil textures in the study area did not have a significant impact on irrigation amounts under CM and H. Both ET and PD do not have a soil component considered in their routine and as such are not impacted by soil texture. In the case of CM, average irrigation was within 1% for all years. For H, the irrigation average of the sandy loam soil was 10% less than the average of the loam soil. Soil hydraulic parameters used for both soil textures were determined using ROSETTA (Schaap et al., 2001) and are presented in table 1.

3.6 Simulated Yield under Irrigation Routines

Following the simulated irrigation for the routines of PD, ET, and H, the (*P*+*I*) time series were reinserted back into the crop model for all years to estimate yield impacts (Fig. 7). The crop model yielded an average 14.6 Mg/ha over the study period. The yield gap (i.e., difference between yield potential and actual yield) of US irrigated maize represents approximately 15% of the potential (Grassini et al., 2013, http://www.yieldgap.org/), suggesting an average actual yield of 12.4 Mg/ha for the study area, which is within 5% of historical reported yield. For the three routines and for all years, simulated yields were on average within 3% of the simulated yield based on the CM. The results indicate that the various irrigation scheduling strategies did not have a large impact on yield while reducing irrigation amounts substantially; hence, they may be a sound economic decision for producers.

3.7 Simulated Growing Season Irrigation Application

Daily time series of simulated irrigation application can be seen in Fig. 8. Data for observed sub-growing season irrigation application is unavailable. Irrigation application tends to begin later in the growing season for the two routines that consider soil (CM and H). This is likely due to the routines first allowing soil moisture to be depleted before irrigation is triggered, thus creating the reduced pumping and irrigation savings. The amount of soil moisture storage is typically near field capacity but in exceptionally dry years (2012) this storage is reduced and thus will lead to less of a delay at the start of the growing season.

4. Discussion

4.1 Temporal Variability of Applied Irrigation

Historically, the study area has had a consistent amount of total seasonal water (P+I) from year to year. The percent of irrigation to applied water (I/(P+I)) was on average 55%, and notably in 2012 this was as high as 88%. The relative weight of irrigation to precipitation highlights the importance for constraining irrigation amounts for proper water balance closure within the study area, as well as in other areas with intense irrigation application. Given the high seasonal rates of irrigation to precipitation, no doubt the soil moisture will be adversely affected when compared to a rainfed area. More importantly, the impacts to the local surface energy balance (Santanello et. al, 2011), rainfall recycling, and skill in observational forecasts may be diminished without proper accounting for irrigation. For example, regional mesoscale modelling illustrated that up to 40% of East African annual rainfall can be attributed to irrigation across India (de Vrese et al., 2016). With the suggested findings here on reduced irrigation needs (up to

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115 mm or 30%), the potential changes to precipitation patterns across the HPA due to adoption of irrigation scheduling technology should be further investigated.

The study area is currently under ground water appropriation, with a historical increase in depth to groundwater of 1.2 m over the period of 1971 to 2013 (SPNRD, 2013; Young, 2013). Precipitation pattern changes in the area induced by global warming are believed to lead to less frequent but more intense storms with an increase in total precipitation (Dai et al., 2011). However, the timing of precipitation is of equal concern to totals, as more infrequent rain events may still lead to increased pumping with the same seasonal totals. The scenario of changing precipitation amounts and timing is not unique to the study area but a more general pattern of the region, highlighting the need for explicit treatment of irrigation depths and timing to fully understand the complex feedbacks that exist beneath the land surface and atmosphere. The irrigation routines suggested in this work can be used as a first assessment of the likely irrigation amounts due to different observed scheduling practices (USDA 2014).

4.2 Spatial Variability of Applied Irrigation

The rainfall sensitivity analysis demonstrated the affects and uncertainty for each of the four irrigation routines investigated. Lower rainfall years had lower spatial variability and as a result simulated irrigation for each routine led to similar values. However, this behavior was not consistent with the observed irrigation data, in which the lowest rainfall year (2012) had the largest standard deviation (168 mm) for applied irrigation. The results are likely due to two reasons: 1) producers give up irrigation at some point during the growing season as their crop parishes in the extreme heat and drought conditions and 2) differences in well-to-well pumping capacity become more apparent with increased pumping demand. Although no direct work has been done to confirm differences in pumping capacity or inefficiencies in the study area, the general effect has been explored through modeling in other areas (Foster et al., 2014). With respect to LSMs, these two factors represent significant deviations away from water balance closure approaches, making it challenging to include realistic irrigation values in dry years. Therefore, additional studies and datasets similar to what is presented here are critical for the calibration and validation of the next generation of hyper-resolution LSMs.

With regard to soil texture differences in the study area, observed irrigation data indicated no difference between fields in these two texture classes. Similar behavior was seen from the irrigation routine simulations that showed 10% difference for H and 1% difference for CM. We note that given the similar soil texture classes (and thus soil hydraulic parameters) this result is not unexpected. In practice, we are finding that producers are being to adopt precision irrigation techniques (Hedley and Yule, 2009; Hedley et al., 2013). Here, small scale features within a field (e.g. sandy or gravelly areas, underperforming parts of the field, water ways, pivot roads, etc.) can be better managed with the new technology. Therefore, managing fields following 1 dominant soil type (i.e. irrigation-pressure trigger point) may be highly inefficient (Kranz et al., 2014). More refined and consistent soil texture data across arbitrary political boundaries (Chaney et al., 2016) are needed to better account for differences in irrigation water application on the sub-field scale, especially in areas with increasing adoption of precision agriculture technology.

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4.3 Potential for Reduced Pumping

The four irrigation routines presented represent different levels of allowable water stress to develop in the maize. The CM routine is the lowest risk approach with respect to yield and represents the modeled upper limit of required irrigation to maintain a stress free management scenario. It is hypothesized that any irrigation application above this represents irrigation application due to risk aversion, and will not appreciably increase yield. Comparisons between 2008-2014 indicate that the slope of the applied irrigation from observed irrigation are indistinguishable, but with a bias of ~80 mm yr^{-1} more observed irrigation. This indicates that producers are averaging an additional 3-4 irrigation cycles beyond what the CM indicates. The differences in irrigation totals from the other three irrigation routines are the result of increasing allowable water deficit in the routines. A reduction of 115 mm or 30% of irrigation was observed for H when compared to the historical average. We note this hypothetical scenario requires perfect management, with full trust of the technology, and may not be achievable in practical applications. However, we anticipate that a 50-75 mm reduction over a short technology adoption period (2-4 years) is feasible, particularly in areas with strong university extension programs and/or producer to producer knowledge exchange (Irmak et al. 2012). In addition, these hypothetical reduced pumping numbers may be useful to local, state, and federal policy makers about future water management decisions and investment in cost-sharing technology programs.

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4.4 Assessment of Center-Pivot Irrigation Routines in Hyper-Resolution Land Surface Models

The four irrigation routines although biased (i.e. contain an offset), capture year-to-year variation in irrigation in Western Nebraska. Given the widespread use of center-pivots we expect the irrigation routines to capture year-to-year variation for the HPA and into parts of the eastern USA. We note that the magnitude of the offset is likely related to local producer behavior and influenced by social norms and risk aversion. Gibson (2016) provides a fuller assessment of irrigation behavior throughout central Nebraska. We note that it is unclear how these routines would behave in areas with center-pivot outside the USA (i.e. Brazil, South Africa, and Australia), where energy costs for pumping may be more restricting and drive human-decisions on irrigation. Assessment of these routines in those areas would require further validation.

We believe the routines combined with a reasonable offset correction could be easily incorporated into future hyper-resolution LSMs with the above routine descriptions and readily available LSM model output or datasets (see Table 1). Clearly, accurate and local precipitation is critical in driving these irrigation routines and capturing producer behavior. This topic deserves more research, particularly and the opportunity to combine low cost in-situ gages with radar and remote sensing products. Additionally, we note the four routines could be run offline in order to provide reasonable guesses of applied irrigation for a given irrigation season. This may be beneficial in representing processes not explicitly considered in LSMs (Kumar et al. 2015), or making future assessments and recommendations about water availability for managers. Finally, the four routines provide reasonable irrigation bounds and more importantly predictions about decreases in irrigation as technology is introduced and adopted in novel areas.

5. Conclusions

In this work we describe four plausible and relatively simple irrigation routines that could be coupled to the next generation of hyper-resolution LSMs operating at scales of 1 km or less. The crop model irrigation outputs reproduce the year-to-year variability of the observed irrigation amounts with a low bias of 80 mm yr^{-1}. Predictions from the vadose zone model indicate potential irrigation savings of up to 120 mm yr^{-1} for maize. In addition, daily precipitation variability across the study area was found to introduce significant variability in

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daily irrigation decision making depending on which value was considered. Future work could focus on providing accurate realtime 1 km daily precipitation products through a combination of in-situ low cost gages, radar, and satellite remote sensing. Accurate and realtime precipitation remains a critical weakness in these rural and vast landscapes. Given the clustering of irrigation fields in Western Nebraska, the number of in-situ gages needed could be significantly reduced to provide high density networks in key areas. Findings from the work may be useful to local water managers and stakeholders in evaluating potential water saving technologies. In addition, the simple routines could be coupled to future hyper-resolution land surface models that seek to understand the degree of land surface atmospheric coupling and consequences to operational forecasts. This understanding is essential as society continually recognizes the importance of human activities on the global water cycle and invests more resources to understand the water-food-energy nexus.

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6. Data Availability

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Meteorological data used in this paper was provided by HPRCC (2016, http://www.hprcc.unl.edu/). Irrigation flow meter data was obtained from the SPRND and is not widely available for public use. Yearly summary reports are available from SPNRD (http://www.spnrd.org/). Soil data was obtained from SSURGO (Soil survey staff, 2016, http://websoilsurvey.sc.egov.usda.gov/App/HomePage.htm). Data and model subroutines can also be requested from the corresponding author.

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Acknowledgments

This research is supported financially by the Daugherty Water for Food Global Institute at the University of Nebraska. Access to field sites and datasets is provided by The Nature Conservancy, Western Nebraska Irrigation Project, and South Platte Natural Resources District. A special thanks to Jacob Fritton for critical insights into producer practices in the study area. TEF would like to thank Eric Wood for his inspiring research and teaching career. No doubt the skills TEF learned while at Princeton in formal course work, seminars, and discussions with Eric will serve him well in his own career.

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Figures and Table

Fig. 1: Study area located in western Nebraska with each field in the data set outlined.

Fig. 2: Area-weighted soil texture of all fields plotted on the USDA soil texture triangle, falling primarily in the sandy loam and loam textures. Data downloaded from NRCS Web Soil Survey.

Fig. 3: Cumulative in-season precipitation depths measured at 7 rain gauges and crop referenced evapotranspiration (ET_c) calculated from a weatherstation <10km away. Precipitation variability tends to increase with incresing seasonal totals.

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Fig. 4: Box and whisker plots of historical irrigation depths for all sites. Upper and lower boundaries of boxes indicated 75th and 25th percentile, respectively. Horizontal line within boxes is the median value. Whiskers are maximum and minimum values. Asterisks indicate that irrigation distribution deviates from a normal distribution (D'Agostino-Pearson test, p<0.01).

Fig. 5: Historical irrigation vs. the four simulated irrigation routines, for sandy loam (left) and loam (right). Verticle error bars are standard error of the mean from the precipitation sensitivity ananlysis and horizontal error bars are standard error of the mean from observed irrigation.

Fig. 6: Observed growing season totals for precipiptation (P), irrigation (I), and P+I. The dashed line represents the historical average for P+I.

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Fig. 7: Potenital yield simulated by Hybrid-Maize using the 4 irrigation routines: crop model (CM), precipitation delayed (PD), evapotranspiration replacement (ET), and Hydrus-1D (H).

Fig. 8: Example of simulated growing season cumulative P and P+I with daily P values plotted on secondary y-axis for the 4 irrigation routines in a wet (2010) and dry year (2012). Irrigation starts later for routines that track soil moisture thus leading to reduced pumping.

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Table 1: Summary of needed inputs and tunable parameters for each irrigation routine.

Table 2: Van Genuchten parameters used in Hydrus-1D simulations.

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Fig. 1: Study area located in western Nebraska with a 1km grid overlain on the study site.

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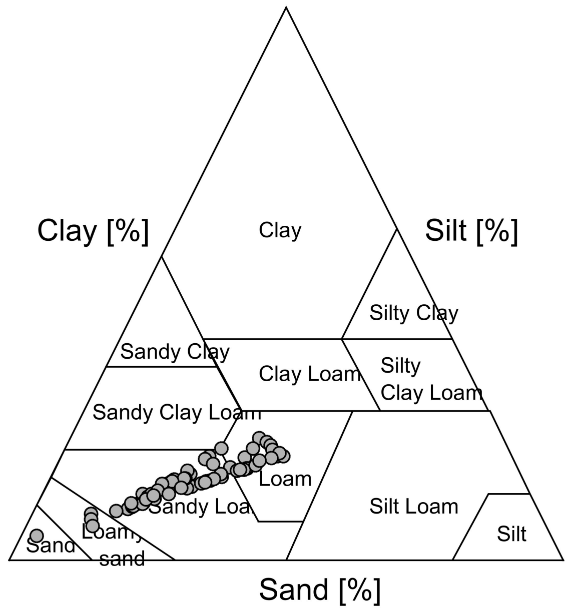

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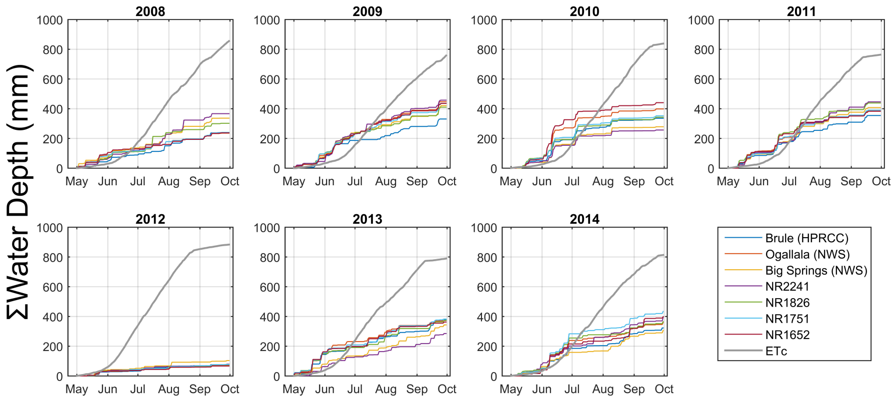

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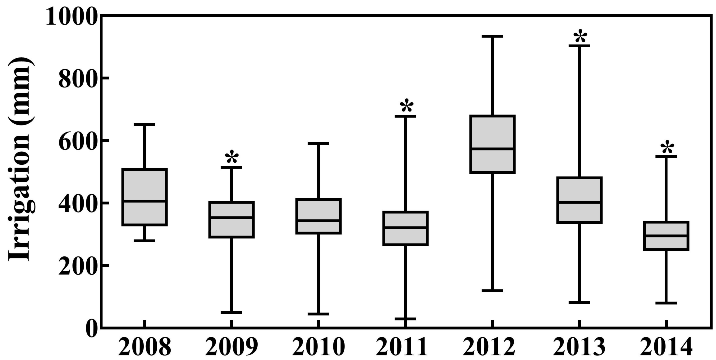

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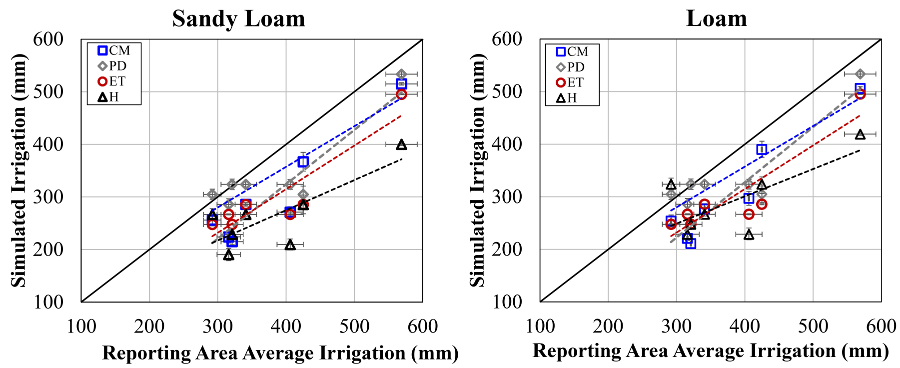

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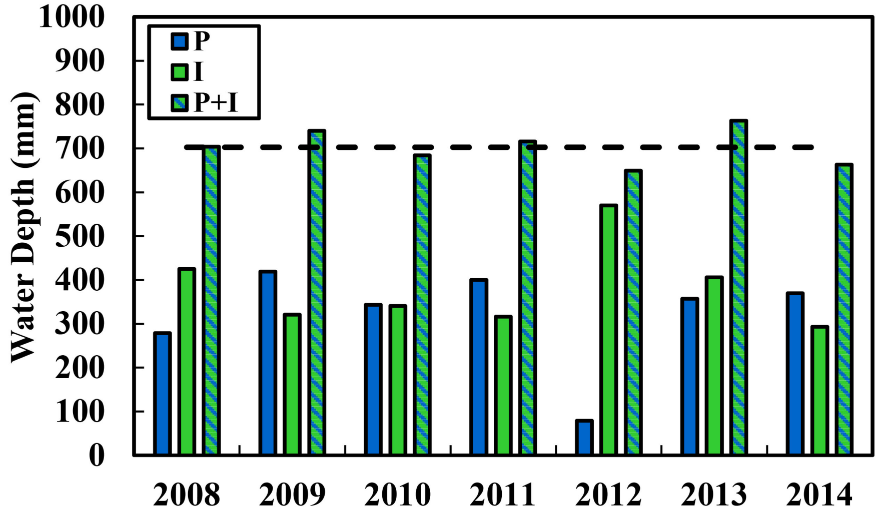

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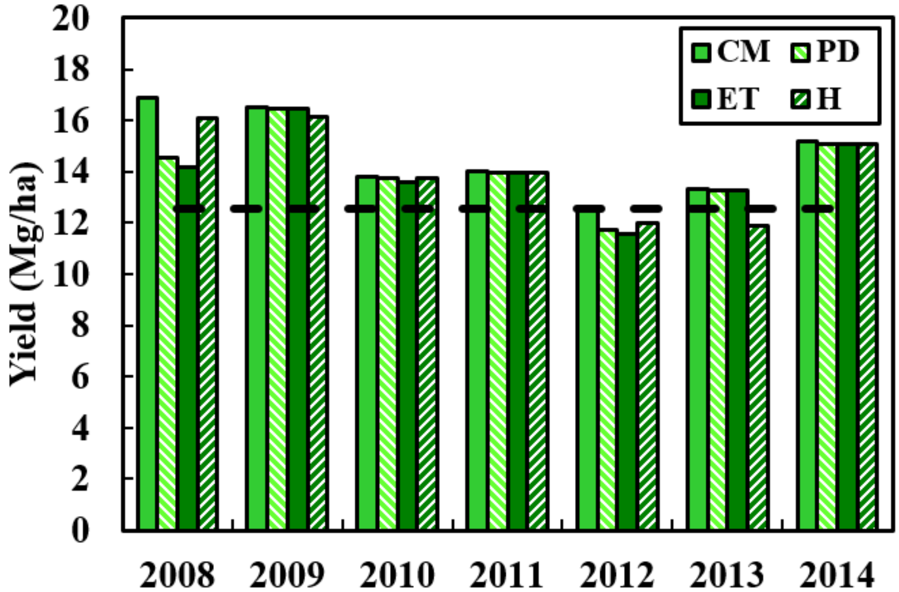

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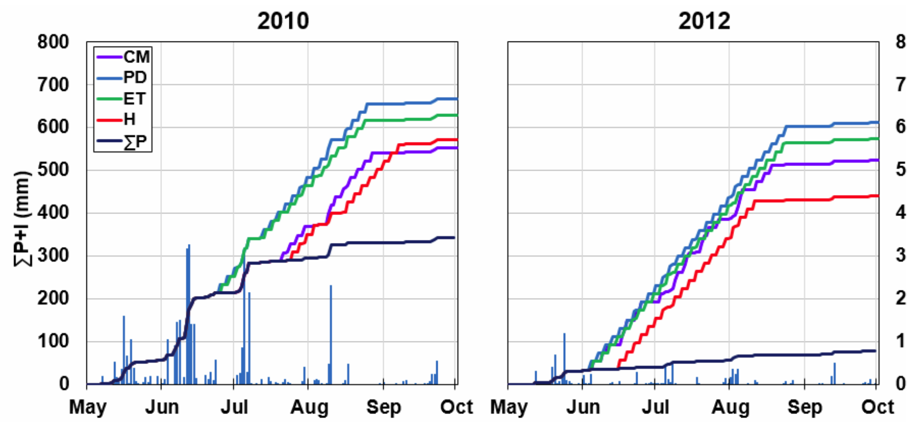

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Table 1: Summary of needed inputs and tunable parameters for each irrigation routine.

Routine	**Needed Inputs**	**Tunable Parameters**
CM	P, ETr, soils	I intensity (mm/day, growing season ETa/growing season length)
PD	P	I intensity
ET	P, ETr, kc	I intensity
H	P, ETr, kc, soils, zr	I intensity, pressure-irrigation trigger point, root depth irrigation-trigger point(s)

Table 2: Van Genuchten parameters used in Hydrus-1D simulations.

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Texture	θ_r (-)	θ_s (-)	α (1/cm)	n (-)	K_s (cm/day)
Sandy Loam	0.048	0.385	0.0289	1.389	31.91
Loam	0.060	0.400	0.0127	1.458	10.85

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