Reviewing the Impacts of Extreme and Excessive Precipitation on U.S. Corn Belt Crops

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Abstract

The U.S. Corn Belt is an invaluable agricultural region of the world. Each year, the Corn Belt loses hundreds of millions of dollars' worth of corn and soybean due to drought and excessive moisture. Most research on climate extreme impacts on crops has focused on extreme heat and drought over heavy precipitation, storms and flooding. However, the IPCC AR6 report has attributed anthropogenic climate change to increased heavy precipitation trends in the Corn Belt. This paper serves to facilitate discussion of extreme and excessive precipitation's impact on corn and soybean in the U.S. Corn Belt by reviewing recently published articles. Section 2 discusses the scientific processes affecting the impact, including regional precipitation climatology, soil drainage properties, and corn and soybean physiological responses to waterlogging. Section 3 connects model studies correlating excessive precipitation with corn and soybean production using Section 2's discussed processes. Extreme precipitation trends and impacts are subregional, at times localized down to a couple of isolated counties. Historical analyses show extreme precipitation does not significantly affect corn or soybean until seasonal, daily, or hourly anomalies went above the ~99th percentile; beyond this, studies reported moderate to severe yield reductions. The average return period for adverse impacts by extreme precipitation is around 10 years under the current climate. Corn in the vegetation phase and soybean in the reproductive phase are most sensitive to waterlogging. Section 4 encourages further research on this topic by integrating more climate, crop, and agricultural management knowledge to better explain observations presented in this paper.

Acknowledgements

I would like to thank Prof. Xin-Zhong Liang for advising me throughout my master's program. He contributed to this paper's development by helping me refine the topic, strengthen this paper's structure, and add to my references using his suggested articles. My thanks also go out to Chuck Baker for serving as my de facto mentor during my time here. Our 1-on-1 discussions we would schedule when I got stuck provided me with additional excellent and timely advice, and he also helped review this paper to ensure its quality. I also thank the University of Maryland and its department of Atmospheric and Oceanic Science for accepting me into their program and supplying me with the knowledge and skills necessary to become a professional scientist. This work was primarily supported by the United States Department of Agriculture-National Institute of Food and Agriculture grant number 20206801231674, awarded to the University of Maryland for the creation of a predictive decision support Dashboard for Agricultural Water use and Nutrient management (DAWN). Partial support was also provided by the National Science Foundation under Award Number #1903249. This paper would not be possible without the people, funding, and organizations listed above.

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List of Symbols & Abbreviations

- Symbols
    - σ: Standard deviation
- Abbreviations
    - Databases
        - STATSGO: State Soil Geographic
    - Organizations and Institutions
        - IPCC: Intergovernmental Panel on Climate Change
            - AR6: Sixth Assessment Report
        - NOAA: National Oceanic and Atmospheric Administration
        - USDA: United States Department of Agriculture
            - NASS: National Agricultural Statistics Service
            - NRCS: National Resources Conservation Service
                - LRR: Land Resource Region
        - USGS: United States Geological Survey
    - U.S. States
        - IA = Iowa
        - IL = Illinois
        - IN = Indiana
        - KS = Kansas
        - MN = Minnesota
        - MO = Missouri
        - ND = North Dakota

- NE = Nebraska
- OH = Ohio
- SD = South Dakota
- WI = Wisconsin

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Section 1. Introduction/Background

The United States is one of the most important global producers of corn and soybean. Between 2019—2023, the U.S. annually produced, on average, ~364 megatons of corn and ~112 megatons of soybean (USDA, 10 Apr. 2025). In return, corn and soybean are the lynchpins to the U.S. agricultural economy. In 2023, corn and soybean cash receipts added up to $132 million, accounting for 49.4% of the U.S.'s total crop cash receipts (USDA, 12 Mar. 2025). Much of this production comes from a region commonly known as the *Corn Belt*, which is illustrated in Fig. 1. The U.S. counties with the largest corn and soybean production are found in the eastern parts of KS, NE, SD and ND, the southern parts of MN and WI, northern MO, most of IA, IL and IN, and western OH. Altogether, the Corn Belt produces around 80% of U.S. corn and around 70% of U.S. soybean (USDA NASS, 2024). Thus, this region is vital in ensuring global food security and U.S. agricultural economic strength. Preserving the Corn Belt's current production, and improving its future production, can be accomplished through technological innovation, improved management practices, or through risk mitigation and adaptation (Kaur et al., 2020; Liu & Basso, 2020; Troy et al., 2015). One such risk lies in extreme weather and climate.

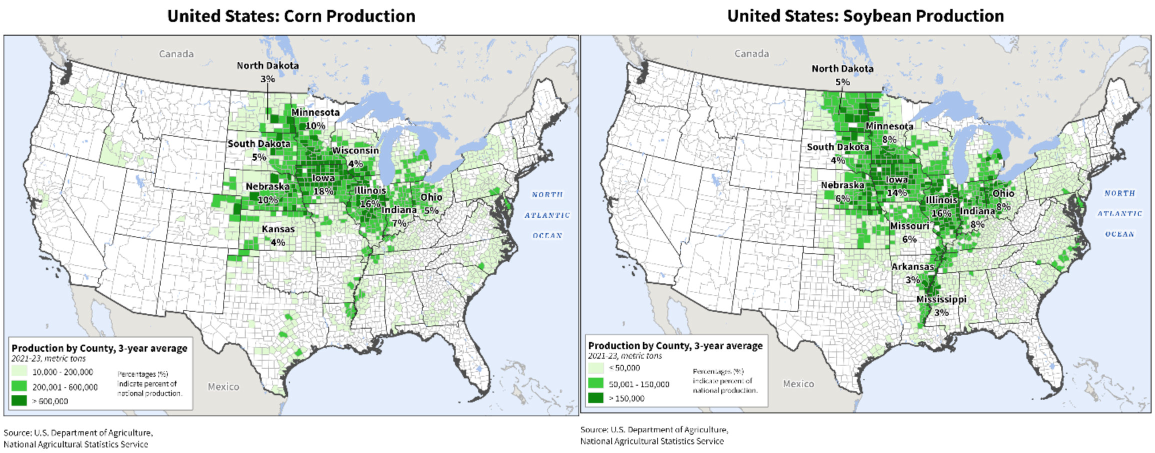

Figure 1. 3-year average of U.S. corn (left) (USDA NASS, 2024a) and soybean (right) (USDA NASS, 2024b) production (2021—2023). County averages are displayed through green shading, highlighting production ranges in metric tons. State averages relative to the national production are displayed as percentages next to the state's name.

Extreme weather & climate have been, and will continue to be, a source of risk for the U.S. Corn Belt. The USDA Risk Management Agency identified drought and excessive moisture as the top two causes of corn and soybean loss over the past three decades (Li et al., 2019). Between 1989—2016, drought led to national losses of ~$17.5 billion for corn and ~$6.2 billion for soybean; in the same period, excessive moisture led to losses of ~$9.5 billion for corn and $5.0 billion for soybean (Fig. 2) (Li et al., 2019). Climate change has led to observed increasing trends in extreme heat, precipitation, and drought across the globe, as displayed in Fig. 3 through the IPCC AR6 report (IPCC, 2023). Their analysis of one-day and five-day precipitation amounts presents at least a medium confidence that heavy precipitation has increased in central and eastern North America since the 1950s (IPCC, 2023). Additionally, there is medium confidence that humans contributed to these trends in central North America, where the Corn Belt region resides. In contrast, there is low agreement that there have been significant changes in extreme heat and drought in central and eastern North America since the 1950s (IPCC, 2023). These assessments suggest that heavy precipitation's contribution to crop loss in the Corn Belt has and will continue to increase in the future relative to drought and extreme heat.

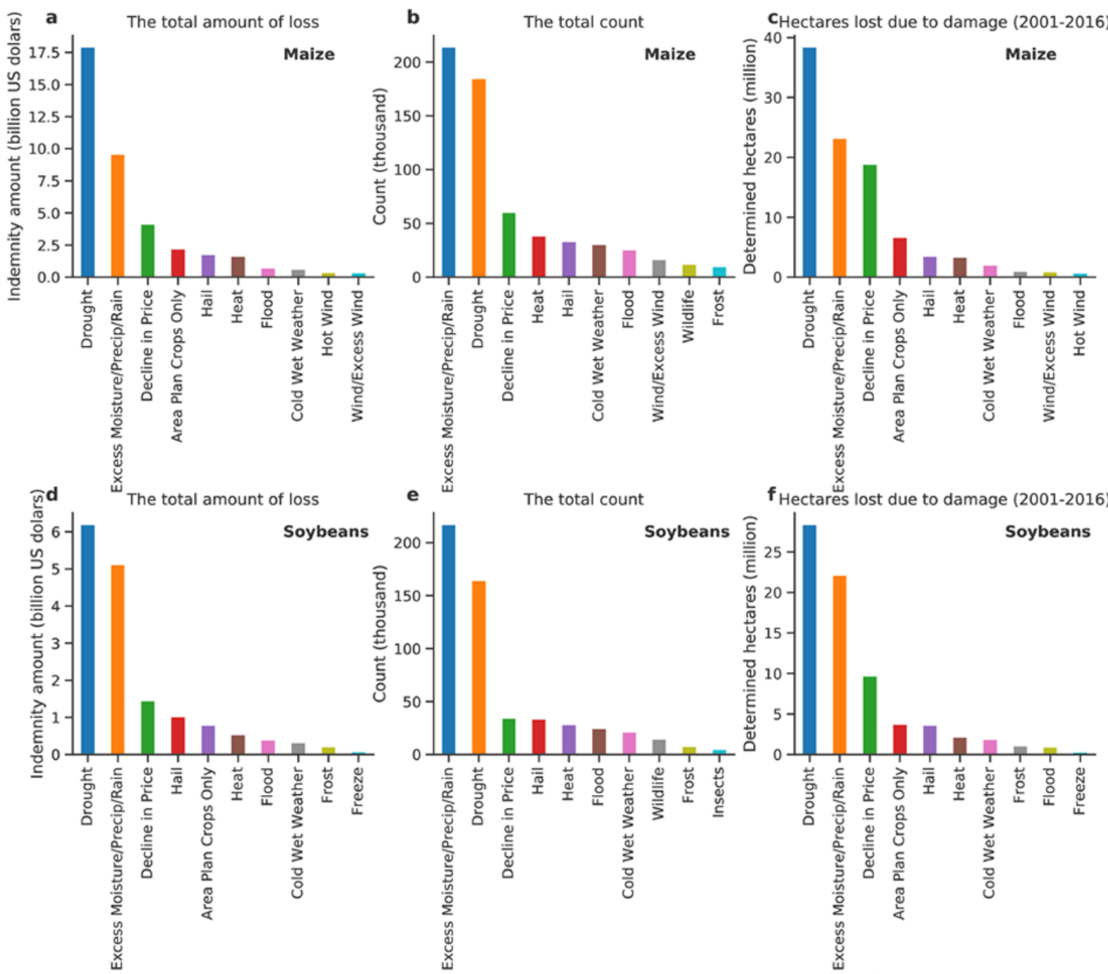

Figure 2. Excerpt from Fig. S1 of (Li et al., 2019): "The top ten causes of crop loss for maize [and] soybeans in the US from the [USDA Risk Management Agency] insurance data. (**a**,**d**) The total amount of loss (sum of indemnity amount) from 1989 to 2016. (**b**,**e**) The total count of loss causes from 1989 to 2016. (**c**,**f**) The total hectares (sum) lost due to damage from 2001 to 2016."

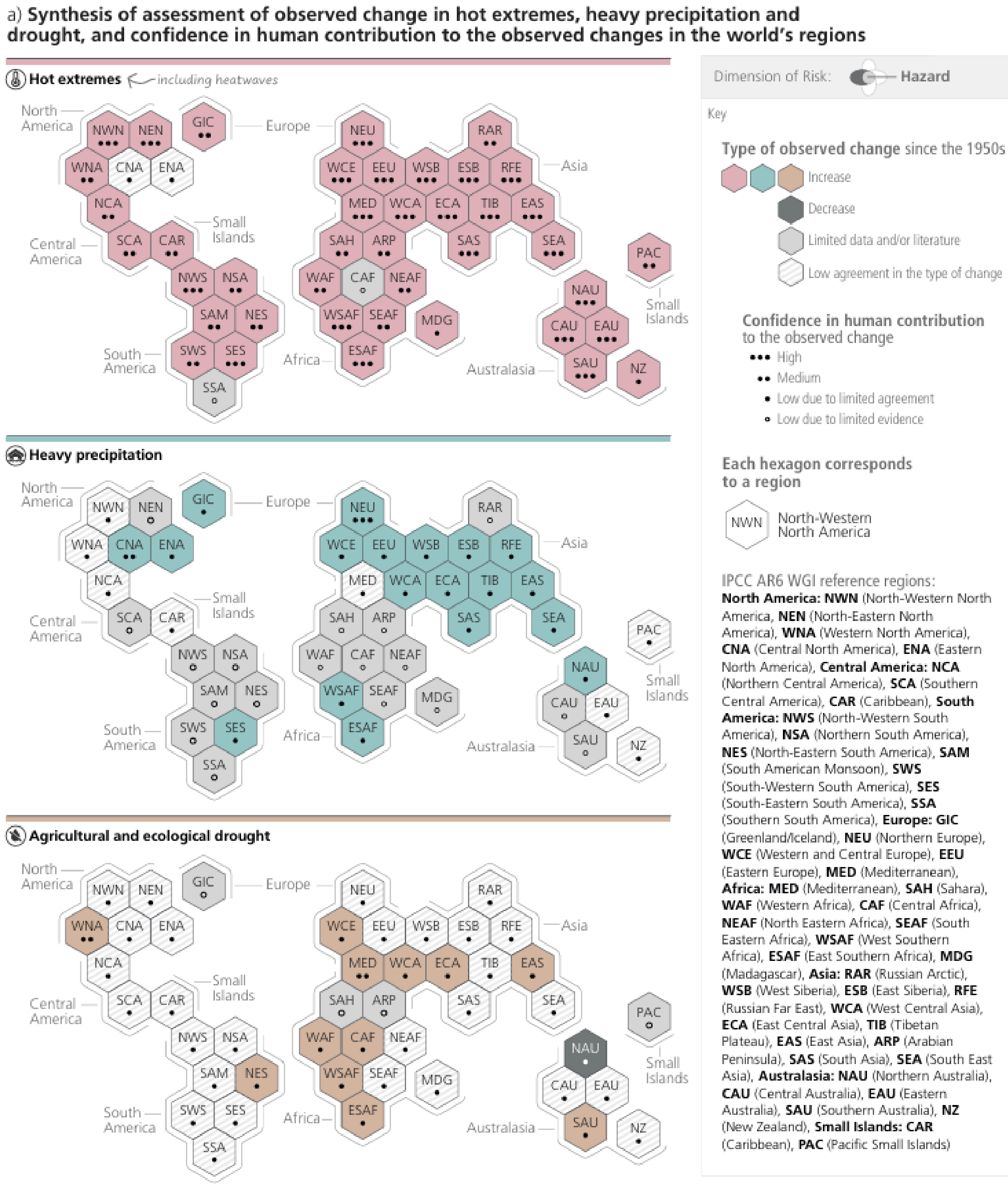

Figure 3. Taken from Fig. 2.3a of (IPCC 2023):

> Synthesis of assessment of observed change in hot extremes, heavy precipitation and drought, and confidence in human contribution to the observed changes in the world's regions…The IPCC AR6 WGI inhabited regions are displayed as hexagons with identical size in their approximate geographical location (see legend for regional acronyms). All assessments are made for each

> region as a whole and for the 1950s to the present. Assessments made on different time scales or more local spatial scales might differ from what is shown in the figure. The colours in each panel represent the four outcomes of the assessment on observed changes. Striped hexagons (white and light-grey) are used where there is low agreement in the type of change for the region as a whole, and grey hexagons are used when there is limited data and/or literature that prevents an assessment of the region as a whole. Other colours indicate at least medium confidence in the observed change. The confidence level for the human influence on these observed changes is based on assessing trend detection and attribution and event attribution literature, and it is indicated by the number of dots: three dots for high confidence, two dots for medium confidence and one dot for low confidence (single, filled dot: limited agreement; single, empty dot: limited evidence). For hot extremes, the evidence is mostly drawn from changes in metrics based on daily maximum temperatures; regional studies using other indices (heatwave duration, frequency and intensity) are used in addition. For heavy precipitation, the evidence is mostly drawn from changes in indices based on one-day or five-day precipitation amounts using global and regional studies. Agricultural and ecological droughts are assessed based on observed and simulated changes in total column soil moisture, complemented by evidence on changes in surface soil moisture, water balance (precipitation minus evapotranspiration) and indices driven by precipitation and atmospheric evaporative demand (IPCC, 2023, pp. 48, 50)

Despite these regional concerns in the heavy precipitation trends, most research covering extreme weather impacts on crops has been focused on extreme heat and drought (Rötter et al., 2018). In (Rötter et al., 2018)'s systematic literature review of research papers covering "weather extremes" impacts on "crop production" between 1995—2016, they found that 90% of 3,641 empirical studies and 86% of 266 modeling studies focused on drought, heat, or the compound of the two (Fig. 4). Only 8% of empirical studies they reviewed concentrated on heavy rain or flooding impacts, and only 12% of modeling studies did the same (Rötter et al., 2018). Greater discussion and research on the impacts of extreme and/or excessive precipitation on crops may be warranted to serve regions that expect to see more of these events in the future, such as the Corn Belt (IPCC, 2023).

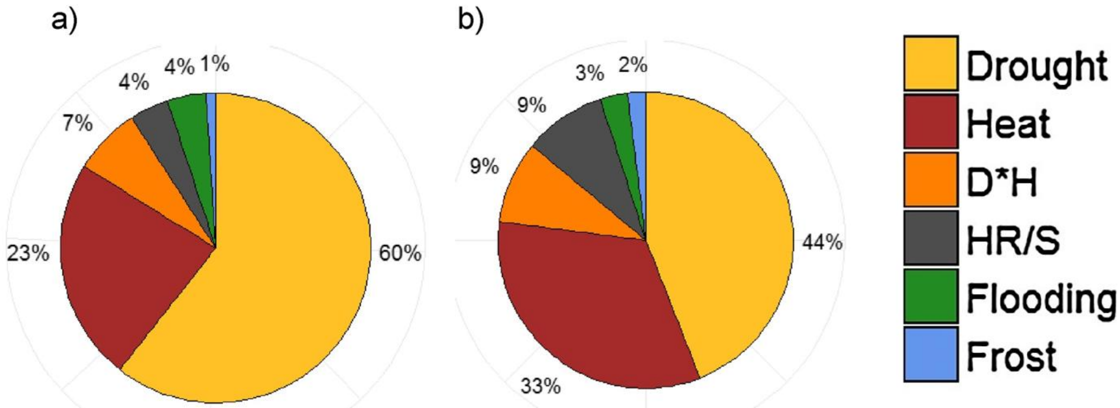

Figure 4. Modification of Figure 3 from (Rötter et al., 2018): "Share of papers per extreme as a) observed (n = 3641) and b) simulated (n = 266)." Pie charts are based off (Rötter et al., 2018)'s systematic literature review where they collect data on the number of papers between 1995—2016 that cover "weather extremes" impacts on "crop production" of the following eight grain crops: corn, rice, wheat, barley, sorghum, pearl millet, soybean, and groundnut. Pie chart (**a**) refers to all papers that conducted empirical observation experiments. Pie chart (**b**) refers to all papers that conducted process-based crop modelling experiments. D*H stands for compounding drought and heat stress, while HR/S stands for compounding heavy rain and storm impacts.

With these motivations in mind, this paper assesses the impact of extreme and excessive precipitation on corn and soybean in the U.S. Corn Belt by reviewing recently published studies. Section 2 discusses the scientific community's ability to fundamentally and theoretically explain the regional influence of extreme and/or excessive precipitation on corn and soybean, more specifically through waterlogging/flooding processes. To facilitate this discussion, subsections on regional precipitation climatology, land—soil properties of the Corn Belt, and corn/soybean physiological responses to waterlogging are present. Section 3 inspects national and regional modeling studies which evaluated the relationship between extreme/excessive precipitation and corn and/or soybean crop production. Section 4 addresses challenges encountered among the reviewed sources, relevant factors to the extreme precipitation—crop production relationship that this paper does not cover in depth, and recommendations for future research on this topic. Finally, Section 5 summarizes the findings of this paper and provides general concluding remarks.

Section 2. Fundamental and Theoretical Explanations of Extreme/Excessive Precipitation Impacts on Corn Belt Crops

This section discusses the current understanding of the scientific processes behind extreme and/or excessive precipitation impacts on corn and soybean in the U.S. Corn Belt. (Li et al., 2019)'s schematic (Fig. 5) provides an efficient synopsis that this paper aims to build off. Their flowchart shows that extreme/excessive precipitation impacts crops through two main mechanisms: physical damage and waterlogging (Li et al., 2019). The heaviest precipitation, in combination with severe weather (i.e., damaging winds, hail and tornadoes), can physically damage crops to the point of lodging, where crops can no longer stand upright (Kaur et al., 2020; Lesk et al., 2020; Li et al., 2019). Lodging results in crop yield reductions by up to 80%, and it adversely impacts grain quality (Berry et al., 2004). Extreme/excessive precipitation may also overwhelm soils beyond their saturation levels, leading to excessive soil moisture, where waterlogging or flooding may result (Li et al., 2019). Waterlogged/flooded soils directly induce crop stress by interrupting essential chemical and biological processes in the root zone, yet they also impact crops indirectly (Kaur et al., 2020; Li et al., 2019; Manghwar et al., 2024). Poor trafficability of waterlogged soils (i.e., vehicles & large entities cannot pass over the soil without damaging it through compaction) can delay planting or harvesting, and certain pests, pathogens, and diseases can exploit excessive soil moisture conditions (Kaur et al., 2020; Li et al., 2019; Shirzaei et al., 2021). All these effects by waterlogging/flooding can lead to reduced crop production and quality, the magnitude of which varies depending on the duration of the event, the crop species, and the crop growth stage (Kaur et al., 2020; Li et al., 2019). The following subsections focus on how extreme/excessive precipitation's role in waterlogging may spatiotemporally vary within the Corn Belt, and how corn and soybean response to waterlogging may itself vary.

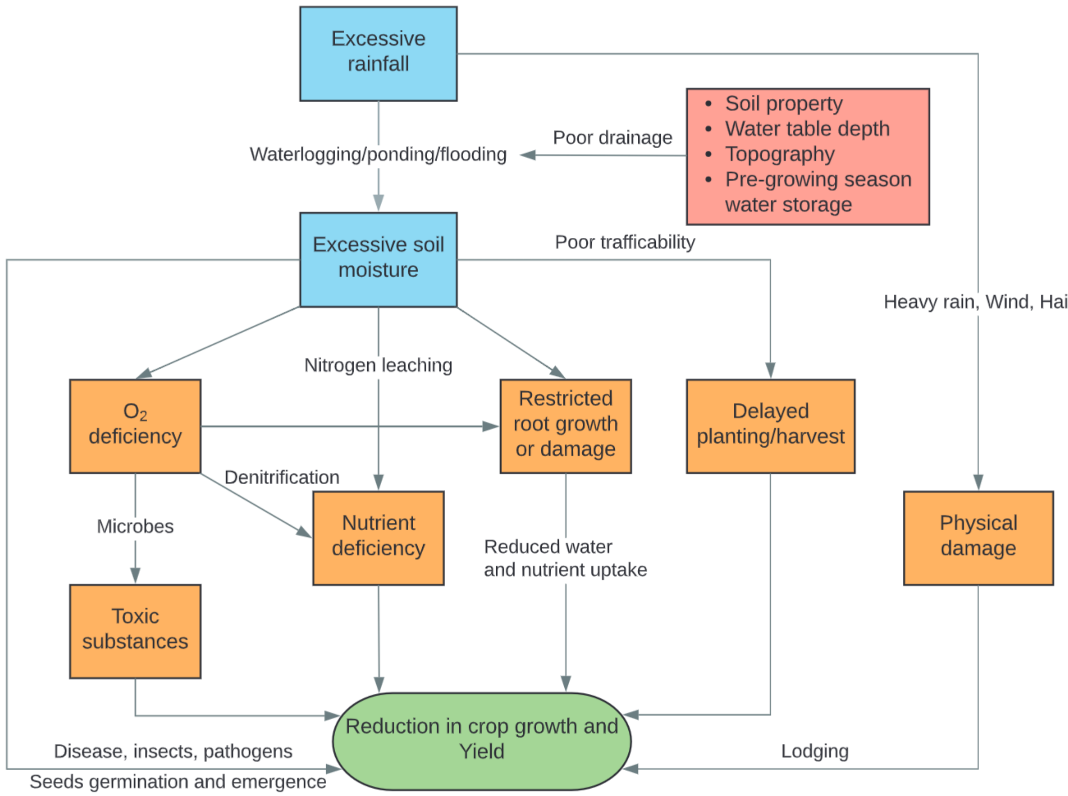

Figure 5. Taken from Fig. 5 of (Li et al., 2019): "Schematic diagram of the main processes by which excessive rainfall affects crop growth and yield."

2.1. Drivers of Waterlogging in the Corn Belt

The physical drivers behind waterlogging are those which lead to an imbalance in the soil moisture budget in the root zone (Datta et al., 2017; Kaur et al., 2020; Ritter, 2024). As seen in Fig. 6, if moisture influx into the root zone overpowers all the moisture fluxes out of the root zone (i.e., evapotranspiration, groundwater infiltration, and net surface runoff) for long enough such that soil water storage becomes supersaturated, then waterlogging/flooding occurs (Ritter, 2024). The upper left portion of Fig. 7 (taken from

(Kaur et al., 2020), in tandem with the top of Fig. 5 (taken from (Li et al., 2019)) list out the primary drivers leading to excessive soil moisture. Excessive precipitation is the most straightforward driver, as moisture influxes overpower the out-fluxes through very heavy showers/storms or prolonged steady accumulation. Evapotranspiration is the predominant counter, especially during the summer months when high temperatures and high water-intake by mature crops enhance its potential. However, outside of the growing season (i.e., October—April), colder temperatures and the absence of field crops lowers evapotranspiration rates below precipitation rates, allowing soils to accumulate surplus moisture (Ritter, 2024; Soil Survey Staff, 2015). It is not until May—June, on average, when evapotranspiration rates rise above precipitation rates in the Corn Belt, which typically makes the first month or two of the growing season the most vulnerable to excessive soil moisture (Lazin et al., 2021; Ritter, 2024; Soil Survey Staff, 2015). Soil properties, such as soil texture, bulk density, and the presence of restrictive layers, affect its drainage capabilities which in turn determine groundwater infiltration rates (Hollinger, 1995; Kaur et al., 2020; Li et al., 2019; Ritter, 2024; Soil Survey Staff, 2015). Suboptimal agricultural management may also lead to excessive soil moisture. Overirrigation would provide unnecessary moisture influx, and placing heavy traffic (i.e., machinery, livestock) on moist soils could lead to compaction, lowering infiltration rates. (Kaur et al., 2020; Li et al., 2019; Manghwar et al., 2024; Ritter, 2024). All these factors contributing to excessive soil moisture suggest that there is considerable spatial and temporal variability in the amount, duration, and frequency of extreme/excessive precipitation required for waterlogging across the Corn Belt.

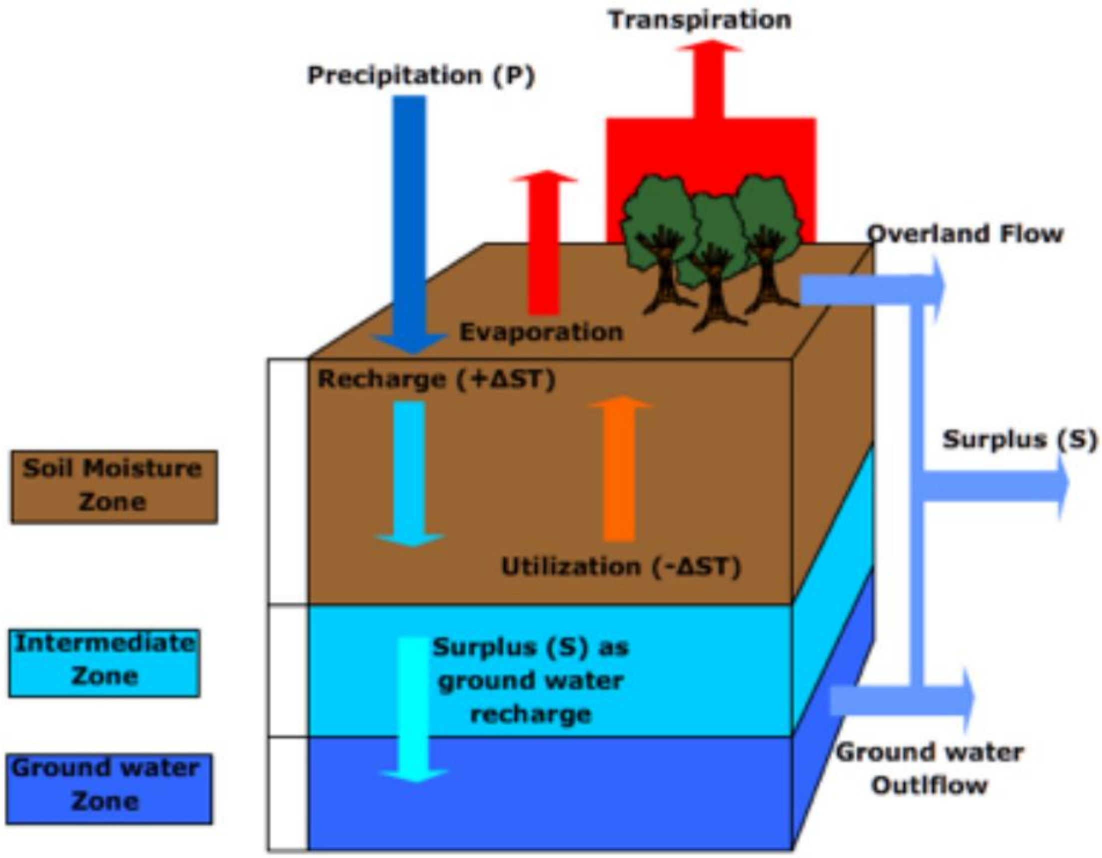

Figure 6. Taken from Fig. 10.3.1 in (Ritter, 2024): “The soil water balance”.

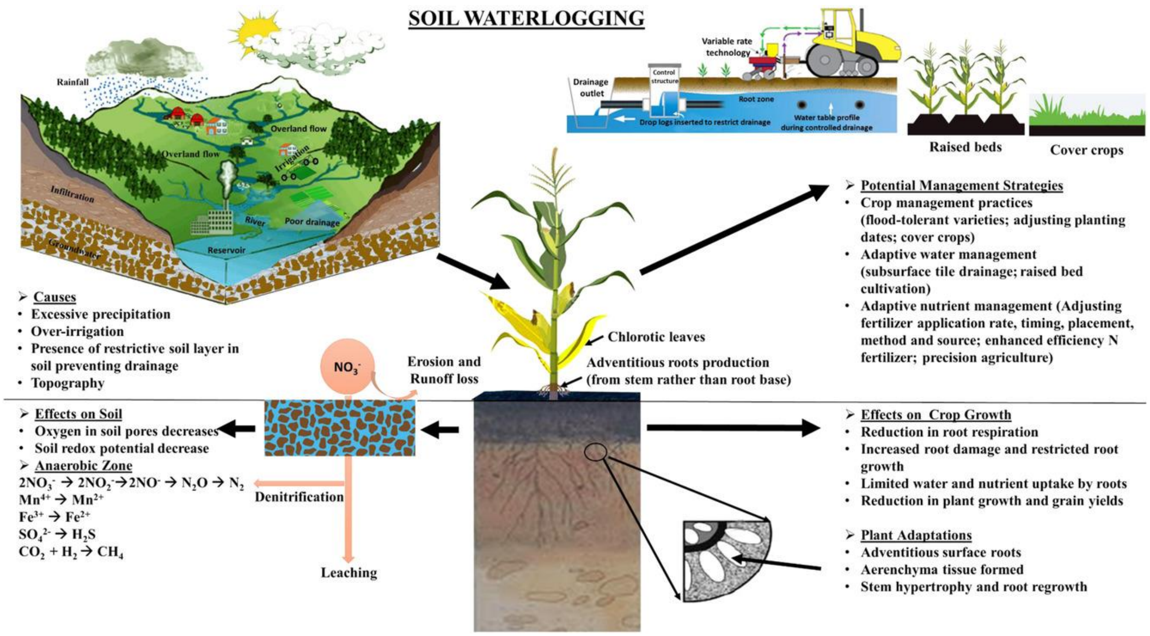

Figure 7. Taken from Fig. 2 of (Kaur et al., 2020): "Overview of soil waterlogging causes, crop production and nitrogen losses, and potential management strategies."

The following subsections explore the spatiotemporal variability of some waterlogging drivers to try to gauge when and where extreme/excessive precipitation would leave the most significant impacts in the Corn Belt. The analysis attempts to stay within the bounds of the USDA NRCS's Land Resource Region 'M,' as displayed in Fig. 8. This LRR represents a region with similar land use, topography, climate, water resources, soil properties, natural vegetation, and geology, on top of having the majority of U.S. corn and soybean production (USDA-NRCS, 2022). While neighboring LRRs, such as 'F,' 'H,' and 'L' have substantial corn and soybean growing areas, the seven properties listed above are significantly different from LRR 'M' (USDA-NRCS, 2022).

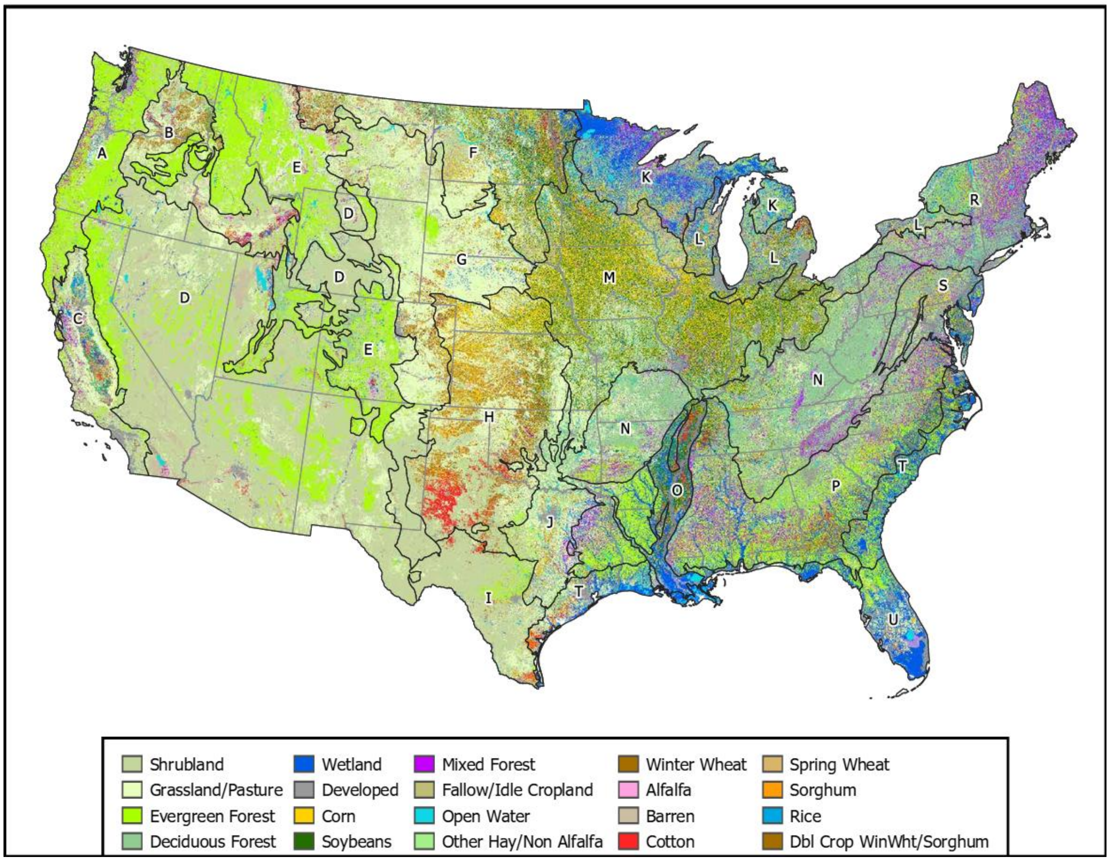

Figure 8. Taken from Fig. 8 of (USDA-NRCS, 2022): “Land use categories and LRR [Land Resource Region] boundaries of the conterminous United States based on 2018 data from the USDA National Agricultural Statistics Service.” LRR **M**, the “Central Feed Grains and Livestock Region”, contains most of the corn and soybean growing areas in the United States.

2.1.1. Extreme/Excessive Precipitation Climatology

All other factors equal, areas that receive more excessive and/or extreme precipitation will be more prone to excessive soil moisture. As seen in Figs. 9 & 10, (Wilson et al., 2022) used the DAYMET data product to examine precipitation climatology and trends in the eastern Corn Belt from 1980—2018, focusing on heavy precipitation. A clear north-to-south gradient exists in both total annual precipitation (PRCPTOT) and most of the heavy precipitation metrics (e.g., R95p, R99p, R20mm)

(Wilson et al., 2022). Total annual precipitation varied from 900—1000 mm (35—39 in) in the northern Corn Belt to 1200—1300 mm (47—51 in) in southern MO, IL, IN, and OH (Wilson et al., 2022). R95p, which represents the annual amount of precipitation that fell on the 95th percentile of wet days, ranged from 180—200 mm (7—8 in) in central IA & IL to 260—280 mm (10—11 in) in the southern-most portions of IL and IN (Wilson et al., 2022). R20mm, the annual number of days with precipitation ≥ 20 mm (~0.78 in), ranged from 10—12 days in the northern Corn Belt to 18—20 days in the southern-most portions of IL and IN (Wilson et al., 2022). Annual maximum 1-day precipitation (RX1day) generally appears to have a northeast-to-southwest gradient, with the smallest values (40—50 mm [1.57—1.97 in]) being found in central OH and the largest values (70—80 mm [2.76—3.15 in]) being found in southern MO, IL, & IN (Wilson et al., 2022). In contrast, the number of wet days (R1mm) has a stark west-to-east gradient, with central IA & MO having 80—90 wet days while central OH has 110—120 wet days (Wilson et al., 2022). These patterns suggest that heavy precipitation days (i.e., at or above the 95th percentile) notably contribute to the total accumulated precipitation in the eastern Corn Belt, regardless of the total number of wet days.

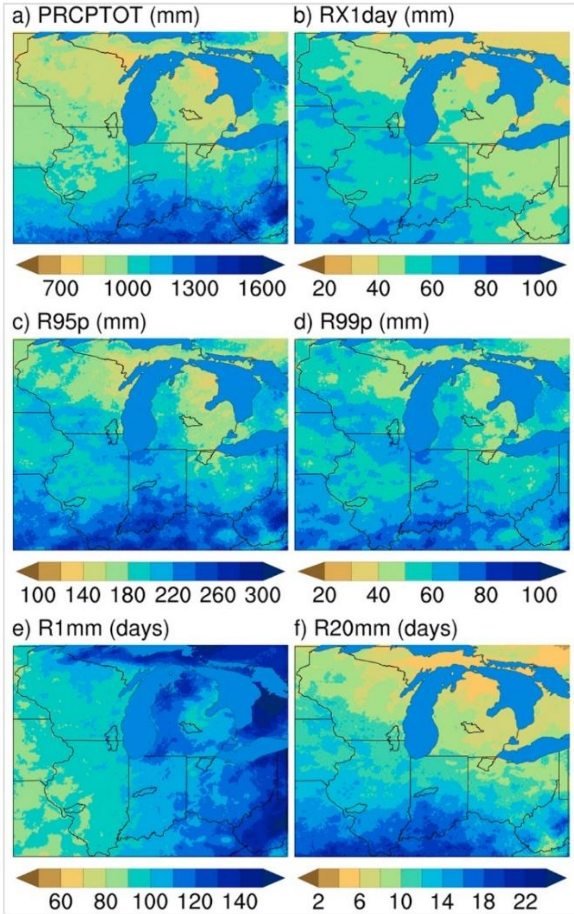

Figure 9. Taken from Fig. 3 of (Wilson et al., 2022): "**DAYMET Precipitation Climatology (1980–2018)** for selected extreme precipitation indices including a) annual total wet-day precipitation [PRCPTOT], b) [annual] maximum 1-day precipitation [RX1day], c) [annual total precipitation on] very wet days [R95p], d) [annual total precipitation on] extremely wet days [R99p], e) number of wet days [R1mm], and f) number of very heavy precipitation days [R20mm]. Units are indicated for each variable."

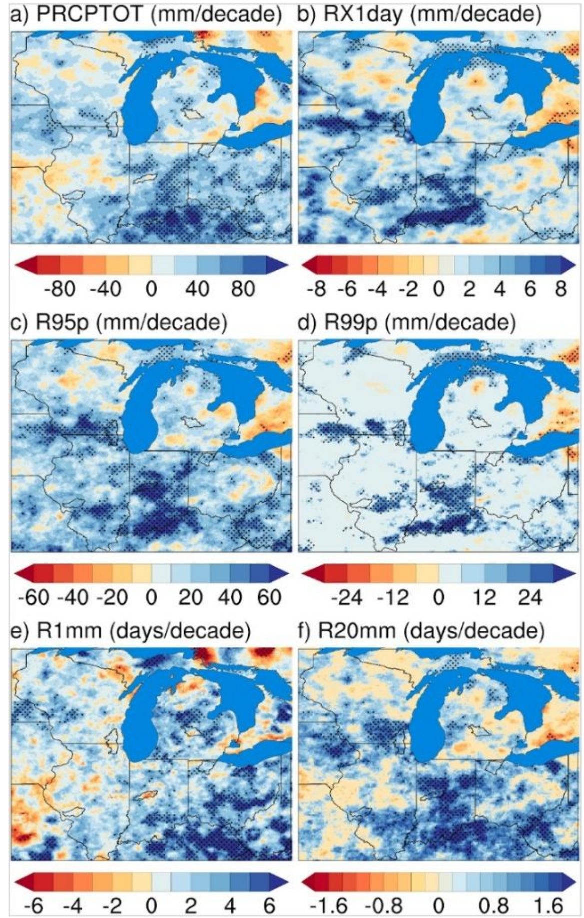

Figure 10. Taken from Fig. 6 of (Wilson et al., 2022): "**Decadal Precipitation Extreme Trends (1980–2018)** including a) annual total wet-day precipitation [PRCPTOT], b) [annual] maximum 1-day precipitation [RX1day], c) [annual total precipitation on] very wet days [R95p], d) [annual total precipitation on] extremely wet days [R99p], e) number of wet days [R1mm], and f) number of very heavy precipitation days [R20mm]. Units are indicated for each variable. Stippled areas indicate where trends are significant at the 95% confidence level using a Mann-Kendall test."

The evident relationship between total and heavy precipitation should apply to the central and western Corn Belt as well, given that the climate gets drier the further west one progresses towards the Rockies (Lesk et al., 2020; Wilson et al., 2022). (Li et al., 2019) explore this idea by analyzing the contribution of different daily precipitation intensities to the total growing season precipitation over the contiguous U.S. for a similar period (1981—2016) (Fig. 11). (Wilson et al., 2022)'s DAYMET results in Fig. 9 represent a climatological average, so (Li et al., 2019)'s daily precipitation contributions for the 0.0σ growing season precipitation anomaly should coincide with the DAYMET output. For example, the ratio between R95p and PRCPTOT in Iowa in Fig. 9 is ~0.2, and the contribution of ≥2σ daily precipitation to the mean growing season total rainfall in Fig. 11 is ~23% (Li et al., 2019; Wilson et al., 2022). This suggests reasonable agreement between the two sources when it comes to the average contribution of heavy precipitation to the total in the Corn Belt. Nevertheless, a more rigorous comparison could be made to verify their agreement. (Li et al., 2019) additionally consider how heavy precipitation's contribution to the total changes during anomalously wet years. As shown in Fig. 11, as the national growing season total precipitation anomaly increases, the contribution to this total by very heavy daily precipitation (i.e., >3.5σ) increases at a much greater rate than any other daily precipitation intensity (Li et al., 2019). For example, >3.5σ daily precipitation contributed ~20% of the total in county-years with +1.5σ total precipitation, and it contributed ~29% of the total in county-years with +3.5σ total precipitation (Li et al., 2019). However, assuming a normal distribution of daily precipitation intensities, the above relationship only represents data above the 99.9th percentile. While the correlation between 2σ (~95th percentile) to 3.5σ daily precipitation intensity and total growing season precipitation is positive, it is nowhere near as strong, percentagewise, as for the heaviest daily precipitation (Li et al., 2019). Fig. 11 appears to imply that anomalously wet years replace dry-to-light precipitation events with very heavy precipitation events, while the contribution of moderately heavy precipitation events remains about the same (Li et al., 2019).

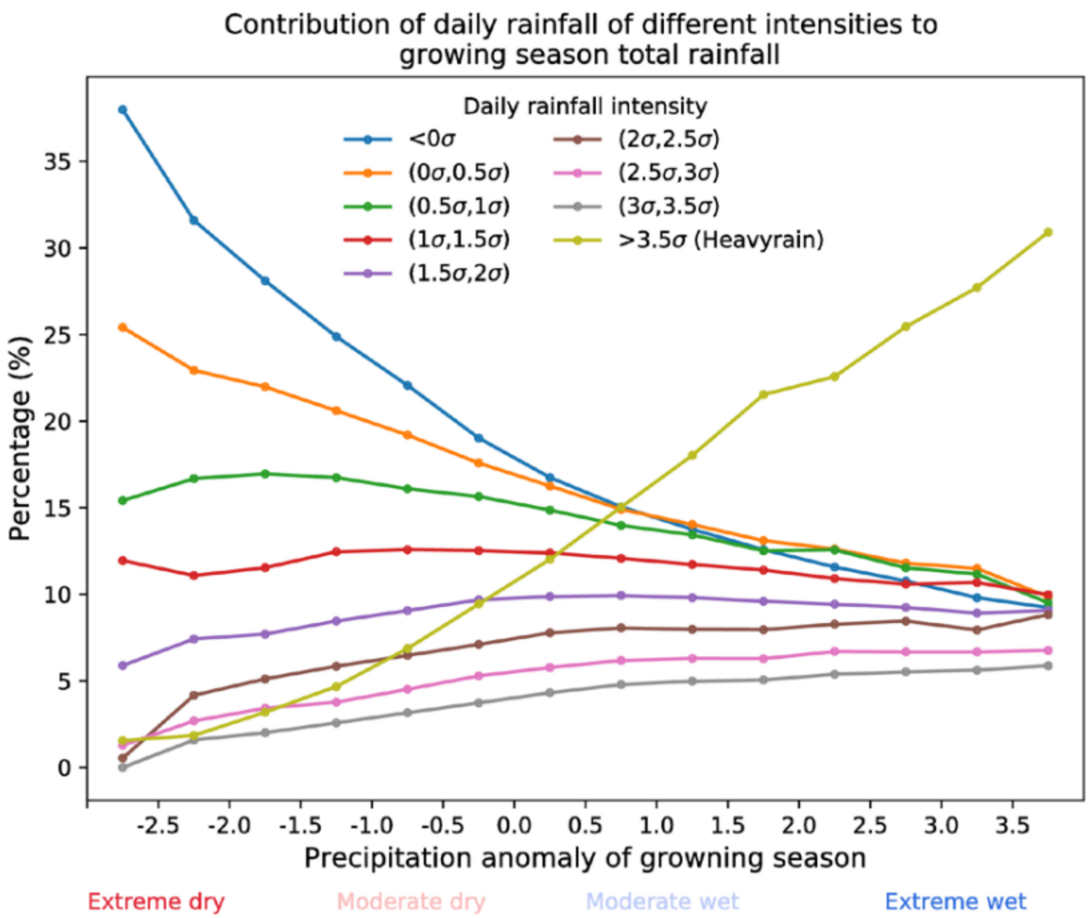

Figure 11. Taken from Fig. [S3] of (Li et al., 2019): "The contributions of different rainfall intensities to the growing season total precipitation from extreme dry to extreme wet conditions, averaged from 1981 to 2016 [across all corn-growing counties in the U.S.]. The rainfall intensity is defined based on the standard anomaly of daily rainfall (i.e., <0σ, 0–0.5σ, 0.5–1σ, 1–1.5σ, 1.5–2σ, 2–2.5σ, 2.5– 3σ, 3–3.5σ, and >3.5σ, see method) and the ">3.5σ" category represents the most intensive heavy rain."

(Wilson et al., 2022) provide confirmation (Fig. 10) for the earlier mentioned IPCC AR6 reports (Fig. 3) regarding the observed increase in heavy precipitation in and around the Corn Belt. The increasing heavy precipitation trends in (Wilson et al., 2022) also appear to line up well with the increasing total annual precipitation trends. However, confidence in these trends is not uniform across the region (Wilson et al., 2022). Most of the heavy precipitation metrics and PRCPTOT observed a statistically significant increase in the following areas: a strip running through northeast IA & south WI, another strip through south-central IL, and the majority of central & southern IN (Wilson et al., 2022). In some localized areas, RX1day increased by over 8 mm/decade (recall annual average ~60 mm), R95p increased by over 60 mm/decade (recall annual average ~240 mm), and R20mm increased by over 1.6 days/decade (recall annual average ~15 days) (Wilson et al., 2022). These ‘hotspot’ areas thus experienced increased heavy precipitation trends representing a large chunk of their annual average, and, for the case of R95p, potentially doubling the annual amount. Nevertheless, areas outside the three mentioned above recorded statistically insignificant precipitation trends (Wilson et al., 2022). While the IPCC AR6 report establishes medium confidence in human attribution to these heavy precipitation trends on a regional scale (IPCC, 2023), the variability of significant changes at the local scale presents uncertainty for projecting impacts for future years (Wilson et al., 2022). Whether or not these regional and/or local trends are reason for concern with respect to corn and soybean depend on other factors, such as the land—soil properties mentioned below.

2.1.2. Corn Belt Soil Properties Relevant for Soil Moisture

Certain locations may be more vulnerable to certain amounts, durations, and/or frequencies of excessive/extreme precipitation if their land/soil properties result in relatively low outgoing moisture fluxes. This subsection will focus on soil properties that affect its drainage capabilities. (Hollinger, 1995) provides a set of maps that regionally approximate soil characteristics relevant to modeling soil moisture in the Midwest U.S. These maps are based on county-averaged soil data obtained from STATSGO map units, alongside empirical equations used to determine soil—water characteristics (Hollinger, 1995). One of the first maps provided by (Hollinger, 1995) is a qualitative drainage classification map, which is displayed in Fig. 12. Sticking with LRR ‘M’ from (USDA-NRCS, 2022) (Fig. 8), the drainage classification map indicates that most Corn Belt counties have either “moderately well” or “somewhat poor” drainage (Hollinger, 1995). Areas with “somewhat poor” drainage mostly make up the core of the Corn Belt (i.e., most of IA, IL, northern MO, southern MN, and central IN & OH), while areas with “moderately well” drainage lie on the fringes (Hollinger, 1995). A few isolated counties are classified as having “well” drainage, and the areas classified as having “poor” or “very poor” drainage lie outside LRR ‘M’ (Hollinger, 1995; USDA-NRCS, 2022). While (Hollinger, 1995) did not quantitatively explain the assignment of these drainage classes, some of his supporting maps, may help to explain these classifications.

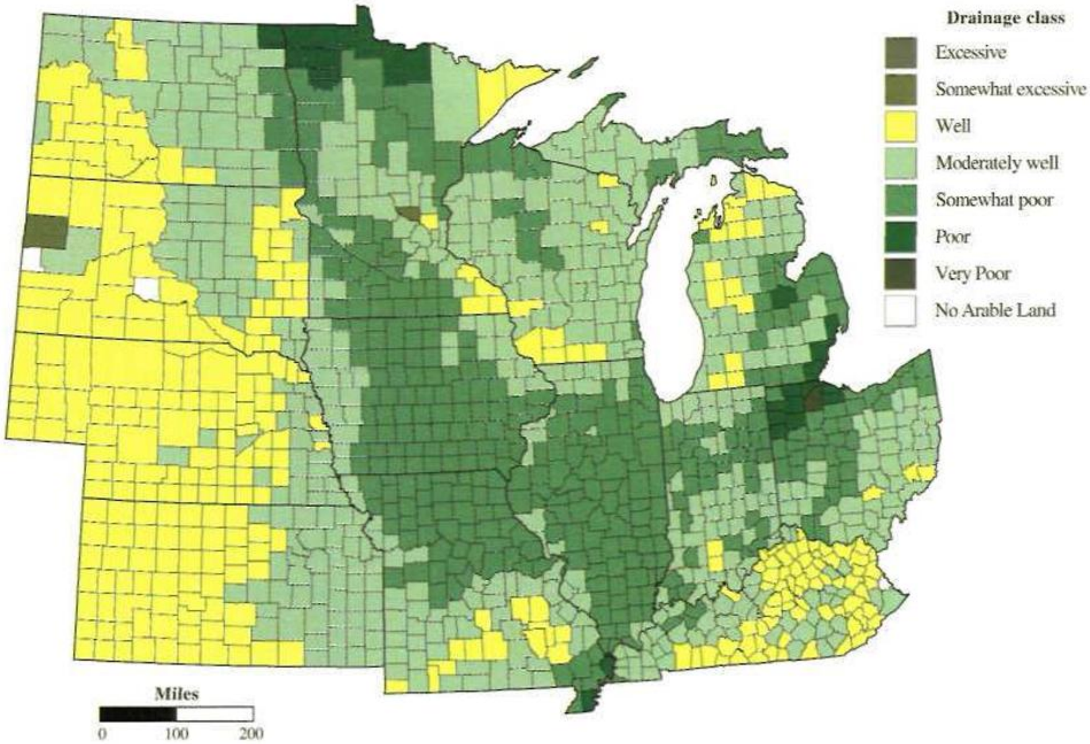

Figure 12. Taken from Fig. 3 of *(Hollinger, 1995)* – "Weighted average of drainage classification of prime farmland or farmland without severe restrictions for tillage purposes"

The relative concentrations of sand, silt, and clay within a soil determine soil texture and average particle size, which in turn influence water infiltration rates and storage capacities. Water can infiltrate through a soil more readily (i.e., the soil is more permeable) if there are large, connected pores in the soil, which occur more in coarser, sandier soils. In contrast, a soil can hold more water if pores make up a larger volume in said soil (i.e., the soil has a higher porosity), which occurs more in finer, clay-soils (Hollinger, 1995; Kaur et al., 2020; Ritter, 2024). While runoff may be more likely to occur in sandier soils because they have less pore space in the event of heavy precipitation, the slower drainage associated with clay-soils leads to more frequent and longer-lasting excessive soil moisture events, and these soils are more prone to compaction (Hollinger, 1995; Kaur et al., 2020; Ritter, 2024). This makes clay-rich soils particularly vulnerable during the early growing season, when soil moisture tends to be highest from pre-growing season accumulation (Lazin et al., 2021; Ritter, 2024; Soil Survey Staff, 2015). As seen in Fig. 13, most of the Corn Belt counties with the highest sand concentrations lie in northern IA, MN, the Dakotas, and IN, while most counties with the highest clay concentrations lie in southern IA, MO, KS, and a region surrounding Lake Erie (Hollinger, 1995). Clay concentrations around Lake Erie reach up to 50%, overlapping with the "Poor" and "Very Poor" drainage classification areas in Fig. 12 (Hollinger, 1995). However, higher clay concentrations in the southern Corn Belt do not appear to influence drainage classification in the same manner (Hollinger, 1995). The next couple of figures from (Hollinger, 1995) will illustrate properties that are partially determined by soil texture, so their relationship with both Fig. 12 & 13 will be evaluated.

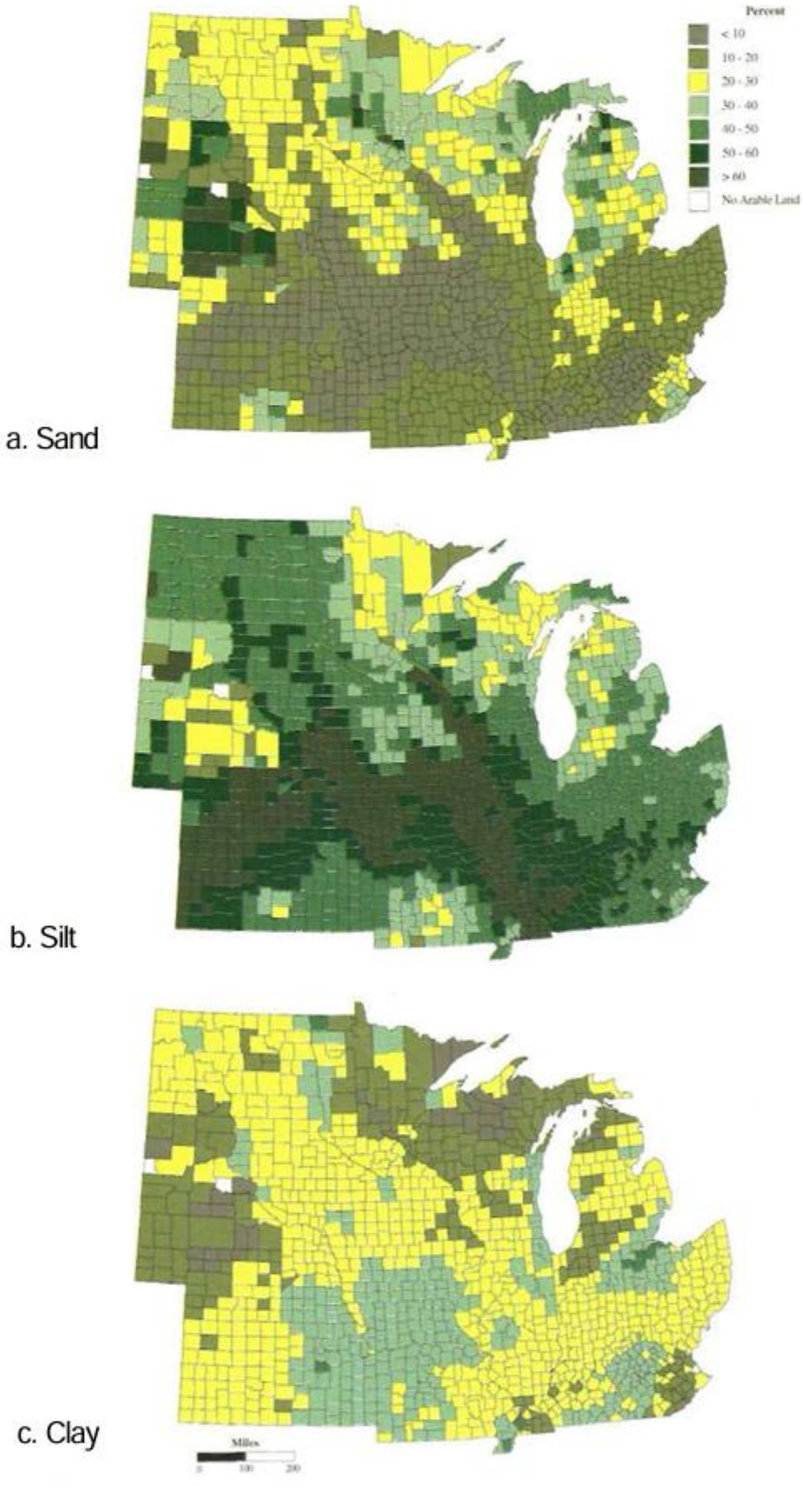

Figure 13. Taken from Fig. 8 of (Hollinger, 1995): “Weighted average of the a) sand, b) silt, and c) clay content in the 0- to 150-cm soil layer.”

As mentioned in the previous paragraph, soil texture partially determines soil permeability, the ability to allow water to infiltrate through the soil. (Hollinger, 1995)'s 0—25 cm layer permeability map, laid out below in Fig. 14, illustrates the influence of the soil texture distribution displayed in Fig. 13 above. The locations with the lowest permeabilities often have the highest clay fraction, as can be seen in eastern KS, northern MO, northeastern IL, and northwestern OH (Hollinger, 1995). Likewise, the areas with the highest permeability often have the highest sand fraction, such as in MN, WI, MI, and northern IN (Hollinger, 1995). Most of the primary growing regions in LRR 'M' reside on top of soils that are classified as a silt loam (~10—20% sand, ~50--70% silt, and ~20—30% clay) and have a permeability rate of ~30—40 mm/hr (Hollinger, 1995; USDA-NRCS, 2022). This permeability rate is well above the average maximum daily precipitation rate for most of the Corn Belt (50—70 mm/day → ~2—3 mm/hr), yet this map only depicts the permeability for a shallow layer near the surface (Hollinger, 1995; Wilson et al., 2022). Waterlogging may impact crops if it occurs within the maximum root depth, which for corn can range between ~80—180 cm and for soybean can range between ~60—125 cm (Datta et al., 2017). The next figure displays a soil property that (Hollinger, 1995) did measure down through these root depths.

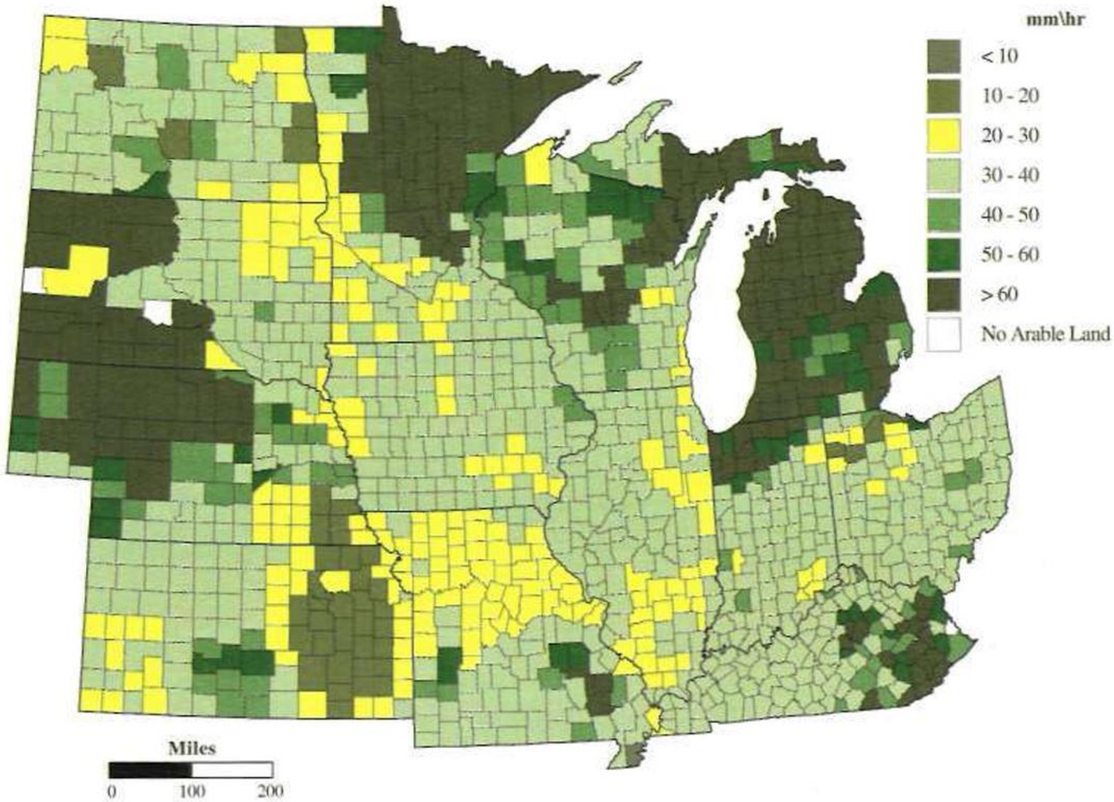

Figure 14. Taken from Fig. 13 of (Hollinger, 1995): "Weighted average of permeability rate for the 0- to 25-cm soil layer"

On top of their shallow-layer permeability map, (Hollinger, 1995) also display measurements for soil bulk density that extend down through the maximum root depths for corn and soybean. A greater bulk density means greater soil compaction, which lowers the overall permeability of the soil (Hollinger, 1995; Kaur et al., 2020; Ritter, 2024). It also increases the air entry water potential of a soil, making it more difficult for air to displace water in a saturated soil (Hollinger, 1995). Additionally, a soil layer with a bulk density value greater than 1.6 Mg/m^3 is considered root-restrictive (Hollinger, 1995). Having said this, looking at Fig. 15, soil bulk density generally increases northward and eastward, with areas north of IA and east of IL generally having bulk densities > 1.5 Mg/m^3 in the 0-150 cm layer (Hollinger, 1995). High bulk density values in combination with relatively high clay content may help to explain regions in the eastern Corn Belt with "somewhat poor" drainage, while high bulk density values in northern IA and southern MN may be offsetting the role of the sandier soils present there. Even though bulk density is not as high in places like northern MO, and the KS/NE border, high clay content in those regions is likely contributing to limiting drainage. This is not the case for southern IA and western IL, whose "Somewhat poor" drainage has yet to be explained. More soil property maps relevant for soil moisture can be found at these three sources: (Hollinger, 1995; Soil Survey Staff, 2015; USDA-NRCS, 2022).

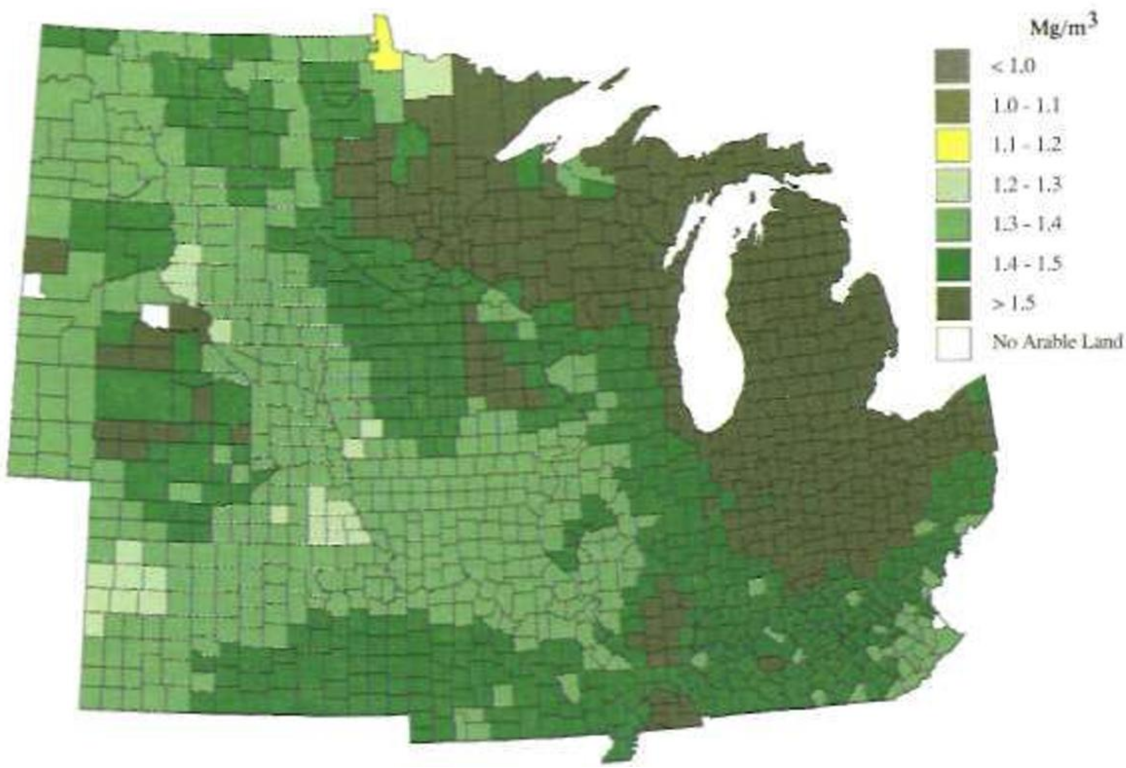

Figure 15. Excerpt of Fig. 11 from (Hollinger, 1995): "Weighted average of soil bulk density for the [0- to 150-cm] soil layer"

2.2. Physiological Responses to Waterlogging

The physiological responses of corn and soybean to waterlogging add onto the complexity of estimating the amount, duration and frequency of extreme/excessive precipitation needed to harm said crops. Fig. 16 shows a web diagram from (Manghwar et al., 2024) that provides more detail on the effects of waterlogging on crops that (Li et al., 2019) touch upon in their flowchart (Fig. 5) and (Kaur et al., 2020) bring up in their diagram (Fig. 7). As water replaces air in all the soil pores in the root zone, this presents multiple problems for the residing plants. Firstly, this water replaces oxygen that had resided in the pores, leading to hypoxic or even anoxic conditions (Kaur et al., 2020; Li et al., 2019). Plants under hypoxic environments must rely on anerobic respiration techniques that produce less than 10% of the energy that aerobic respiration would produce in normal conditions (Kaur et al., 2020; Manghwar et al., 2024). Compounding this, waterlogged/flooded soils lose nitrates from the root zone, depriving plants of a vital nutrient (Kaur et al., 2020; Li et al., 2019). These nitrate removal processes include surface runoff, denitrification (chemical reactions undertaken by certain soil bacteria under hypoxic conditions), and nitrate leaching (nitrate drained by water through the soil) (Kaur et al., 2020; Li et al., 2019). The lack of air-filled pores also reduces gas exchange between the roots and the environment, inhibiting the ability of plants to chemically regulate themselves (Manghwar et al., 2024). The combination of hypoxic conditions, nitrate/nitrogen loss, and reduced gas exchange leads to several consequences. Reduced nutrient uptake occurs due to both the loss of nutrients and the loss of plant energy (Manghwar et al., 2024). Many essential plant functions are interrupted, including photosynthesis, hormone regulation, detoxification, and antioxidation (Manghwar et al., 2024). All these consequences result in waterlogging stress on the plant, which can be seen through health complications such as root damage, stunted plant growth, stomata closure, chlorosis, senescence, and even cell death (Kaur et al., 2020; Li et al., 2019; Manghwar et al., 2024). Ultimately, prolonged waterlogging/flooding reduces crop yield and/or quality, so quantifying this relationship may help determine corn/soybean sensitivity to excessive precipitation.

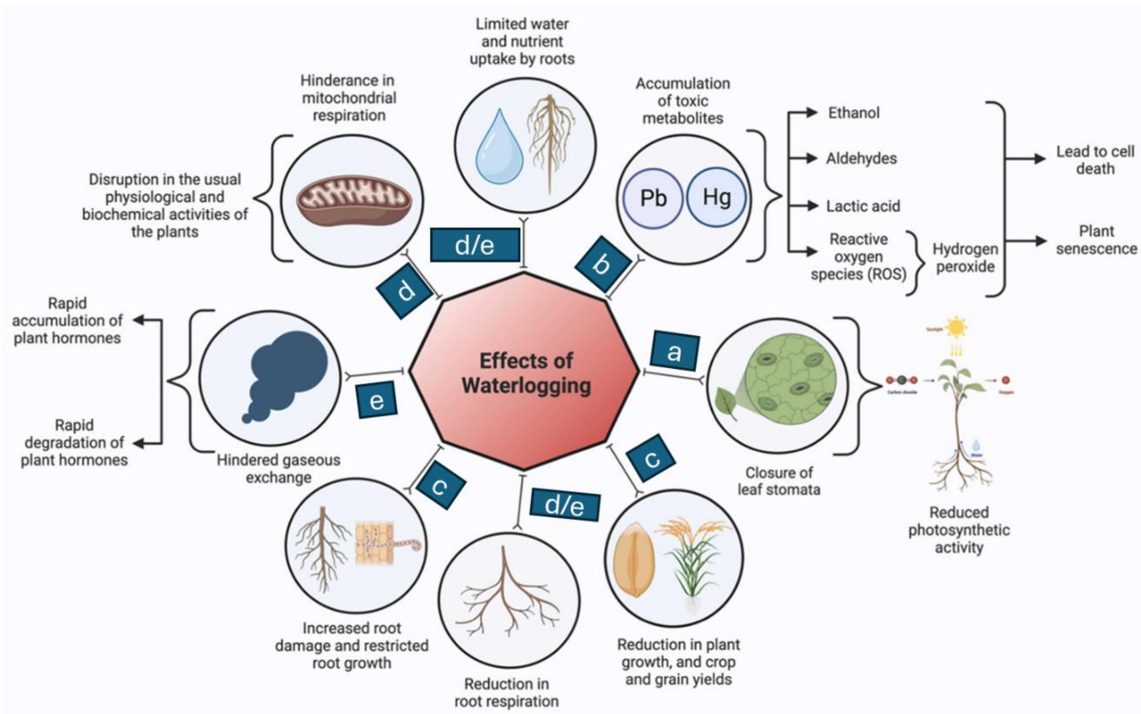

Figure 16. Modification of Fig. 1 from (Manghwar et al., 2024): "Effects of waterlogging on plants/crops."

> [a.] Waterlogging causes the closure of leaf stomata, resulting in reduced photosynthetic activity due to chlorophyll degradation and leaf senescence. [b.] Prolonged waterlogging can result in the accumulation of toxic metabolites like ethanol, aldehydes, and lactic acid and an increase in ROS, such as hydrogen peroxide. These toxic substances can cause cell death and plant senescence. [c.] Waterlogging can also affect root and plant growth, resulting in reduced grain yield. [d.] Moreover, waterlogging affects mitochondrial respiration, which in turn disrupts the usual

physiological and biochemical activities of plants. [e.] Furthermore, waterlogging hinders the gaseous exchange, which then degrades the plant hormones. (Manghwar et al., 2024)

Letters a—e added to the figure to allow quicker association between caption descriptions and the web diagram.

2.2.1. Variational Responses to Waterlogging

The extent to which waterlogging/flooding impacts corn/soybean production and quality, as discussed in the previous paragraph, greatly varies "depending upon the crop [genetics (i.e., species, variety, cultivar)], waterlogging duration, and crop growth stage" (Kaur et al., 2020). To obtain a more quantitative understanding of these variations, (Kaur et al., 2020) compiled field studies on corn & soybean yield losses associated with waterlogging stress of different durations and at different points in the crop phenological cycle. The recorded yield loss percentages for each field experiment are listed in Table 1, while the physiological responses associated with these yield losses are laid out in Table 2 (Kaur et al., 2020). They compiled 19 field studies across four decades (four studies from 1969—1980, six studies from 1986—1991, three studies from 1998—2004, and six studies from 2010—2017). Waterlogging duration varied from as short as <1 day to as long as 14 days across the tabled field studies, with most studies testing around three discrete duration values (e.g., 1, 3, and 7 days) (Kaur et al., 2020). Corn growing stages between V1 to R1 were studied, and soybean growing stages between V1 and R6.3 were considered. 'V' stages refer to 'vegetative' or 'early-stage' crops, while 'R' stages refer to 'reproductive' or 'late-stage' crops. To estimate thresholds at which waterlogging/flooding start to significantly impact corn and soybean, the following paragraph briefly discusses (Kaur et al., 2020)'s field studies that recorded moderate yield losses.

Table 1. Excerpt of Table 1 from (Kaur et al., 2020): "Yield losses due to waterlogging stress at different growth stages of [corn and soybean in] the United States"

Crop	Timing of waterlogging initiation[a]	Waterlogging duration d	Yield loss[b] %	References
Corn	V6	1, 3, 7	10–36	Kaur et al. (2017)
	V3	7	16–38	Kaur (2016)
	V6, VT	1 ,2, 3	1–22	Singh & Ghildyal (1980)
	V2, V7, VT, R1	10	8–80	Zaidi et al. (2004)
	20 and 40 d after planting	0, 11	51–69	Sandhu, Singh, Singh, & Khera (1986)
	V6, VT	5	25–43	Shah et al. (2012)
	V1, V6, VT, R1	2, 4, 6, 8, 10	9–100	Liu et al. (2013)
	V3,V6, 10 d after VT	3, 6	7–33	Ren et al. (2014)
	V3	-	40	Bhan (1977)
	Early and late vegetative, flowering	10	19–64	Mukhtar, Baker, & Kanwar (1990)
	4 weeks after planting	1, 2, 3, 4, 5, 6	6–61	Chaudhary, Bhatnagar, & Prihar (1975)
	6- and 30-inch height of corn and at silking	1, 2, 3	2–33	Ritter & Beer (1969)
	V6	3, 6, 9, 12	27–56	Ahmad (1991)
Soybean	V5, R1, R5	2, 4, 6, 8	20–41	Rhine et al. (2010)
	V4, R2	2, 4, 7, 14	20–84	Scott et al. (1989)
	V4, R2	7	39–52	Oosterhuis et al. (1990)
	V1, V4, R2	7	12–56	Scott et al. (1989)
	V2, V3, V7, R1, R3, R5, R6, R6.3	7	9–93	Linkemer et al. (1998)
	V2, V3	3, 6, 8	20–93	Sullivan et al. (2001)

"[a]Growth stages description for the corn and soybean plants can be obtained from Abendroth et al. (2011) and Fehr and Caviness (1977)." (Kaur et al., 2020)

"[b]Yield loss is compared to non-flooded control." (Kaur et al., 2020)

Table 2. Taken from Table 2 of (Kaur et al., 2020): "Corn and soybean responses to soil waterlogging stress at different growth stages."

Crop	Growth Stages[a]	Plant responses to waterlogging stress	References
Corn	V1	Reduced plant height and leaf area	Liu et al. (2013)
	V2	High plant mortality; reduced plant height, leaf area, dry weight, stem and total carbohydrate content, short anthesis–silking interval	Zaidi et al. (2004)
		Reduced N, P, K, and Zn concentrations in leaves; ears per plant; and grain weight per ear	Sandhu et al. (1986)
	V3	Reduced leaf greenness and stomatal conductance	Kaur (2016)
		Decreased grains per ear, 1000-grain weight, plant height, ear height, leaf area, grain-filling rate, and dry matter accumulation	Ren et al. (2014)
	V6	Chlorosis	Kaur et al. (2017)
		Retarded growth, reduced plant height, N and K uptake, increased P uptake	Singh & Ghildyal (1980)
		Decrease in total leaf number, leaf area, and dry matter accumulation	Shah et al. (2012)
		Reduced plant height and leaf area	Liu et al. (2013)
		Decreased grains per ear, 1000-grain weight, plant height, ear height, leaf area, grain-filling rate, and dry matter accumulation	Ren et al. (2014)
		Reduced leaf area, root length, and weight	Ahmad (1991)
	V7	High plant mortality; reduced plant height, leaf area, dry weight, stem and total carbohydrate content; short anthesis–silking interval	Zaidi et al. (2004)
	VT	Retarded growth, plant height, N and K uptake, increased P uptake	Singh and Ghildyal (1980)
		High plant mortality and short anthesis–silking interval	Zaidi et al. (2004)
		Decrease in total leaf number, leaf area, and dry matter accumulation	Shah et al. (2012)
		Reduced plant height and leaf area	Liu et al. (2013)
	R1	Reduced total carbohydrate content	Zaidi et al. (2004)
		Reduced plant height and leaf area	Liu et al. (2013)
Soybean	V1	Reduced N and K concentrations	Scott et al. (1989)
		Reduced plant population and plant height	Sullivan et al. (2001)
	V2	Reduced plant height and branch number	Linkemer et al. (1998)
		Reduced plant population and plant height	Sullivan et al. (2001)
	V3	Reduced plant height	Linkemer et al. (1998)
	V4	Reduced N and K concentrations and canopy height, reduced dry matter accumulation, yellowing, and abscission of leaves, stunting	Scott et al. (1989)
		Reduced photosynthesis, dry matter accumulation, growth and stomatal closure	Oosterhuis et al. (1990)
	V5	Reduced plant growth and biomass accumulation	Cho and Yamakawa (2006)
	V6	Reduced height, chlorosis, stunting; diminished plant growth	Griffin & Saxton (1988)
	V7	Reduced branch number	Linkemer et al. (1998)
	R1	Suppressed nodule nitrogenase and leaf nitrate reductase activities	Sung (1993)
		Reduced branch number and reduced pods per branch	Linkemer et al. (1998)
		Reduced shoot dry weight and leaf area	Youn et al. (2008)
	R2	Reduced N and K concentrations and canopy height; higher Mn, Fe, Al concentrations	Scott et al. (1989)
		Reduced canopy height and dry matter accumulation	Scott et al. (1989)
		Reduced photosynthesis, dry matter accumulation, growth, and stomatal closure	Oosterhuis et al. (1990)
	R3	Reduced seed size and reduced pods per branch	Linkemer et al. (1998)
	R5	Reduced seed size	Linkemer et al. (1998)
		Suppressed nodule nitrogenase and leaf nitrate reductase activities	Sung (1993)

[a]Growth stages description for the corn and soybean plants can be obtained from Abendroth et al. (2011) and Fehr and Caviness (1977).

Here are some field studies from (Kaur et al., 2020) (Table 1 & Table 2) that provide useful information on the waterlogging duration needed to induce adverse impacts on corn and soybean at varying growth stages. In (Kaur et al., 2017) (cited in (Kaur et al., 2020)), waterlogged corn in the V6 stage, planted on poorly drained claypan soil in northeast MO, exhibited chlorosis as yield losses ranged from 10% (1-day duration) to 36% (7-day duration) (Kaur et al., 2020). In support of these numbers, they provide a photo showcasing the visible difference that waterlogging duration had on the corn's development. The photo, shown in Fig. 17, shows visibly obvious damage and delayed growth in the "3-day flooding" field, and the damage is amplified in the "7-day flooding" field (Kaur et al., 2020). Similar to this study, Tables 1 & 2 show that (Ahmad, 1991) (cited in (Kaur et al., 2020)) also studied waterlogged corn in the V6 stage, but instead had waterlogging durations vary from 3—12 days (Kaur et al., 2020). Observed impacts included reduced leaf area, root length, and weight of the corn, resulting in a 27% yield loss for 3-day duration to a 56% yield loss for 12-day duration (Kaur et al., 2020). The table also lists (Shah et al., 2012)'s study, who used a 5-day waterlogging duration on both the V6 and VT stages for corn. Both stages experienced a decrease in total leaf number, leaf area, and dry matter accumulation, but the V6 (earlier) stage suffered more (43% yield loss) than the VT (later) stage (25% yield loss) from the 5-day duration (Kaur et al., 2020; Shah et al., 2012). Interestingly, another study in the table, (Kaur, 2016) (cited in (Kaur et al., 2020)), evaluated an earlier crop stage (V3) that underwent a longer waterlogging duration (7 days) and observed a relatively smaller yield loss (16—38%). That study listed different physiological responses, those being reduced leaf greenness and stomatal conductance (Kaur et al., 2020). From these studies, it appears that corn starts to see >20% yield losses at around 3 days of waterlogging, particularly in the early vegetative stages before tasseling (VT).

Figure 17. Taken from Fig. 6 of (Kaur et al., 2020): "Effects of flooding duration on corn growth on poorly drained claypan soil in northeast Missouri. Corn was flooded at V6 (corn plant with 6 leaves) growth stage. (Kaur et al., 2017)"

The same two tables by (Kaur et al., 2020) also provide information regarding soybean response to waterlogging. One of the listed experiments, conducted by (Scott et al., 1989), retrieved a large range of yield losses (20—84%) depending on the waterlogging duration (2, 4, 7, and 14 days), soybean growing stage (V4 vs. R2) and soil type (clay vs. silt). Their field experiment noted a linear relationship between yield declines and waterlogging duration, and yield losses on the clay soil were greater than that on the silt soil (Scott et al., 1989). However, the most notable find was the relatively high waterlogging sensitivity of soybean in the reproductive (R2) phase (Scott et al., 1989). In a follow-up study, which is also represented in (Kaur et al., 2020)'s table, (Scott et al., 1990) found that soybean waterlogged for 7-days on a poorly-drained clay soil recorded a 56% yield loss in the R2 stage while only recording a 17% yield loss in the V4 stage and a 12% loss in the V1 stage. Most of the other soybean studies listed in (Kaur et al., 2020)'s table come to the similar conclusion that the reproductive stages of soybean are more sensitive to waterlogging than most of the vegetative stages. This is in contrast with corn, where most studies indicated a greater sensitivity in the early vegetative stages (Kaur et al., 2020). A higher vulnerability to excessive soil moisture in the earlier part of the growing season may pose a greater risk because that is when soil moisture & water storage, in general, are higher. As the growing season progresses, more intense solar radiation, higher temperatures, and increased plant uptake will raise evapotranspiration rates, making it less likely for soils to accrue moisture (Ritter, 2024; Soil Survey Staff, 2015).

Section 3. Modeling Studies on Extreme Precipitation Impacts on U.S. Corn Belt Crops

This section reviews and pieces together a collection of studies that have mapped and modeled extreme/excessive precipitation impacts on corn and/or soybean production in and around the U.S. Corn Belt. Most of the studies brought up here used historical meteorological and crop data, aggregated to the county/state level on a seasonal-to-annual basis, to retrieve correlations between extreme precipitation metrics and crop performance. Information from the previous section (i.e., regional precipitation climatology, regional soil drainage properties, and corn/soybean sensitivity to waterlogging) are brought in when appropriate to verify the statistical results presented below.

The first modeling study comes from (Troy et al., 2015), who took standardized monthly precipitation metrics and plotted them with standardized & detrended corn and soybean yields using conditional density functions on nationally pooled county data across the U.S. (Fig. 18). Across all three of their precipitation metrics: mean daily precipitation on wet days (*Prcp. Intensity*), total precipitation (*Prcp. Total*), and maximum 5-day precipitation (*Max. 5 day Prcp*.), the standardized corn and soybean yields increase together with the precipitation metrics, all the way up until the last slice of the conditional density plots, where the standardized precipitation metrics have a value of ~2 (Troy et al., 2015). Even at this value, the mode and 50% highest density region of standardized yields are positive except for maximum 5-day precipitation on corn, which has both signs (Troy et al., 2015). Their results suggest that precipitation metrics beyond 2 standard deviations are required to obtain a signal for adverse excessive/heavy precipitation impacts at a regional scale. Additionally, a calculated correlation among the three precipitation metrics in the High Plains (0.69 < r < 0.82) supports the visual similarity between the metrics on the conditional density plots (Troy et al., 2015). This correlation also supports that which is found between PRCPTOT and R95p, R99p, and RX1day in Fig. 9 (Wilson et al., 2022). The next modeling study extends beyond the 2 standard deviation limit in (Troy et al., 2015)'s work to assess the impacts of the greatest precipitation anomalies on corn yields.

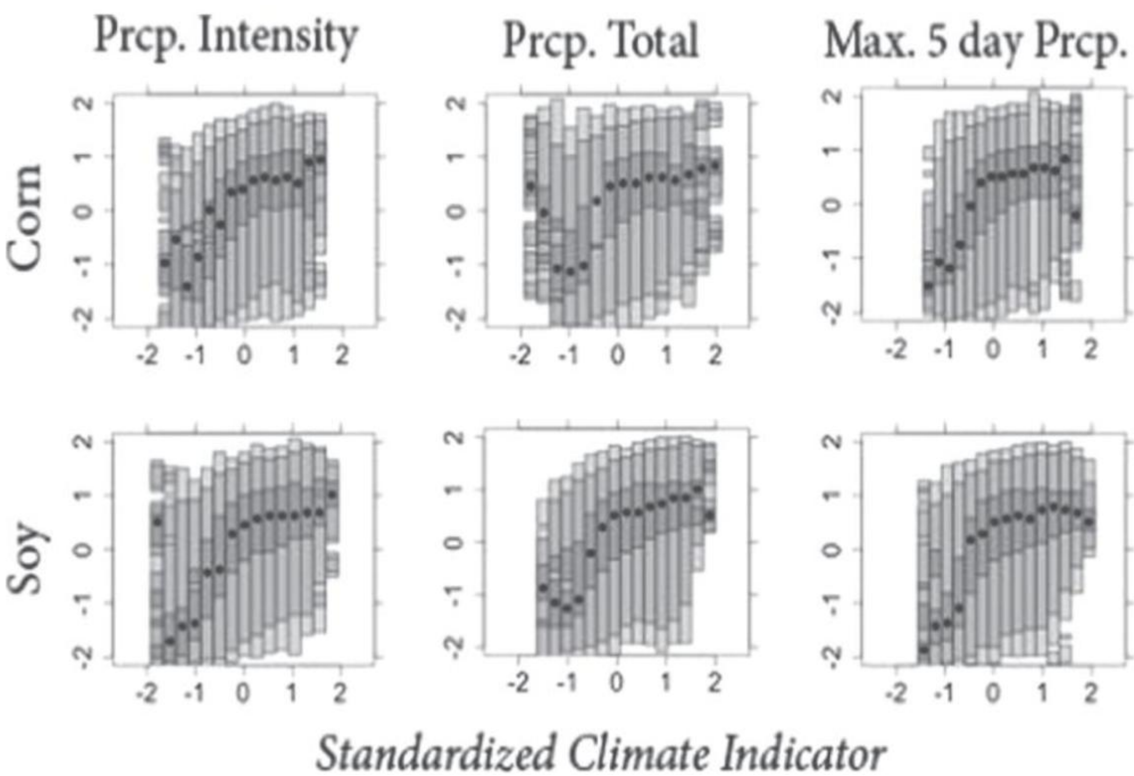

Figure 18. Excerpt of Fig. 3 from (Troy et al., 2015): "Conditional probabilistic relationships between…growing season precipitation characteristics [(x-axis)] … and [crop] yields (y-axis) … [All variables were calculated for each month of the growing season. **Prcp. Intensity** is the mean daily precipitation exclusively on days with precipitation. **Prcp. Total** is the total monthly precipitation. **Max. 5 day Prcp.** is the maximum precipitation in a five-day period.] The black dot in each panel of the figure is the mode of the conditional probability of yield for each slice of the climate index values; the darkest grey

color contains the 50% highest density region, the medium grey the 95% density, and the light grey the 99% density."

With little-to-no sign of adverse crop impacts by daily or seasonal precipitation within 2σ, according to (Troy et al., 2015), (Li et al., 2019)'s observations focus on the impact that extreme anomalies (i.e., >2.5σ, or ~99th percentile) of total growing season precipitation have on corn yield. Fig. 19 displays their analysis of this impact among Corn Belt counties and states between 1981—2016 (Li et al., 2019). At the individual county level, years in which total growing season precipitation was >2.5σ were associated with large (>50%) corn yield reductions over a swath of the Corn Belt stretching from eastern ND, down through eastern SD & southwestern MN, and all throughout central and southern IA (Li et al., 2019). Most of the other Corn Belt states had this degree of impact limited to a few isolated counties for at least one year in the period (Li et al., 2019). When (Li et al., 2019) aggregated this data to the state level, they found that the states of MN, IA, and MO had the most negative corn yield changes associated with >2.5σ total growing season precipitation, with average losses of -35.7%, -32.2%, and -31.3%, respectively. These findings suggest that, since 1981, high total growing season precipitation anomalies have impacted the north-central Corn Belt the most (Li et al., 2019). One of their supplemental figures (Fig. 11 in this paper) further informs that extremely heavy daily precipitation (i.e., >3.5σ) made up (~23—31%) of all precipitation during those highly anomalous precipitation years, suggesting that these very anomalously high daily precipitation events led to most of the observed corn damage (Li et al., 2019). Because of this, it is not clear how much waterlogging or physical damage is responsible for these observations.

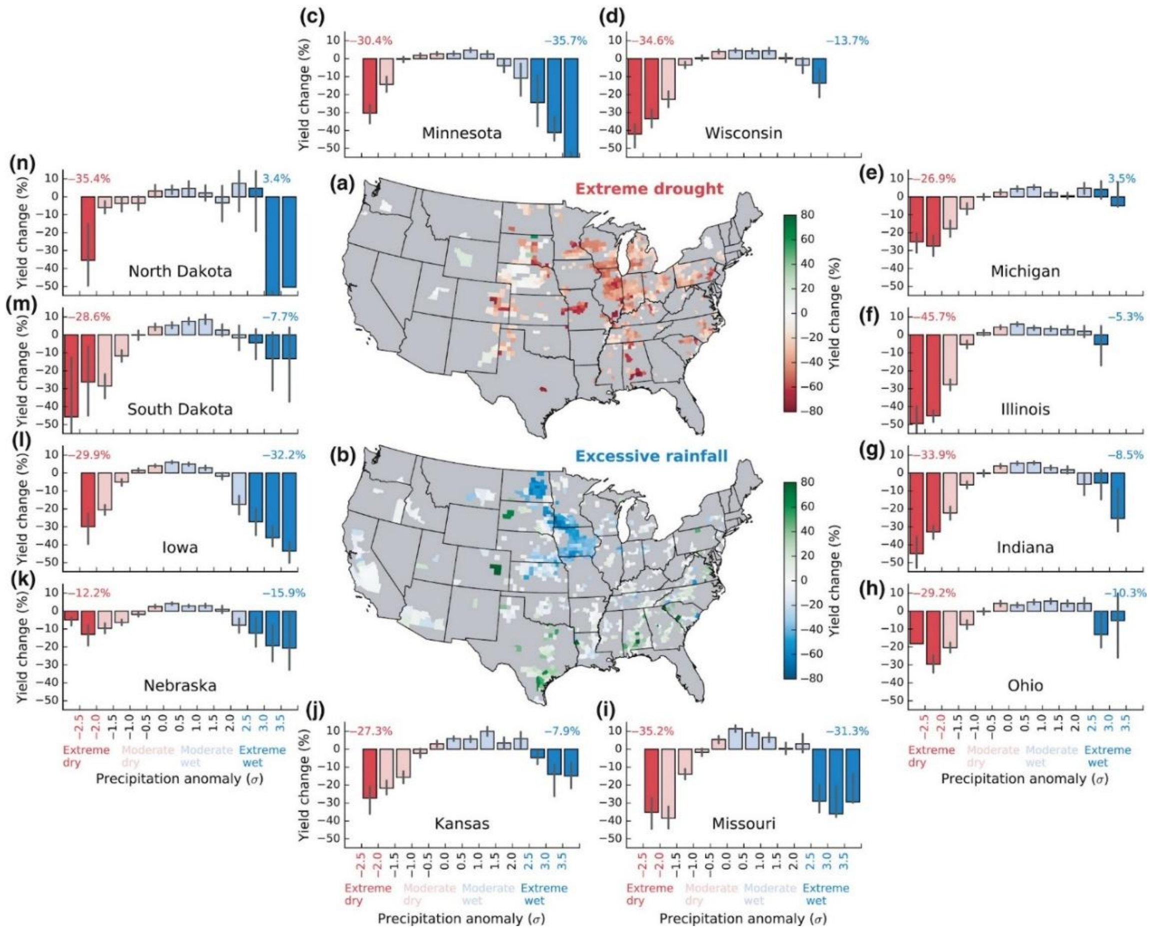

Figure 19. Taken from Fig. 2 of (Li et al., 2019): "The impacts of extreme drought and excessive rainfall [(i.e., **growing season total precipitation**)] on maize yield from 1981 to 2016 at the county level (a, b) and in major maize production states (c–n). The extreme climate impact for any individual county on the map is the yield percentage change averaged from extreme years during the period, weighted by their harvest area...The bar chart in c–n is the same as Figure 1a but for different states. [From Figure 1a description: "Each bar shows the yield change weighted by harvest area…in the corresponding precipitation range. The percentages shown on top are the averaged impacts of extreme drought (<-2σ, red) and extreme rainfall (>2.5σ, blue) on maize yield…Error bars…denote the 95% confidence interval estimated from 1,000 time bootstrap."]"

Despite the notable findings by (Li et al., 2019), there are some properties of their results to keep in mind. Because of the county-to-county variance in annual exposure to

>2.5σ growing season precipitation and in total harvest area, the weighted impact on the state level is visually distinct from the county-mapped impact (Li et al., 2019). For example, ND has many individual counties that experienced >50% corn yield reductions from extreme precipitation years on average, but when aggregated to the state level, the impact on yields is a net positive (3.4%) (Li et al., 2019). In contrast, MO does not visibly have many counties with a large negative yield impact, but the aggregated state metric indicates that >2.5σ growing season precipitation county-years reduced yields by -31.3% on average (Li et al., 2019). In addition, the overall occurrence of growing season precipitation >2.5σ is small over the 36-year period. Most Corn Belt counties in Fig. 19 are grayed out, indicating no occurrence of >2.5σ growing season precipitation in any year. This outcome is most common in the eastern Corn Belt states, where ~75% of all counties did not record an “extreme precipitation” year (Li et al., 2019). On the state level, the eastern Corn Belt (i.e., WI, IL, IN, OH) did not record a single county-year with >3.5σ total growing season precipitation, and the states of IL and WI did not even capture a county-year with >3.0σ total growing season precipitation (Li et al., 2019). Not only does this imply that the central & western Corn Belt have experienced more anomalous extreme precipitation years, but it also indicates the overall rarity of these events. (Li et al., 2019) mention in their paper that much of the harmful impacts in their study came from 3—4 anomalously wet years, with 1993 being an exceptionally wet year. Averaged over the period of study, this suggests that the Corn Belt should expect to endure significant crop losses due to heavy precipitation about once per decade, at least, under the climate of the past 36 years (Li et al., 2019). The following article echoes similar ideas when focusing specifically on hourly precipitation impacts on corn and soybean.

(Lesk et al., 2020)'s article supports that of (Li et al., 2019) in terms of describing the rarity of destructive heavy precipitation, but they also show how its overall impacts are relatively small compared to other precipitation intensities. After obtaining Stage IV radar-derived hourly rainfall data from 2002—2017 and aggregating them to the growing season/county-level using intensity-binned histograms, they used a "linear fixed-effects multiple regression model" to estimate the specific impact of hourly precipitation intensity on U.S. corn and soybean yields (Lesk et al., 2020). In the process, they attempted to eliminate the influence of (i.e., control for) seasonal total precipitation on those yields (Lesk et al., 2020). As seen in Fig. 20, corn and soybean are both sensitive, with statistical significance, to very heavy precipitation on a per-hourly basis (Lesk et al., 2020). For corn, 23 bushels (bu) per acre (ac) were lost per hour of 80 mm precipitation on average, and one hour of 90 mm rain led to a loss of 45 bu/ac. For soybean, 50 & 60 mm/hr rain led to -2 bu/(ac*hr), and 70 mm/hr rain led to -4 bu/(ac*hr) (Lesk et al., 2020). However, all these hourly intensities (i.e., ≥ 50 mm/hr) are above the 99.95th percentile of the U.S. hourly rainfall distribution east of the Rockies, as (Lesk et al., 2020) indicate in Fig 20 and Fig 21. Furthermore, these hourly intensities are not an annual occurrence (on average) across U.S. counties (Lesk et al., 2020). According to Fig. 21, each individual county averages ~0.03 hours of 50 mm/hr precipitation annually, and the return frequency[1] of 50 mm/hr [rain] in *any* county is ~0.5. For 70 mm/hr rain, each county averages ~0.004 hours of exposure, and the return frequency is ~0.1. For 90 mm/hr rain, each county averages ~9*10^-4 hours of exposure, and the return frequency

[1](Lesk et al., 2020)'s *return frequency* approximation is the ratio between (Number of county—years with non-zero exposure to a certain hourly precipitation intensity) / (Total number of county—years). If the return frequency is 1, each county experiences rainfall of an assigned intensity for a least one hour per year. If the return frequency is 0.5, only half of all counties experience an assigned rainfall intensity for even one hour per year.

is ~0.02 (Lesk et al., 2020). These intensities correspond to approximately 2-year, 10-year, and 50-year return periods, respectively, for exposure in *any* U.S. county east of the Rockies. The probability of a specific county experiencing these intensities is much lower, as seen by the average hours of exposure (Lesk et al., 2020). When weighing corn & soybean yield sensitivity to very heavy precipitation by average exposure hours (Fig. 22), the sensitivity magnitude becomes very small (by 1—2 orders of magnitude) compared to the positive influence of moderately heavy precipitation (5—20 mm/hr) and the negative influence of drizzle (0.1—1 mm/hr) (Lesk et al., 2020).

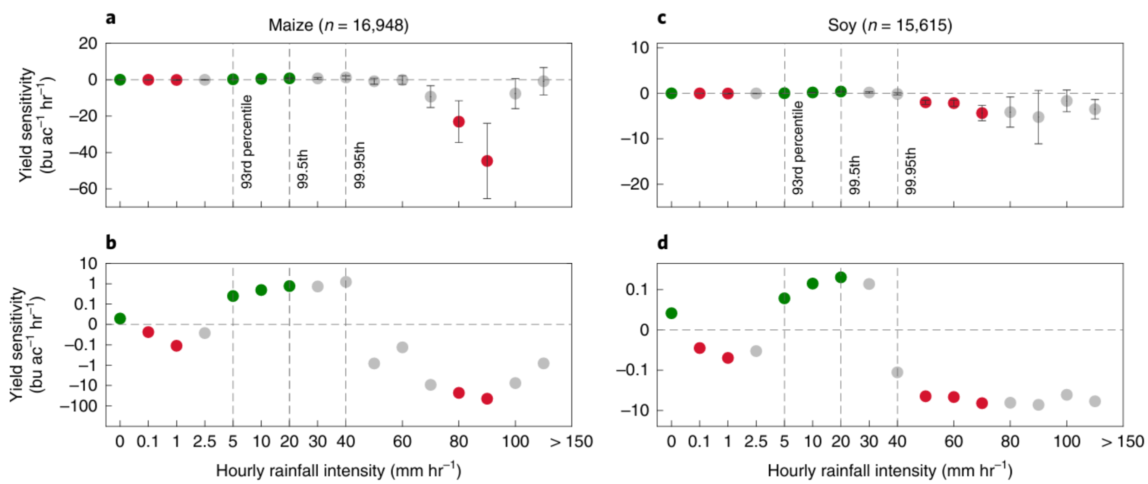

Figure 20. Taken from Fig. 1 of (Lesk et al., 2020):

> **Sensitivity of maize and soy yields to hourly rainfall intensity. a**, National mean county-level maize yield sensitivity (±s.e.m.) to hourly rainfall intensity per hour of exposure over 2002–2017. **b**, Same as in a, but on symmetric logarithmic axes. **c,d**, Same as in **a,b**, but for soy. The vertical dashed lines denote the indicated percentiles of climatological rainfall intensity. The sensitivities are inferred from a model controlling for exposure to beneficial and excessive heat and seasonal total rainfall. the sample sizes reflect county–year pairs. The dark-green and red points indicate significant positive and negative sensitivities (two-sided P < 0.05…). Transformed standard error estimates are omitted in **b** and **d** for clarity. (Lesk et al., 2020)

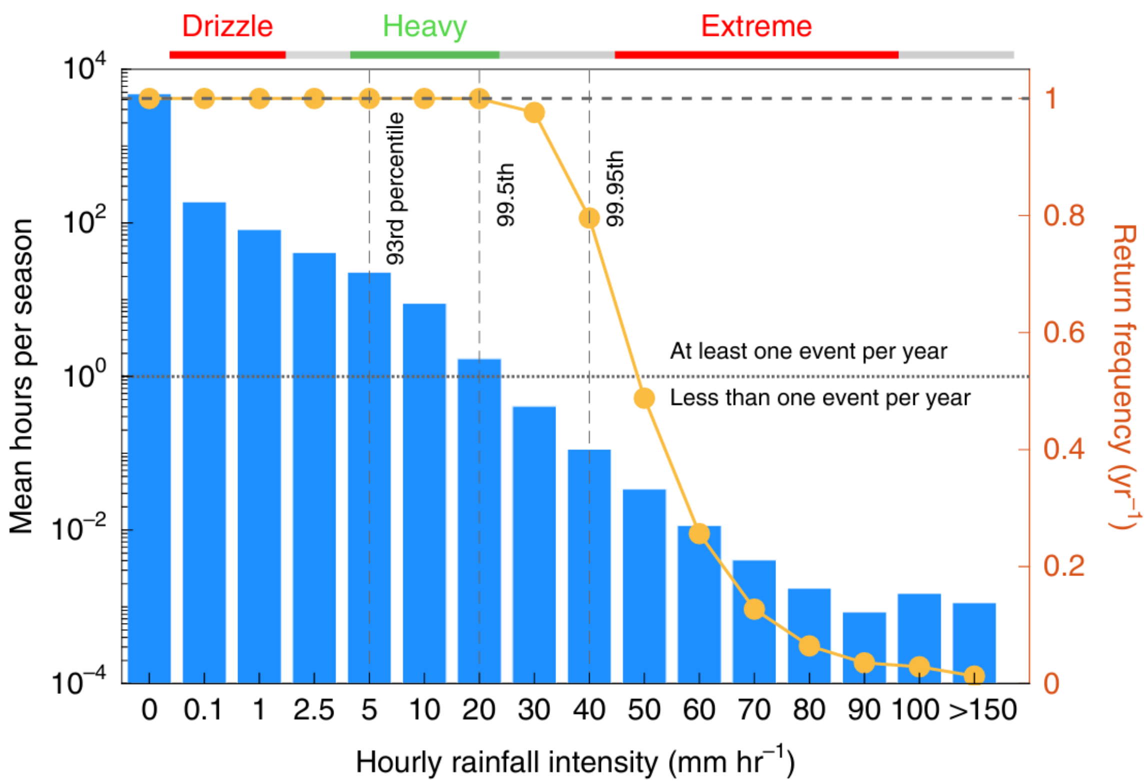

Figure 21. Taken from Fig. 2 of (Lesk et al., 2020):

> **Frequency distribution of hourly rainfall intensities**. National average county-level number of exposure hours per season (blue bars) and estimated national return frequency (yellow curve) for each hourly rainfall intensity bin over 2002–2017. The horizontal dotted line represents a once-per-year occurrence (mean hours per season of 1), such that bars above the line occur annually on average while bars below the line occur less than once per year. For the return frequency, a value of 1 (horizontal dashed line) indicates an event that occurs in every year for each county in the sample. the vertical dashed lines denote the indicated percentiles of climatological rainfall intensity. (Lesk et al., 2020)

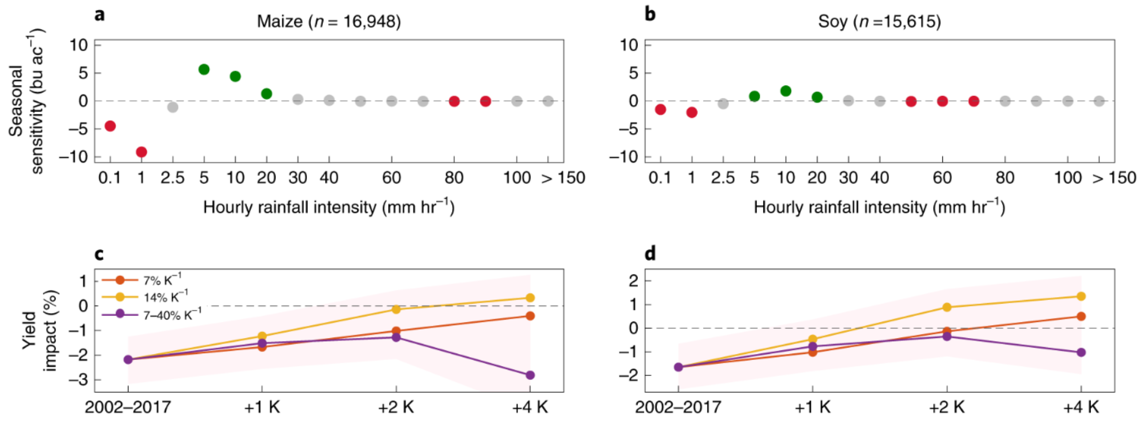

Figure 22. Taken from Fig. 4 of (Lesk et al., 2020):

> **Current and projected future net yield impacts of hourly rainfall intensity. a**,**b**, Integrated seasonal yield sensitivities for maize (**a**) and soy (**b**), estimated by <u>weighting the per-hour sensitivity by total exposure hours</u> [between 2002—2017]. **c**,**d**, Net impacts across all intensities on maize (**c**) and soy (**d**) yields under the 2002–2017 climate and for 1, 2 and 4 K warming for three rainfall intensification scenarios: low change (red), high change (yellow) and amplified (purple). The shaded area shows the 90% confidence interval accounting for regression and scenario uncertainties. The net impacts are presented as percentages of the national mean yield. (Lesk et al., 2020)

(Lesk et al., 2020)'s results in the previous paragraph invite a few callbacks to the previous section's information. Recall that the maximum *1-day* precipitation throughout most of the eastern Corn Belt was 50—70 mm (Wilson et al., 2022). The threshold for significantly harmful hourly precipitation, according to (Lesk et al., 2020), is 50 mm/*hour* for soybean and 80 mm/*hour* for corn. (Lesk et al., 2020) calculated the average maximum hourly precipitation (for the eastern 2/3 of the U.S.) to be a little over 20 mm/hr. It is unlikely that (Wilson et al., 2022)'s maximum daily precipitation values fell in the span of a single hour; instead, it probably fell over several hours to be more in line with the 20 mm/hr maximum hourly precipitation value. Assuming (Lesk et al., 2020)'s claims that 20 mm/hr rainfall is beneficial to corn and soybean, (Wilson et al., 2022)'s spatial data confirms that even the heaviest precipitation in an average year is not expected to harm Corn Belt crops. Additionally, recall the comment by (Li et al., 2019) mentioning that harmful extreme precipitation impacts occurred around once per decade on average. 70 mm/hr rainfall, which lies just below the significant intensity for corn and on the higher end for soybean, represents around a 10-year return period. The connection makes even more sense when remembering that the heaviest daily precipitation anomalies contributed greatly to the highest growing season precipitation anomalies (Li et al., 2019). All of this suggests that, while extreme precipitation impacts may not produce a strong annual signal at a regional scale, they are still capable of causing severe impacts at longer time scales at the local level.

(Shirzaei et al., 2021) take a different approach compared to the sources mentioned above, opting to focus instead on the impact of flooding on crops in the Midwest. This leans more into assessing the impacts of excessive precipitation in general, rather than heavy precipitation extremes specifically. Using approximately continuous gauge data obtained over the western & central Corn Belt from ~1969—2019, they calculated the correlation between unlikely (i.e., <33% chance) spring maximum stream discharge at an individual station and the corresponding state's corn/soybean yield loss (relative to a 5-year moving average), as displayed in Fig. 23 (Shirzaei et al., 2021). Analyzing this during the spring is useful because this is generally the period where soil water storage is the highest during the growing season, and corn is most sensitive to waterlogging during the vegetative stage (Kaur et al., 2020; Ritter, 2024). Fig. 23 shows that the correlation between spring discharge and yield decline ranges between 10—70%, with a regional average of 43% (Shirzaei et al., 2021). The regional correlation histograms between corn and soybean are extremely similar; around eighty percent of gauges observed a ~30—50% occurrence of yield declines (Shirzaei et al., 2021). For corn, the gauges with the highest correlation appeared to be in KS, central IL, and southeastern SD. The same regions apply for soybean as well, in addition to portions of central IA and eastern NE (Shirzaei et al., 2021).

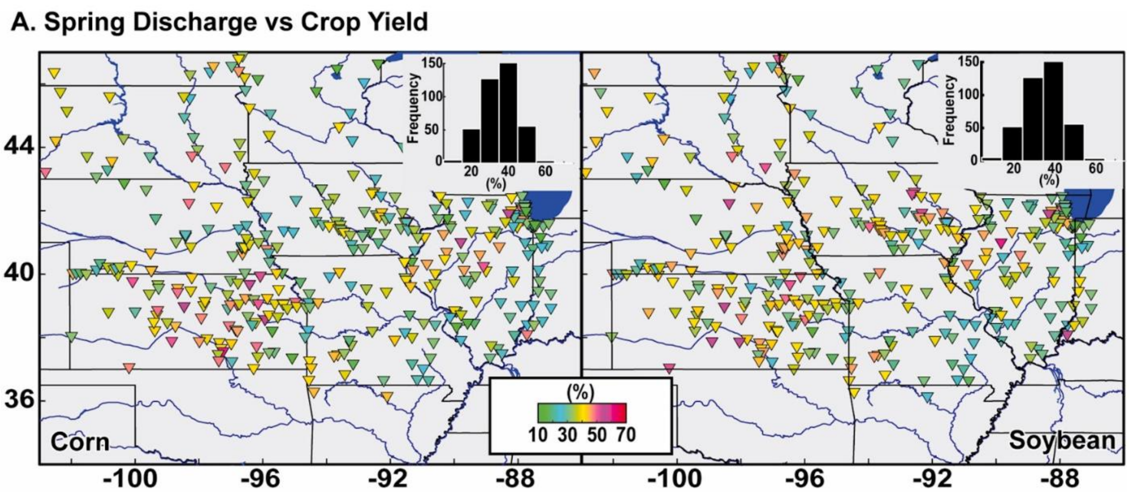

Figure 23. Excerpt of Fig. 4 of *(Shirzaei et al., 2021)*:

> **Long-term [ca. 1969—2019] relationship of discharge data sets with crop loss.** A. Long-term association between spring unlikely discharge and crop yield decline for corn (left) and soybeans (right). Triangles are discharge stations color-coded to the number of years that unlikely spring discharge and crop yield decline cooccur, divided by the total number of years with unlikely spring discharge. Insets are histograms of the ratios indicating the overall relation between spring unlikely discharge and crop loss. (Shirzaei et al., 2021)

'Unlikely discharge' is defined as a maximum spring (March 20—June 20) discharge with a less than 33% chance of occurrence according to a normalized Extreme Value Density function. Crop yield declines are determined by evaluating each state's detrended annual crop yield against the average of the previous five years. (Shirzaei et al., 2021)

The observations in the above paragraph appear to carry different messages depending on the spatial scale considered. At the local scale, flooding may be a decisive factor in determining yield declines, particularly in the ~70% correlation zones (Fig. 23). However, (Shirzaei et al., 2021)'s usage of local stream gauge data alongside state crop yield data may result in inaccurate representation of the flooding—yield relationship. There could be false positives if crop yields decrease in one part of the state where flooding isn't occurring, or false negatives if state yields are high despite local flooding impacts. At the regional scale, flooding does not appear to be a decisive contributor to corn/soybean yield declines, given the 43% overall correlation between the two (Shirzaei et al., 2021). This is linked in one of (Shirzaei et al., 2021)'s take-home messages, that "technological, biological, and environmental [factors] can act in concert" alongside flooding to affect regional crop yields each year. Additionally, the mere occurrence of flooding is not enough to lead to significant crop impacts. As explained in section 2.2.1 of this paper, it takes around 2—3 days for waterlogging to cause a >20% reduction in yields, and soybeans may be more vulnerable during the summer, when it is in its reproductive stage (Kaur et al., 2020).

Section 4. Challenges and Recommendations for Future Research

Here provides perspectives on the limitations surrounding the material presented in this paper on assessing extreme/excessive precipitation's impact on Corn Belt crops. Based off the information in the previous two sections, this section examines challenges encountered, discusses elements related to studying the impact that were not brought up in depth (or at all), and recommends future research strategies.

First off, studies, including this paper, use the term *extreme precipitation* as an umbrella term. The term may be used to categorize certain precipitation metrics, such as "R99p" or "Max 5-day" (e.g.: (Troy et al., 2015; Wilson et al., 2022)), or it may be used when discussing large positive anomalies (or high percentiles) on precipitation metrics in general (e.g., standard deviations of total growing season precipitation, hourly precipitation percentiles, normalized daily precipitation) (Lesk et al., 2020; Li et al., 2019; Troy et al., 2015). Sometimes, sources analyze the spread of anomalous precipitation metrics like "Max 5-day", essentially obtaining the extremes of the 'extremes' (Troy et al., 2015). Some articles, particularly if their focus is not on precipitation itself, but on byproducts like flooding, implicitly mention *extreme precipitation* without providing further explanation of the kind they are referring to (e.g., (Lazin et al., 2021; Shirzaei et al., 2021)). It may be beneficial for future papers to clarify the types of precipitation extremes their studies are based upon; otherwise, readers may have to assume that all timescales (i.e., hourly, daily, multi-daily, monthly, seasonally, annually) of precipitation are valid.

The spatiotemporal resolution of extreme/excessive precipitation impacts makes them more complicated to assess than most other meteorological/climatological impacts.

The central U.S. receives a large chunk of their precipitation from mesoscale convective events, particularly during the growing season, resulting in impacts that are more locally variable than extreme temperature and drought events. Because the impacted locations change drastically from event-to-event, there are less available data to analyze extreme precipitation events compared to extreme heat and drought (Li et al., 2019; Rötter et al., 2018; Troy et al., 2015; Wilson et al., 2022). These data limitations prompted most studies in this paper to aggregate local/county-level data to state/national-level analyses to obtain statistically significant results; however, doing so may have masked the local impacts and trends of extreme/excessive precipitation on crops (Lesk et al., 2020; Li et al., 2019; Troy et al., 2015). Future studies should also consider the balance between data representation and physical relevancy when it comes to communicating extreme precipitation impacts.

This paper listed two means by which extreme/excessive precipitation impacts crops: waterlogging/flooding soils and physically damaging the crops to the point of lodging (Li et al., 2019); however, this paper mainly focused on the waterlogging aspect as compared to the lodging aspect. When determining waterlogging potential, the amount/duration/frequency of excessive precipitation is one of the more variable components (i.e., compared to soil properties, crop lifecycles, and, to some extent, temperature), so it plays a big role in influencing when & where waterlogging occurs (Kaur et al., 2020; Lazin et al., 2021; Shirzaei et al., 2021). In contrast, extreme/excessive precipitation is one of several highly variable components when it comes to dictating physical damage. The compound impact of very heavy rain and severe weather (i.e., damaging winds, hail, and tornadoes) must be considered when discussing lodging potential, as each of these variables may be the key damage contributor depending on the event (Lesk et al., 2020; Li et al., 2019). While these severe weather events commonly occur in the Corn Belt, separating the effects of extreme/excessive precipitation from the other components does not appear to be as practical as it is with waterlogging/flooding.

In addition, this paper did not go into detail on any of the physical or dynamical meteorological/climatological processes surrounding extreme/excessive precipitation in the Corn Belt. Linking precipitation climatology observations with relevant synoptic and mesoscale processes in the region, such as mid-latitude cyclone evolution, baroclinic interactions, low-level heat & moisture transport from the Gulf, and (severe) thunderstorm formation may justify and/or provide better diagnostics & prognostics for results such as those in Figs. 9 & 10 (Wilson et al., 2022). Analyzing climate teleconnections may help verify that (Wilson et al., 2022)'s observed extreme precipitation trends are associated with anthropogenic forcings as opposed to internal climate variability. Indeed, a few sources in this paper brought up the Clausius—Clapeyron relationship to explain and/or predict future Corn Belt precipitation trends resulting from global warming (i.e., 7% increase in available water vapor / Kelvin) (Lesk et al., 2020; Wilson et al., 2022).

Some sources in this paper went beyond statistical modeling for extreme/excessive precipitation vs. crop yields. (Li et al., 2019) examined whether process-based crop models could replicate their observed extreme precipitation impacts and found that most of them predicted *positive* corn yields even under >2.5σ total growing season precipitation years. A few sources tried to use machine learning techniques, like (Lazin et al., 2021)'s convolutional neural network study, to evaluate the usefulness of meteorological and/or remote sensing predictors on predicting extreme precipitation/flooding impacts on crop production. This paper did not have time to cover these techniques in detail, but it warrants further study on prediction-based experiments to see if current scientific knowledge can establish connections with them.

Plant adaptation mechanisms to waterlogging were outside the scope of the previous two sections because of their heavy involvement in the biology and botany fields, but they may serve well in explaining the physiological responses that (Kaur et al., 2020) recorded in their tables for corn and soybean. Knowing more about these mechanisms (e.g., adventitious root growth, aerenchyma tissue formation, stem hypertrophy) and how they may vary depending on the environment or crop may assist in finding waterlogging-resistant crop cultivars that would reduce the impact of extreme precipitation on Corn Belt crops (Kaur et al., 2020; Manghwar et al., 2024). Other mitigation and adaptation strategies, such as irrigation, artificial drainage, and no-tillage practice are likely influencing the overall Corn Belt crop response to excessive precipitation (Datta et al., 2017; Kaur et al., 2020; Liu & Basso, 2020; Manghwar et al., 2024).

Section 5. Conclusions

The sources reviewed in this paper helped to gather insight on how, and to what extent, extreme & excessive precipitation impacts corn and soybean in the U.S. Corn Belt. In general, southern Corn Belt locations receive the most amount of total and heavy precipitation (i.e., R95p, R99p, RX1day) annually. While locations in the western Corn Belt receive less total annual precipitation, a larger share of it comes from heavy precipitation compared to the eastern Corn Belt. Regional decadal trends in both total and heavy precipitation are not uniform, which prompts further examination for any deterministic cause by the changing climate. Several soil properties associated with soil moisture, such as soil texture, permeability, and bulk density can visually explain, to an extent, the drainage capabilities of the Corn Belt. Corn and soybean yields appear to be adversely affected by waterlogging after ~2 days, suffering quasi-linear declines with each additional day of waterlogging. Corn appears to be most sensitive to waterlogging in the early vegetative stages, while soybean seems to be most sensitive in the reproductive stage. Nevertheless, Corn Belt soils are most prone to waterlogging/flooding during the first two months of the growing season when soil moisture stored during the preseason is still high.

Modeling studies showed, in general, precipitation does not adversely impact corn or soybean until anomalies (seasonal, daily, or hourly) go above at least 2 standard deviations. The worst impacts, however, are saved for anomalies that go above the 99^{th} percentile. The north-central Corn Belt has historically seen the most negative impacts by high anomaly precipitation events, but the expected return period for significantly negative impacts anywhere in the Corn Belt is around 10 years, under current climate conditions. This return period may decrease under a warming climate. Extreme/excessive precipitation and flooding impacts on Corn Belt crops are localized phenomenon, as the signal for both weakens when viewing it on the regional scale. Recommended research beyond this paper includes determining extreme precipitation's influence on crop lodging, tying physical/dynamical meteorology/climatology into observed extreme precipitation trends, investigating plant adaptation mechanisms to waterlogging, and assessing the effects of mitigation & adaptation strategies by agricultural management (ex: artificial drainage).

Determining the quantitative impact that extreme & excessive precipitation have on Corn Belt crops will help communicate the level of concern of these impacts to agricultural management teams. With the constant threat of extreme drought and heat, management teams must determine the relative risk that each may bring each year to properly allocate water and nutrients to crops that will most likely need them. For flooding and extreme precipitation, the best plans of action may be needed at the local level, as compared to extreme heat and drought, whose impacts tend to be more regionally uniform. If future extreme/excessive precipitation impacts can be estimated, managers may implement mitigation and/or adaptation plans to adjust to new flooding and/or lodging risks. Optimal preparation for climate extremes is one way to ensure a productive and efficient Corn Belt that may continue to provide its crops to the world.

References

Berry, P. M., Sterling, M., Spink, J. H., Baker, C. J., Sylvester-Bradley, R., Mooney, S. J., Tams, A. R., & Ennos, A. R. (2004). Understanding and Reducing Lodging in Cereals. In Advances in Agronomy (Vol. 84, pp. 217–271). Academic Press. https://doi.org/https://doi.org/10.1016/S0065-2113(04)84005-7

Datta, S., Stivers, J., & Taghvaeian, S. (2017). Understanding Soil Water Content and Thresholds for Irrigation Management. https://doi.org/10.13140/RG.2.2.35535.89765

Hollinger, S. E. (1995). Midwestern Climate Center Soils Atlas and Database. https://www.isws.illinois.edu/pubdoc/C/ISWSC-179.pdf

IPCC, 2023: Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, H. Lee and J. Romero (eds.)]. IPCC, Geneva, Switzerland, 184 pp., doi: 10.59327/IPCC/AR6-9789291691647

Kaur, G., Singh, G., Motavalli, P. P., Nelson, K. A., Orlowski, J. M., & Golden, B. R. (2020). Impacts and management strategies for crop production in waterlogged or flooded soils: A review. Agronomy Journal, 112(3), 1475–1501. https://doi.org/10.1002/agj2.20093

Lazin, R., Shen, X., & Anagnostou, E. (2021). Estimation of flood-damaged cropland area using a convolutional neural network. Environmental Research Letters, 16(5). https://doi.org/10.1088/1748-9326/abeba0

Lesk, C., Coffel, E., & Horton, R. (2020). Net benefits to US soy and maize yields from intensifying hourly rainfall. Nature Climate Change, 10(9), 819–822. https://doi.org/10.1038/s41558-020-0830-0

Li, Y., Guan, K., Schnitkey, G. D., DeLucia, E., & Peng, B. (2019). Excessive rainfall leads to maize yield loss of a comparable magnitude to extreme drought in the United States. Global Change Biology, 25(7), 2325–2337. https://doi.org/10.1111/gcb.14628

Liu, L., & Basso, B. (2020). Impacts of climate variability and adaptation strategies on crop yields and soil organic carbon in the US Midwest. PLoS ONE, 15(1). https://doi.org/10.1371/journal.pone.0225433

Manghwar, H., Hussain, A., Alam, I., Khoso, M. A., Ali, Q., & Liu, F. (2024). Waterlogging stress in plants: Unraveling the mechanisms and impacts on growth, development, and productivity. Environmental and Experimental Botany, 224, 105824. https://doi.org/10.1016/j.envexpbot.2024.105824

Ritter, M. E. (2024). THE PHYSICAL ENVIRONMENT (RITTER). LibreTexts. https://geo.libretexts.org/Bookshelves/Geography_(Physical)/The_Physical_Environment_(Ritter)

Rötter, R. P., Appiah, M., Fichtler, E., Kersebaum, K. C., Trnka, M., & Hoffmann, M. P. (2018). Linking modelling and experimentation to better capture crop impacts of agroclimatic extremes—A review. Field Crops Research, 221, 142–156. https://doi.org/10.1016/j.fcr.2018.02.023

Scott, H. D., DeAngulo, J., Daniels, M. B., & Wood, L. S. (1989). Flood Duration Effects on Soybean Growth and Yield. Agronomy Journal, 81(4), 631–636. https://doi.org/https://doi.org/10.2134/agronj1989.00021962008100040016x

Scott, H. D., J., D., L.S., W., & and Pitts, D. J. (1990). Influence of temporary flooding at three growth stages on soybeans grown on a clayey soil. Journal of Plant Nutrition, 13(8), 1045–1071. https://doi.org/10.1080/01904169009364134

Shah, N. A., Srivastava, J. P., & Shahi, J. P. (2012). Morphological and Yield Responses of Maize (Zea mays L.) Genotypes Subjected to Root Zone Excess Soil Moisture Stress. Plant Stress, 6, 59–72. https://www.researchgate.net/publication/235913180

Shirzaei, M., Khoshmanesh, M., Ojha, C., Werth, S., Kerner, H., Carlson, G., Sherpa, S. F., Zhai, G., & Lee, J. C. (2021). Persistent impact of spring floods on crop loss in U.S. Midwest. Weather and Climate Extremes, 34. https://doi.org/10.1016/j.wace.2021.100392

Soil Survey Staff. (2015). Illustrated Guide to Soil Taxonomy (2nd ed.). U.S. Department of Agriculture, Natural Resources Conservation Service, National Soil Survey Center. https://www.nrcs.usda.gov/sites/default/files/2022-06/Illustrated_Guide_to_Soil_Taxonomy.pdf

Troy, T. J., Kipgen, C., & Pal, I. (2015). The impact of climate extremes and irrigation on US crop yields. Environmental Research Letters, 10(5). https://doi.org/10.1088/1748-9326/10/5/054013

USDA (10 Apr. 2025). Country Summary. *International Production Assessment Division*, Foreign Agricultural Service. https://ipad.fas.usda.gov/countrysummary/Default.aspx?id=US. Accessed 23 April 2025

USDA (12 Mar. 2025). Farming and Farm Income. In Ag and Food Statistics: Charting the Essentials. *Economic Research Service*, U.S. Department of Agriculture. https://www.ers.usda.gov/data-products/ag-and-food-statistics-charting-the-essentials/farming-and-farm-income. Accessed 23 April 2025

USDA NASS (2024a). United States: Corn Production [PNG file]. *International Production Assessment Division,* Foreign Agricultural Service. https://ipad.fas.usda.gov/rssiws/al/crop_production_maps/US/USA_Corn.png. Accessed 22 April 2025

USDA NASS (2024b). United States: Soybean Production [PNG file]. *International Production Assessment Division,* Foreign Agricultural Service. https://ipad.fas.usda.gov/rssiws/al/crop_production_maps/US/USA_Soybean.png. Accessed 22 April 2025

USDA-NRCS. (2022). Land Resource Regions and Major Land Resource Areas of the United States, the Caribbean, and the Pacific Basin (Vol. 296). U.S. Department of Agriculture. https://www.nrcs.usda.gov/sites/default/files/2022-10/AgHandbook296_text_low-res.pdf

Wilson, A. B., Avila-Diaz, A., Oliveira, L. F., Zuluaga, C. F., & Mark, B. (2022). Climate extremes and their impacts on agriculture across the Eastern Corn Belt Region of the U.S. Weather and Climate Extremes, 37. https://doi.org/10.1016/j.wace.2022.100467