Is Snow Drought a Messenger for the Upcoming Severe Drought Period? A Case Study in the Upper Mississippi River Basin

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Highlights

- Snow drought has had an increasing trend in the Upper Mississippi River Basin since 1980.
- Agricultural droughts that took place after 2000 occurred during the La Nina years.
- Spatial estimation of agricultural drought can be obtained when snow drought and water deficit maps are combined.

Abstract

The exacerbation of floods and the extension of droughts, attributed to climate change and other human-induced factors, are posing a substantial risk to communities by causing water scarcity and insecurity. The significance of safeguarding water resources and managing them is increasingly gaining prominence. Snow is an efficient source of water for recharging groundwater compared to rainfall. This is attributed to its gradual melting process and capacity to infiltrate the soil, thereby providing sustenance to the groundwater. Thus, snow drought can be considered a major contributing factor to the issue of water scarcity. The objective of this study was to investigate the evolution of snow drought over the period spanning from 1980 to 2022, as well as its impact on agricultural drought across the Upper Mississippi River Basin (UMRB). This research employed the AgERA5 reanalysis gridded data at surface level with a spatial resolution of 0.1°, obtained from the European Center for Medium-Range Weather Forecasts (ECMWF), to assess the snow drought. An analysis is conducted for comparison between the spatial estimations of snow drought in the UMBR and two other drought indicators, namely the evaporative demand drought index (EDDI) and water deficit amounts. The effects of the El Niño and La Niña phenomena on the UMRB as well as the results of the summer drought conditions were reviewed. The results point to two important findings. The former is that the snow-drought-affected zones show an increasing trend from the past to the present in the UMRB. The latter is that severe snow droughts in the winter of a water year trigger severe agricultural droughts in the summer months of the same water year. It is seen that monitoring snow droughts is as essential as following rainfall regimes in the planning of water resources, agricultural production, and irrigation methods.

1. Introduction

Snow cover has significant effects on the regional and global climate. Because it reflects up to 80% of incoming solar radiation, it helps keep the environment cool (Zhang, 2005). The loss of snow cover on the surface absorbs solar energy, which exacerbates the warming of the climate (Räisänen, 2016). Snow also plays a crucial role in water resources (Qi et al., 2020), wildlife (Johnston et al., 2021; Reinking et al., 2022), forest fires (Alizadeh et al., 2021), and recreational activities (Hatchett and Eisen, 2019). A lack of snow accumulation in the winter season is defined as a "snow drought" (Harpold et al., 2017; Huning and AghaKouchak, 2020). Drought is a very complex and insidious multidimensional extreme hydroclimatological phenomenon that has many negative impacts, not only on the community (Kiem and Austin, 2013), but also on agricultural production (Madadgar et al., 2017) and environment (Contosta et al., 2019). Agriculture suffers from drought events, and agricultural drought can be defined as a deficiency of soil water content in the crop root zone (Narasimhan and Srinivasan, 2005). According to EM-DAT (2022), it is estimated that total damage from the drought in the UMRB has reached over $40 billion.

The 6th Assessment Report (AR6) published by the Intergovernmental Panel on Climate Change (IPCC) has emphasized that there has been an increase in the severity and frequency of extreme hydrometeorological and climatological events (Pörtner, 2022). In addition, an increasing population has put significant pressure on water resources. It is also reported that snow accumulation will decrease (Dierauer et al., 2021; Hatchett et al., 2022) under different future climate projections (Stresha et al., 2021) and at different snow-dominated watersheds (Sproles et al., 2017; Nolin et al., 2021). A study by Notaro et al. (2014) simulated that snowmelt is expected to occur earlier with the increase in air temperature (between 3.5 and 6°C) in the Midwest for the 21st century under different optimistic and pessimistic climate change scenarios. They also indicated that the largest reductions in snowpack will occur in the Upper Midwest. Zhu et al. (2022) quantified the projected snowpack insulation and snowmelt impacts on winter wheat yields for the years between 2080 and 2100.

In recent years, the number of snow-related studies has increased in literature. Most studies have indicated that trends in snowfall and the snowfall/precipitation ratio (S/P) have been decreasing (Feng and Hu, 2007). Snow drought can be experienced when there is below-average precipitation (*dry snow drought*), above-average temperatures (*warm snow drought),* or both (*warm+dry snow drought*) in winter (Harpold et al., 2017; Dierauer et al., 2019). Snow droughts reduce streamflow, cause water supply shortages, and diminish groundwater quality and quantity (Huntington and Niswonger, 2012; Godsey et al., 2014). Its impacts on streamflow (Berghuijs et al., 2014) have been investigated in mountainous areas like western North America (Dierauer et al., 2019; Barsugli et al., 2020), the Cascades (Cooper et al., 2016), the Italian Alps (Colombo et al., 2022), and the American Cordillera (Rhoades et al., 2022) with a remote sensing approach for operational use (Shamir and Georgakakos, 2014; Lou et al., 2021).

Some studies have shown that the lack of or limited snow accumulation in winters plays an important role in the following period of streamflow (Dierauer et al., 2018) and its predictability during drought periods (Modi et al., 2022), and groundwater recharge and its monitoring (Sit et al., 2021). Understanding snow accumulation is an important factor for flood forecasting (Krajewski et al., 2021; Muste et al., 2022) and mapping (Li et al., 2022) to support mitigation (Alabbad et al., 2022) and agricultural planning decisions (Yildirim and Demir, 2022). Earlier snow disappearance has increased the possibility of wildfire and tree mortality (Hall et al., 2015; Gergel et al., 2017; Bales et al., 2018), negatively impacted agricultural activities (Moursi et al., 2017; Qin et al., 2020; 2022), reduced water transit time (Segura, 2021), and affected the community as well (Musselman et al., 2021). Moreover, changing sowing dates of major crops (corn and soybean) cause crop biomass and yield fluctuations (Abendroth et al., 2017; Baum et al., 2019; Lou et al., 2021). Li and Wang (2022) found that 35% of snow droughts were followed by heatwaves during 1981–2020. These snow impact studies show that snow-related analysis need to be conducted in different vulnerable basins and shared using watershed information systems for planning and management (Demir and Beck, 2009).

Reanalysis data sources (i.e., ERA5, ERA5-Land, NCEP/NCAR) have been investigated to determine the representativeness of the snow product. Lei et al. (2022) compared the snow depth observation with ERA5, ERA5-Land, MERRA-2, and MODIS data over the Tibetan Plateau. They mentioned that reanalysis data with fine resolution has better consistency with observation, and ERA5-Land matches in-situ measurements better than other data sources. Alonso-Gonzalez et al. (2022) assessed the performance of SWE observation with the abovementioned reanalysis products in the Upper Euphrates. Their findings highlighted that ERA5-Land data had promising results compared with limited observations. In addition, ERA5-Land reanalysis SWE data have performed well in comparison with other gridded data development efforts (Yoon et al., 2022), including diurnal quantification of the surface energy balance over the Canadian Prairies (Betts et al., 2019). Mortimer et al. (2020) evaluated the different gridded SWE data sources, and their findings showed the ERA5 products had low error and high accuracy.

In this study, the Evaporative Demand Drought Index (EDDI) was selected as an agricultural drought indicator. EDDI was developed (McEvoy et al., 2016; Hobbins et al., 2016) to measure the signal of wildfire danger, floods, and droughts. EDDI has been tested in capturing the flash drought at global scale (Hoffmann et al., 2021) and over the CONUS (Lesinger and Tian, 2022) and its interactions with teleconnections (i.e., El Niño-Southern Oscillation) in Australia (Parker et al., 2021). There are also some efforts to capture agricultural drought in China (Yao et al., 2018; Wu et al., 2021), South Korea (Won et al., 2018), and the contiguous US (McEvoy et al., 2016; Pendergrass et al., 2020) for major agricultural crops like corn, winter wheat, and soybean (Goble et al., 2022). EDDI was also compared with other common drought metrics (i.e., Standardized Precipitation Index - SPI, Evaporative Stress Index - ESI, and US Drought Monitor - USDM). Operational drought monitoring systems can benefit from EDDI's representativeness and usefulness (McEvoy et al., 2016; 2019; Nogueera et al., 2021). Dewes et al. (2017) assessed the drought risk under different climate scenarios over the CONUS with SPEI and EDDI. Furthermore, Pendergrass et al. (2020) declared that snow and flash droughts might be related and require attention.

The UMRB, which is composed of Illinois, Iowa, Minnesota, Missouri, and Wisconsin states, is a habitat for a wide variety of aquatic creatures and mammals, a flyway for more than 300 kinds of birds, a fishery area, a water source, and a basin that covers a major part of the Corn Belt. In short, a drought in the UMRB will have a very serious impact on a wide variety of ecosystems and environmental fields. The aim of this study is to reveal the change in snow drought in the UMRB over time and analyze its effect on agricultural drought. Since 2000, according to data from the National Oceanic and Atmospheric Administration (NOAA, 2022), the years with severe and extreme summer droughts in the UMRB are 2000, 2012, 2017, and 2021. After 2000, the years in which severe and extreme agricultural droughts were experienced in the UMRB were selected for this study. This is unique study in which the relationship between the droughts in these years and the snow drought in the current water year has been investigated for the UMRB.

This paper is structured as follows: Section 2 explains the study area, data, and methodology to define the snow drought, agricultural drought, water deficit, and trend analysis. The results of the snow drought and its impacts on the following summer drought can be found in Section 3. Some suggestions and evaluations were provided in Section 4.

2. Materials and Methods

2.1. Study Area

The study was conducted in the Upper Mississippi River Basin (UMRB) at HUC2 level, which covers important agricultural lands (e.g., the Corn Belt) for soybean and corn production between the years 1979 and 2022. Besides, this basin has a variety of biodiversity and is home to many endemic species (King et al., 2021). According to the 10-meter spatial resolution land use/land cover map based on Sentinel-2 (Karra et al., 2021), percentages of croplands and trees were calculated as 58.5 and 25.6, respectively. The percentage of the built area was also calculated at 6.5. There are dense forest areas in the northeast (mostly Wisconsin and Minnesota) of the UMRB and some forest areas in the southern parts (Missouri) (see Figure 1). In the central part of the study area, there are intensive agricultural areas.

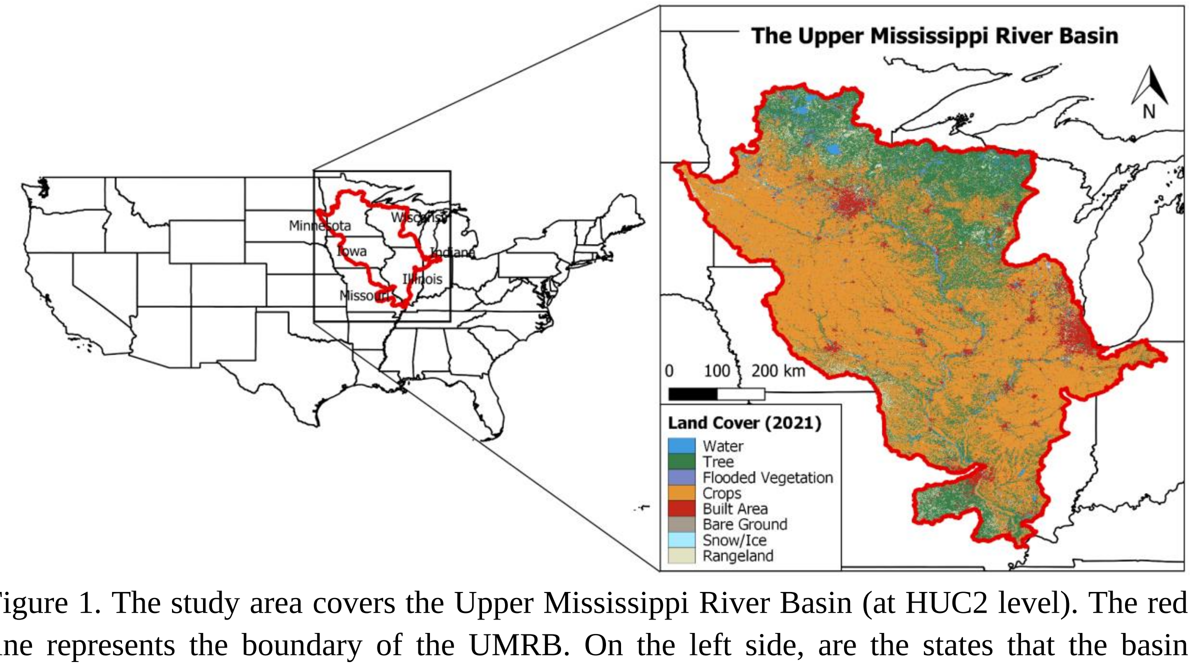

Figure 1. The study area covers the Upper Mississippi River Basin (at HUC2 level). The red line represents the boundary of the UMRB. On the left side, are the states that the basin encompasses.

2.2. Data Collection

In this study, snow water equivalent (SWE, mm/day), rainfall (mm/day), and mean air temperature (°C/day) were downloaded from the European Centre for Medium-Range Weather

Forecasts (ECMWF) AgERA5 reanalysis gridded data at surface level with 0.1° spatial resolution between the years 1979 and 2022. (Boogard et al., 2020). ERA5-based reanalysis data have been scientifically accepted and used as real data in snow (Betts et al., 2019; Alonso-Gonzalez et al., 2022), drought (Kelebek et al., 2021), and both (Habibi et al., 2021; Cammalleri et al., 2022). To calculate snow drought, daily SWE were converted to seasonal maximums, while daily total rainfall data were converted to seasonal totals. Thawing degree days were also calculated with the daily mean air temperature. All seasonal data were compared to the long-term mean to characterize snow drought events. To capture historical drought events, the Evaporative Demand Drought Index (EDDI) and potential evapotranspiration (PET) data were obtained from the University of Idaho's gridded meteorological data (gridMET). The daily gridMET data (Abatzoglou et al., 2013) covers the contiguous US with a 4-km spatial resolution. In addition, the Oceanic Niño Index (ONI) was obtained to capture El Niño and La Niña years in the Niño 3.4 region (5°N-5°S, 120°-170°W) and investigate the impacts on the UMRB of the summer drought conditions.

2.3. Snow Drought Calculation

There have been several attempts to categorize snow droughts in the literature. First of all, the snow drought was classified as below-average precipitation (Ludlum, 1978; Wiesnet, 1981). Harpold et al. (2017) proposed a simple classification scheme that was based on the April 1st SWE and November to April cumulative precipitation. Hatchett and McEvoy (2018) discussed that SWE on April 1st cannot capture snow drought conditions because of its spatiotemporal variability. Dierauer et al. (2019) suggested a new approach that uses daily SWE, precipitation, and air temperature variables. This classification method was used in this study. Because snow melting and accumulation are more sensitive to thawing degrees than to average winter temperatures (Dierauer et al., 2018). In this study, snow drought was calculated as follows (Eqs. 1-3):

$$if\ \{(SWE_i < \overline{SWE})\ \&\ (P_i < \bar{P})\ \&\ (TD_i < \overline{TD})\}Drought_{type} = DRY \tag{1}$$

$$if\{(SWE_i < \overline{SWE})\ \&\ (P_i > \bar{P})\}Drought_{type} = WARM \tag{2}$$

$$if\ \{(SWE_i < \overline{SWE})\ \&\ (P_i < \bar{P})\ \&\ (TD_i > \overline{TD})\}Drought_{type} = WARM + DRY \tag{3}$$

where SWE_i, P_i, and TD_i are the peak SWE, winter precipitation, and winter thawing degrees in year *i*, respectively. $\overline{SWE}$, $\bar{P}$, and $\overline{TD}$ are the long-term means. Thawing degrees (°C) are calculated as the sum of average daily temperatures for all winter days with a mean daily temperature above 0°C. $Drought_{type}$ represents the type of snow drought. Snow drought calculations were made for the months from October to April in every water year between 1979-1980 and 2021-2022.

2.4 Summer Drought Condition

The Evaporative Demand Drought Index (EDDI) is a metric employed in the monitoring of drought and the implementation of preemptive alert systems (van Ginkel et al., 2021). The EDDI metric integrates multiple atmospheric variables, including humidity, temperature, wind speed, and solar radiation, to assess the atmospheric evaporative demand (McEvoy et al., 2019).

This indicator is crucial for evaluating crop productivity (van Ginkel et al., 2021) and water resource management (Hobeichi et al., 2022). The EDDI issues a notification regarding drought conditions when the atmospheric requirement for evaporation surpasses the standard range, as determined by the prevailing climatic conditions in the area. In contrast to alternative drought metrics such as reduced precipitation or elevated temperatures, the Evaporative Demand Drought Index (EDDI) quantifies atmospheric drought (Won et al., 2020).

We also determined the water deficit with PET-P_{eff} (Potential Evapotranspiration – Effective Precipitation) over the region. Potential Evapotranspiration (PET) and Effective Precipitation (P_{eff}) are both important hydrological variables that are used to estimate water balance and drought conditions in a region (Maréchal et al., 2022). P_{eff} (mm/day) is the amount of precipitation that contributes to soil moisture and can be used by plants for growth and other purposes. It is calculated by the USDA-SCS method (Eqs. 4 and 5) (Nearing et al., 1989):

$$P_{eff} = \frac{P_{day}(4.17 - 0.2P_{day})}{4.17}, P_{day} < 8.3\ mm \quad (4)$$

$$P_{eff} = 4.17 + 0.1P_{day}, P_{day} \geq 8.3\ mm \quad (5)$$

where P_{day} is the daily total precipitation (mm/day). PET – P_{eff} is more representative of water deficit conditions than precipitation because it reflects the balance between evaporative demand and water supply by precipitation (Helman and Bonfil, 2022).

2.5. Trend Analysis

To detect trends and tendencies in snow drought conditions, the Innovative Trend Analysis (ITA) method, which was proposed by Şen (2012) was applied to the seasonal percentage of affected land. The ITA methodology is provided by a 1:1 trendless line in the Cartesian coordinate system. The ITA involves the partitioning of a given time series into two distinct segments, namely the initial (or first) and subsequent (or second) halves. These segments are then subjected to a ranking process based on an ascending (or descending) order. The scatter plot is generated by plotting the ordered values of the two series on equally scaled vertical and horizontal axes. The resulting straight line constitutes the primary framework of the ITA (Şen, 2012; 2017). Şen's ITA methodology, which is linked to visual attention, has recently been popular in hydrological (Zakwan and Ahmad, 2021) and climatological (Güçlü, 2020) studies in several parts of the world (Thapa et al., 2020; Yeşilköy and Şaylan, 2022).

3. Results and Discussions

The analysis steps of this study can be summarized as follows: Firstly, snow droughts were calculated using data from October to April for each water year according to the methodology developed by Dierauer et al. (2019). In this methodology, snow droughts can be categorized into three classes as dry, warm, and warm and dry (warm+dry). Dry, warm, or dry and warm (dry+warm) snow droughts range from mild to severe. In this step, snow drought maps were plotted for each water year. Secondly, the annual snow drought maps were compared with the EDDI maps for the following months. We also analyzed the PET-P_{eff} for the study area to indicate water deficit conditions comprehensively. The purpose of this step is to analyze the effect of a snow drought occurring in a water year on the following months in the same water year.

Figure 2 shows the mean of the SWE for the first half of the water years (October to April), thawing degree days, and rainfall for the water years between 1979 and 2022. From Figure 2a, it can be seen that the mean SWE is between 40 and 80 mm in the north and northeast of the UMRB, with limited snow accumulation (< 20 mm) in the southern part of the study area. Concordantly, the number of thawing degree days in the south UMRB is higher than in the northern part (Figure 2b). Figure 2c indicates that there is a gradually decreasing transcurrent precipitation trend from the north to the south of the UMRB.

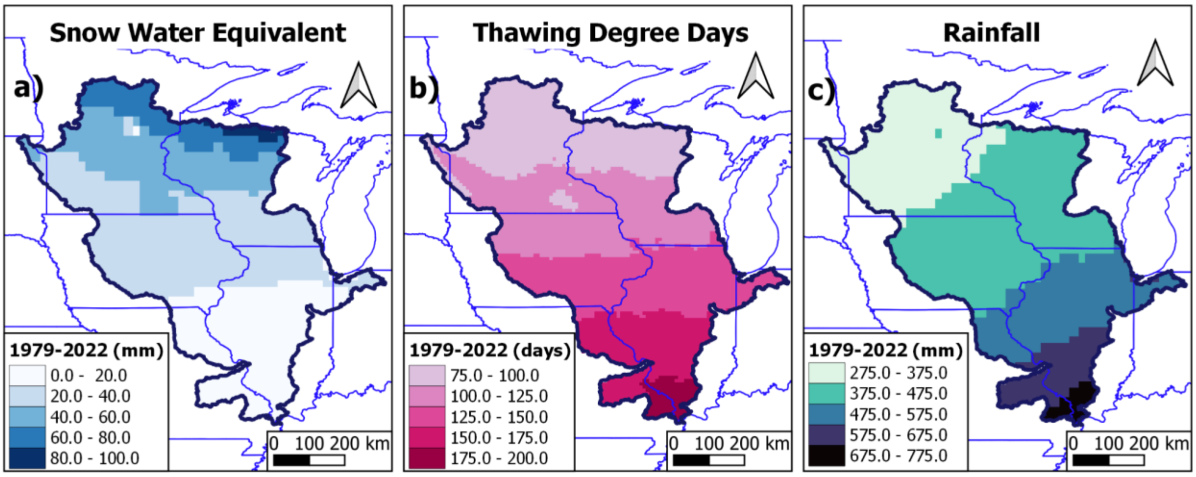

Figure 2. Seasonal (October to April) Mean of SWE, Total Thawing Degree Days, and Total Rainfall for the years between 1979-2022.

Figure 3 shows the percentage of snow-drought-affected areas in the UMRB. According to this figure, it can be said that snow-drought-affected areas in the UMRB have gradually increased between the years 1979 and 2022. Increasing trends in affected lands from the snow drought were detected, and the mean value was calculated as +0.39% per year. The cumulative percentage change over a period of 43 years was determined to be 16.8%. The increase in snow droughts observed over the past 43 years can be attributed to climate change. The absence of a consistent upward trend may be attributed to climate variability. Prior to the year 2000, the maximum estimated incidence of snow drought in the study area was 68%. Since the year 2000, it has been determined that there have been seven water years with snow droughts exceeding the threshold. During the periods of 2011–2012 and 2016–2017, snow droughts were observed in the entire region with a frequency of 100% and 89%, which is the maximum, respectively.

The ITA diagram of the percentage of the affected lands from snow drought from 1979-1980 water years can be found in Figure 4. It can be clearly seen that the data is located on the left side of the graph. There is a monotonic positive characteristic, which can be said to indicate that percentages of affected lands from snow drought have been increasing due to climate change.

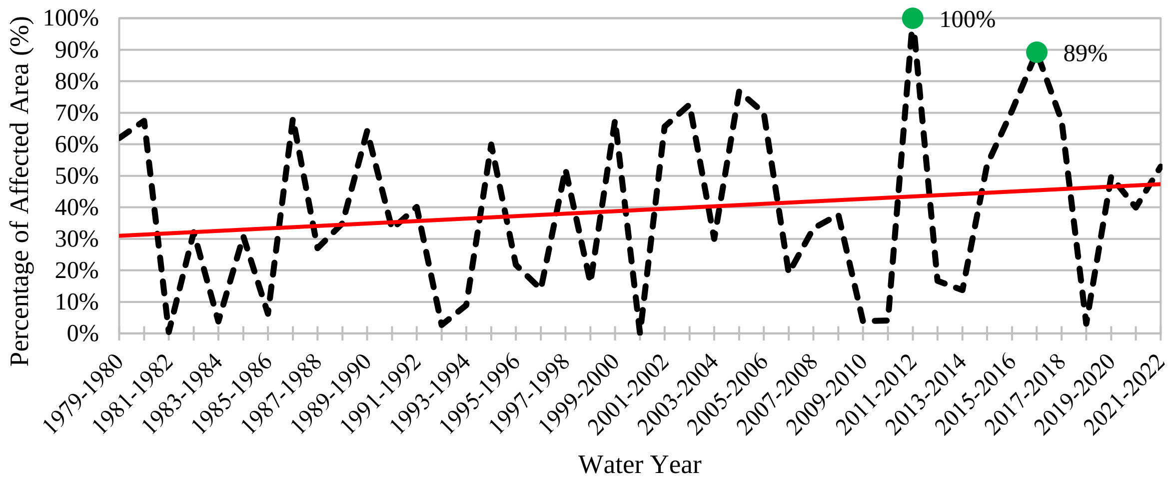

Figure 3. The black dash line is the time series of the percentage of affected areas from the snow drought in the UMRB for 43 water years. The red line represents the trendline of the affected lands. Greed dots represent the 2011–2012 and 2016–2017 water years' values.

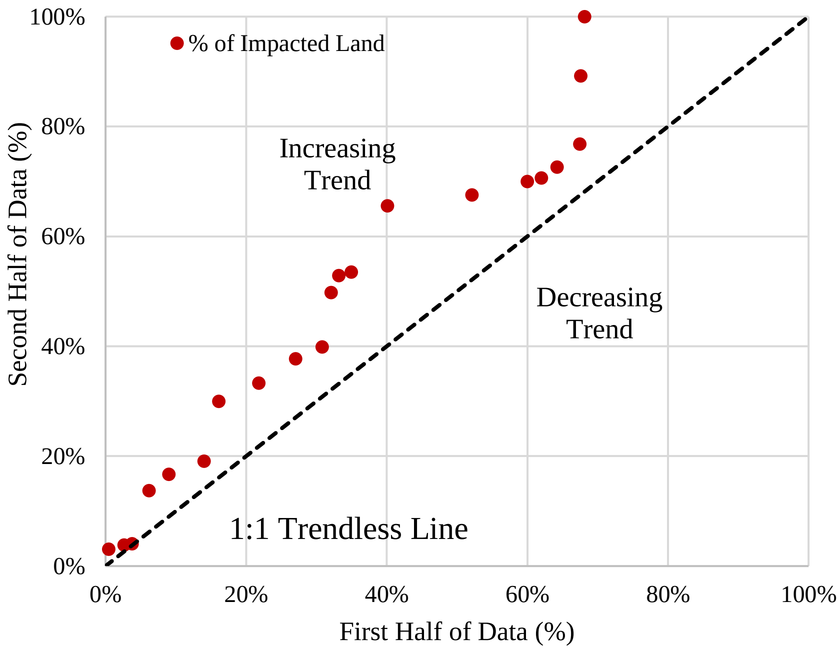

Figure 4. ITA diagrams of Suffered Land Percentage of Snow Drought. The black dashed line represents the 1:1 trendless line. The right side of the graph indicates a decreasing trend, and the left side indicates an increasing trend.

In Figure 5, snow drought, EDDI, and water deficit (PET-P_{eff}) maps for the years when there is agricultural drought in the study area after 2000 are shown. We selected the four significant agricultural drought periods (i.e., 2000, 2012, 2017, and 2021) that the study area experienced after 2000. Throughout the summer of 2000, a significant proportion of the UMRB, specifically 64.7%, encountered a severe drought. Prior to the summer season, a significant portion of the region comprising Minnesota, Wisconsin, Iowa, and the northeastern part of Missouri, amounting to 67.6% of the area, encountered a snow drought characterized by warm and dry (warm+dry) conditions, particularly in areas that typically receive substantial snowfall. The current year has been documented as a strong La Niña year, exhibiting an ONI value of -1.58. Regions exhibiting a discrepancy between snow drought and agricultural drought, such as Wisconsin and eastern Minnesota, demonstrate comparatively lower water deficit values (<300 mm) in contrast to other regions. The present scenario can be argued to offset the impacts of the snow drought in these areas through the occurrence of summer rainfall. The regions in the southern part of the area experiencing drought have water deficit values of 500 mm or greater.

During the summer of 2012, there was a significant drought. During the water year of 2011-2012, it was observed that the region experienced a snow drought characterized by dry and warm (dry + warm) conditions, as well as a La Niña event that ranged from strong to moderate in intensity. Furthermore, exceedingly elevated water deficit values were computed as a result of substantially low summer precipitation and high PET rates within the vicinity. The indicators have led to a significant reduction in crop yields, particularly in corn and soybean, as well as a decline in animal production by approximately 20-25% in the area. According to recent reports, there is an anticipated increase in consumer price index values ranging from 0.5 to 1.0 percent within the upcoming time frame of 6 to 12 months (USDA-ERS, 2012).

In the winter months of the 2016–2017 water year, which aligned with the La Niña period, the majority of the region, specifically 89%, encountered an episode of snow drought. It was found that this significant proportion of the area experiencing snow drought, specifically 86%, experienced warm snow drought conditions, while a smaller proportion of 14% experienced warm and dry snow drought conditions. To clarify, despite the high temperatures during the specified period, the precipitation levels exceeded the mean climate normal. The eastern region of the basin did not experience a shortage of snow. During the summer of 2017, a significant proportion of the region, specifically 48%, experienced a severe drought. The occurrence of a summer drought has been noted in areas where a warm and dry snow drought is prevalent and where the values of PET-P_{eff} are approximately 500 mm or higher. In certain regions, precipitation levels exceed the established climatic norms during the winter season, resulting in a diminished water deficit. Hence, it is possible that the soil's water content level did not decrease to a point where it could be considered a critical threshold for agricultural drought.

In the winter season of the 2020–2021 hydrological year, a large portion of the snow-covered region in the basin encompassing Minnesota and Wisconsin, specifically 39.9%, encountered a warm and dry snow drought, which accounted for 83.7% of the affected area. During this time frame, it was ascertained that a moderate La Niña event had occurred in the Pacific Ocean. The occurrence of an agricultural drought was observed in the vicinity and surrounding areas, which was subsequently followed by a snow drought during the summer of 2021. The primary factor contributing to this phenomenon is the notable discrepancy between the precipitation levels during the summer months and the corresponding PET values. This discrepancy was believed to have played an essential part in the propagation of drought conditions across these areas. The presence of agricultural drought is observed particularly in areas where the value of the water deficit exceeds 500 mm. The absence of agricultural drought in the northeastern region, where snow drought is prevalent, may be attributed to the roughly 300 mm water deficit.

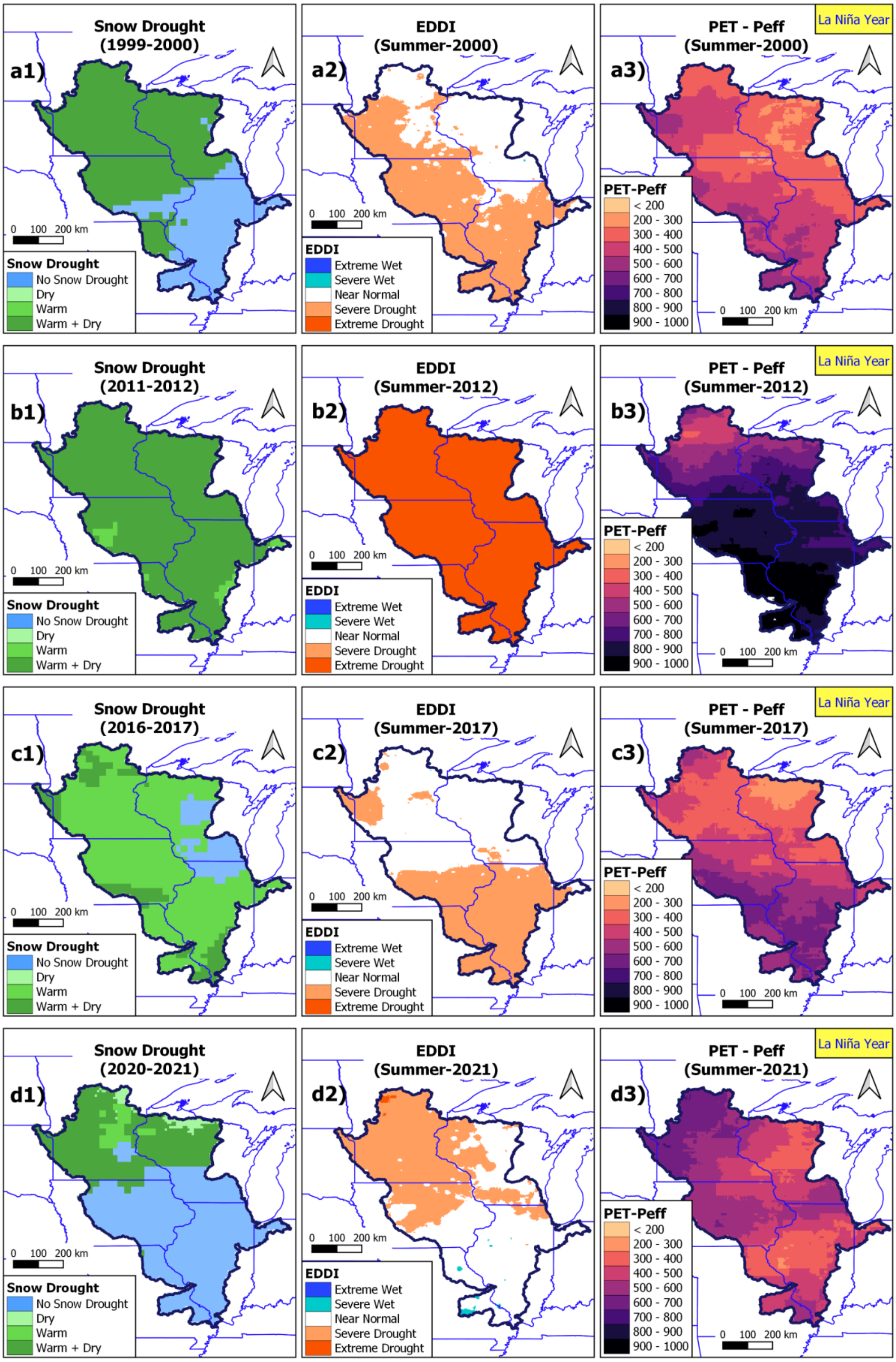

Figure 5 (a-d). Maps of the Snow Drought, EDDI, and PET-P_{eff} for the selected years. The yellow box shows which phase ENSO is in (e.g., El Niño, La Niña or neutral).

4. Conclusion

Snow drought is a form of drought that has a direct impact on the quantity and quality of water, given that snow is among the most crucial water resources. The current study aimed to analyze the long-term occurrence and variability of snow drought and assess its impact on agricultural drought of the following period in the UMRB, which covers 58.5% of agricultural lands (Figure.1).

Snow drought, EDDI, and water deficit maps for every summer drought event were created and compared with each other. The analysis was focused on the correlation between the water deficit and four crucial agricultural droughts that occurred after 2000, during a period of heightened drought severity, as well as the preceding snow drought and associated teleconnections. The observation from Figure 2 indicates that the region underwent a significant agricultural drought during the summer season subsequent to the years 2011-2012 and 2016-2017, which were characterized by the most impactful snow drought in the area. Furthermore, it has been ascertained that La Niña phenomenon transpired during all the phases of snow droughts.

In the literature, snow researchers have found clear evidence about a relationship between climate change and snow drought at different scales (Cooper et al., 2016; Dudley et al., 2017; Dierauer et al., 2018; Mote et al., 2018; Huning and AghaKouchak, 2020). Our findings show that there is an increasing trend (Figure 4) in the snow-drought-affected lands between 1979 and 2022 in the UMRB, which can be related to climate change. It has been determined that the possibility of agricultural drought in a region is quite high, with the deterioration of the soil water balance (Iwata et al., 2010) in the region experiencing snow drought in winter and low precipitation in the following months.

Since 2000, four agricultural drought occurrences (2000, 2012, 2017, and 2021) were selected. For these droughts, EDDI, water deficit (PET-P_{eff}), and snow drought maps were spatially analyzed and compared. The depicted regions in Figure 5 a1, b1, c1, and d1 that range from light green to dark green signify the presence of snow drought, whereas the blue region shows the absence of snow drought. The agricultural drought areas are represented by the orange regions, ranging from light to dark orange, in Figure 5 a2, b2, c2, and d2. The areas exhibiting elevated water deficits ranging from purple to black are those situated above the critical water deficit threshold of 500mm, as identified in Figure 5 a3, b3, c3, and d3.

Upon examining the snow drought, EDDI, and water deficit maps presented in Figure 5, it is evident that a significant proportion of the regions that exhibit snow drought (as indicated by the green areas) coincide with those that experience agricultural drought (as indicated by the orange areas). Regions where there is no overlap between snow drought and agricultural drought exhibit a low level of water deficit. In other words, it was observed that the occurrence of severe and extreme drought is highly probable in regions where the soil water balance is disrupted during winter, owing to the high PET and low P_{eff} (PET-P_{eff} > 500 mm) values recorded during the following period. The reason for this condition is that these particular regions do not experience a water deficit, and consequently, agricultural drought is not observed as a result of receiving ample rainfall during the summer season.

In brief, a significant snow drought may serve as a precursor to a severe or extreme agricultural drought that is likely to transpire in the summer season. In addition, it is noteworthy that the absence of snow drought zones depicted in the snow drought maps does not correspond to the absence of severe or extreme drought zones as illustrated in the EDDI maps. The results enable us to generate snow drought maps that can furnish crucial insights into the agricultural drought for the subsequent summer. Moreover, by taking into account the teleconnection patterns observed during periods of winter snow deficits, it is feasible to make inferences about the probable occurrence of agricultural drought conditions in the ensuing summer season.

The aforementioned information has the potential to make noteworthy contributions to decision-makers, drought planners, and local producers who are seeking to undertake specific actions. Simultaneously with monitoring the occurrence of insufficient snow and associated teleconnections in the region, it is postulated that the possible disruption of soil moisture balance during this period, along with the likelihood of increased PET-P_{eff} values (>500 mm) in the following period, could offer valuable information on the areas where agricultural drought may emerge in the summer season.

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