Impact of the Gannon Storm on corn production across the Midwestern USA

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Abstract

Corn planting progress was behind schedule for several states prior to the Gannon Storm on the weekend of 10 May 2024. Midwestern farms were unusually vulnerable to a signal degradation associated with Global Navigation Satellite System (GNSS) accuracy due to reduced fieldwork days associated with terrestrial weather, delaying planting. Estimating regional losses due to GNSS outage is a multi-step process. First, foregone production due to delayed planting for a representative farm is estimated. Analysis of a representative farm is necessary because no other method is feasible to arrive at the intended metric of number of acres affected by downtime. The second step is to determine the number of farms adversely affected in each state. Third, production losses are calculated for each state then summed into regional estimates. Agricultural data sources includes publicly available USDA statistics and Land Grant University Extension publications. Space weather data sources include the GFZ German Research Centre for Geosciences at Potsdam (GFZ) and the NOAA Space Weather Prediction Center (SWPC). A range of estimates are provided including yield sensitivity to delayed planting, effective planter capacity, and percentage of farms vulnerable to GNSS signal degradation, such that the reader can repeat the analysis to arrive at their own conclusions. One of the leading corn-producing states, Illinois, is used to demonstrate how the analysis and calculations are conducted before reporting across 12 selected Midwestern states. Due to the Gannon Storm, the representative GNSS-reliant corn farm in Illinois experienced foregone revenue between $12,000 and $17,000. Summing across all vulnerable farms in Illinois, production decreased from 3.1M bushels valued at $12.4M to 75M bushels valued at $298M due to delaying planting into later weeks. Applying this analysis to the remaining Midwestern states, between 17.4M bushels to 424M bushels valued at $69.6M to $1.7B, respectively, were foregone compared to the optional scenario in which GNSS-enabled navigation technology remained operational. Valuation assumed $4 per bushel corn price, however, a $5 per bushel price is reflected by adding 25% to the reported valuation. Although affected acreage experienced substantial penalties, when considering across all 90.6M US acres, a negligible one to two bushel per planted acre was at risk. Although unprecedented during the precision agricultural era, the events of 10 May 2024 were not likely unique, such that GNSS signal degradation may occur again in spring planting time of 2025 and into 2026, during the descending phase of Solar Cycle 25. Early warning alerts of GNSS signal degradation may be useful for many practitioners, but not likely sufficient to prevent agricultural production losses due to the complex biological and climatic interaction. However, a nowcast informing practitioners of regional GNSS signal degradation may be useful to prevent frustration, costs of performing local diagnostic tests on equipment, and adverse affects on the joint utility of the rural household. Results are of interest to farmers, commodity traders, grain handling facilities, policy makers, and space weather professionals and enthusiasts.

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In memoriam: Tiffany M. Cookus.

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Introduction

Midwestern farms were unusually vulnerable to additional reduction in suitable fieldwork days associated with terrestrial weather that had delayed planting. Spring corn planting progress was behind schedule for several states prior to the extreme geomagnetic storm (hereafter, referred to as the 'Gannon Storm') on the weekend of 10 May 2024. Global Navigation Satellite System (GNSS) signal degradation associated with the Gannon Storm was unprecedented especially at the specific timing with respect to peak agricultural activities. Lack of GNSS for planting for subset of farms reliant upon the technology led to production and economic losses. Estimating regional losses due to GNSS signal degradation is a multiple-step process that is presented to ensure transparency. Economic logic framework and equations are presented using assumed parameters that are believed to be best available. The interested reader may substitute their chosen parameters to arrive at their own estimates.

Farmers planted 90.6M acres of corn (*Zea mays* L.), 11.7M acres of cotton (*Gossypium hirsutum* L.), 1.8M acres of peanuts (*Arachis hypogaea* L.), 2.9M acres of rice (*Oryza sativa* L.), M acres of sorghum (*Sorghum bicolor* (L.) Moench), 86M acres of soybean (*Glycine max* (L.) Merr.), 1M acres of sugarbeets (*Beta vulgaris*), 33.4M acres of winter wheat (*Triticum aestivum* L.), 10.6M acres of spring wheat, and 2M acres of durum wheat (*Triticum durum* Desf.) in 2024 (USDA NASS, 2025). Long-run average acreage for each crop is somewhat stable over the previous decade (Figure 1).

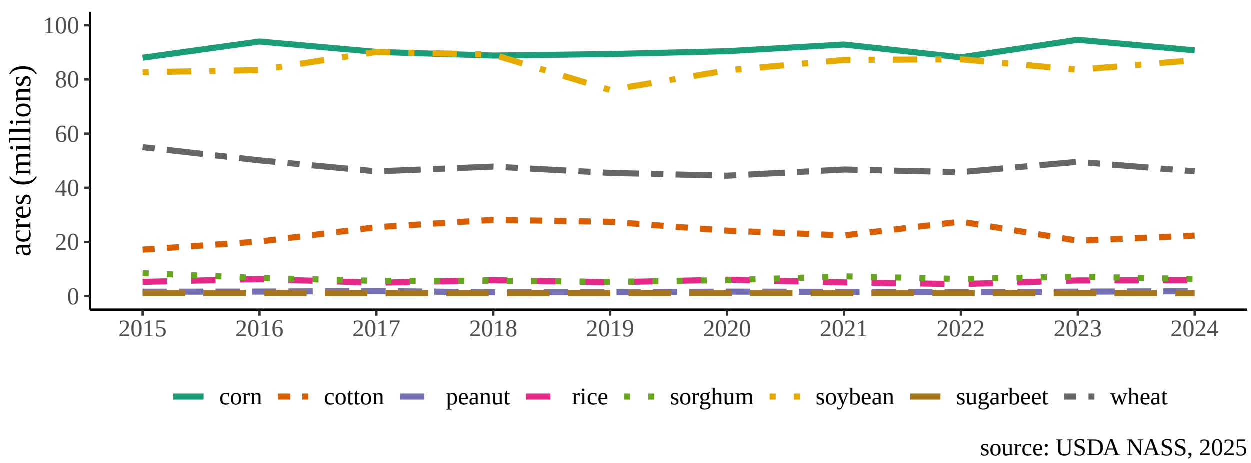
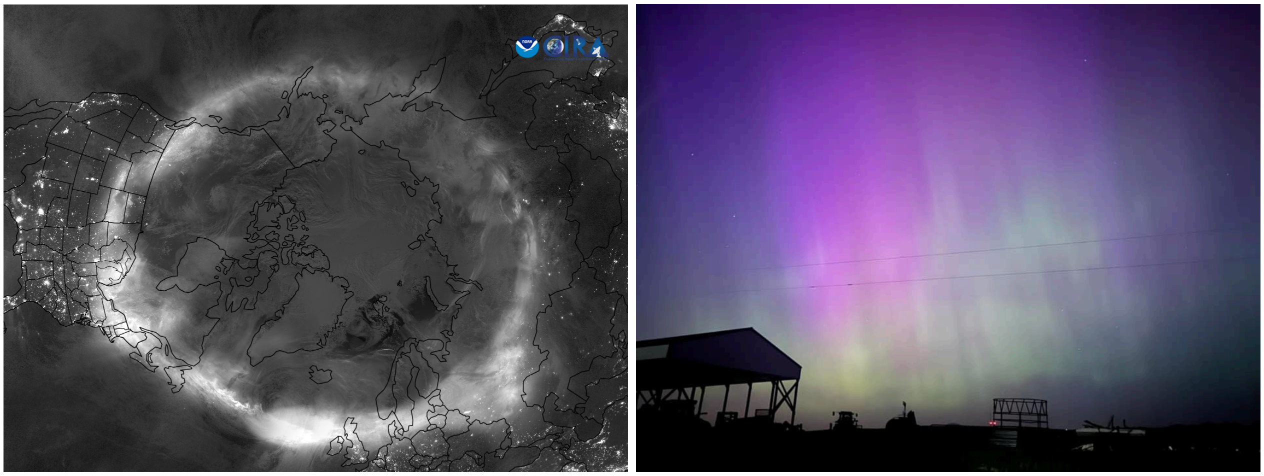


Figure 1: planted acreage, select crops, 2015 to 2024

Solar and Space Weather Background for the May 2024 'Gannon' Event

The strongest geomagnetic storm of the last 20 years commenced on 10 May 2024 (Elvidge & Themens, 2025; Muhlestein, 2024; NOAA SWPC, 2024a). The storm was the culmination of several eruptive events from the Sun that were rooted in two solar Active Regions (AR) designated by the National Oceanic and Atmospheric Administration (NOAA) Space Weather Prediction Center (SWPC) as ARs 10664 and 10668. Both regions contributed coronal mass ejections (CMEs) aimed at Earth. CMEs are eruptions of mass and magnetic field from the Sun's outer atmosphere, called the corona. Such ejecta are particularly potent when traveling at speeds exceeding 600 km s^{-1} that support consolidation during their transit to Earth (e.g., Liu et al., 2024). The measured solar wind speed exceeded 700 km s^{-1} between 10 May and 12 May 2024. The accumulated solar material arrived at Earth in several tangled packets between 10-14 May 2024. Thus, the disturbance(s) in the near-Earth environment lasted for several days as the stored energy in Earth's magnetic field fitfully dissipated. The first packet, arriving on 10-11 May, was the most geoeffective and is the primary focus of this paper. Note that this geomagnetic storm is herein called the "Gannon Storm" in honor of a scientist, Jennifer L. Gannon, who was passionate about the science of space weather (details of her work are documented in Lugaz et al., 2024).

When CMEs disturb and energize Earth's magnetic field there are many paths for dissipating the energy. One of the most obvious and spectacular paths is through the generation of aurora. Because of their intensity and visibility at unusually low latitudes, the Gannon Storm auroral displays lit up the skies and the internet. The so-called auroral oval was observed globally for dozens of hours by polar orbiting satellites, as shown in the auroral oval mosaic of Figure 2a, and regionally by almost anyone who ventured outside in the Midwestern USA. The expanded auroral oval, and the accompanying stable auroral red (SAR) arc (Barbier, 1960; Mendillo et al., 2016), were at the heart of the agriculture-impacting GNSS outages of 10-11 May 2024.



(a) northern lights over the North Pole (b) aurora columns (credit: Brooke Michele)

Figure 2: geomagnetic activity, 11 May 2024

An expanded auroral oval is associated with energetic particles that rain (precipitate) from Earth's magnetosphere to the upper atmosphere. Under mild auroral conditions, precipitation of these keV particles excite neutral atoms and molecules (mostly atomic oxygen) that produce the red and green emissions typical of aurora that human eyes see. Under more severe conditions, the highest energy aurora particles strip electrons from parent atoms, thus adding to the Total Electron Content (TEC) of the ionosphere. Enhanced TEC creates irregularities in the Earth's ionized upper atmosphere (the ionosphere), which affect the propagation of radio signal communications. The frequency of GNSS signals is in the GHz range of radio signals; thus, they interact with small-scale irregularities in the ionosphere. The interaction causes the phase and the amplitude of the radio waves to change or "scintillate", resulting in degraded performance or signal loss of lock (Lamb et al., 2019). Phase scintillations are typically more important in the auroral regions (e.g., Enengl et al., 2024; Spogli et al., 2009; van der Meeren et al., 2015).

On the night of 10 May (early UT hours of 11 May) a series of particularly strong auroral precipitation events occurred over what is generally considered the US corn belt. The image in Figure 2b shows the columns of light created by these particles from an external vantage point in Garwin, Iowa. Inside the columns of light, the ionosphere TEC content sky-rocketed from slightly disturbed values of less than 10 TEC units (TECu) to more than 60 TECu. See Foster et al. (2024) Figure 3 for the US view and Themens et al. (2024) for a northern hemisphere view. Beneath the columns of auroral light in the Heartland, Northern Crescent, and Northern Great Plains, GNSS guidance for spring planting was compromised or non-existent. The unreliable GNSS reception under these conditions lasted for hours as the aurora repeatedly surged during 10-11 May.

The geomagnetic storm was classified as a G5, the highest on the scale reported by NOAA SWPC, and characterized as 'extreme' (NOAA SWPC, 2024b). This characterization was based on observations of peak three-hour disturbances at selected geomagnetic observatories in sub-auroral regions around the globe. The Kp three-hourly index reached the theoretical maximum value of 9 twice during the storm. Recently higher time-resolution Kp-like measurements have been adapted to rate storm severity in 30-minute intervals in a similar, but open-ended index, called Hp30 Matzka, Stolle, et al. (2021). Values as high as Hp30 = 12 were reported during the first several hours of the storm (Figure 3) (Yamazaki et al., 2024). They note the extreme Hp30 value was one of the highest since the mid-1980s.

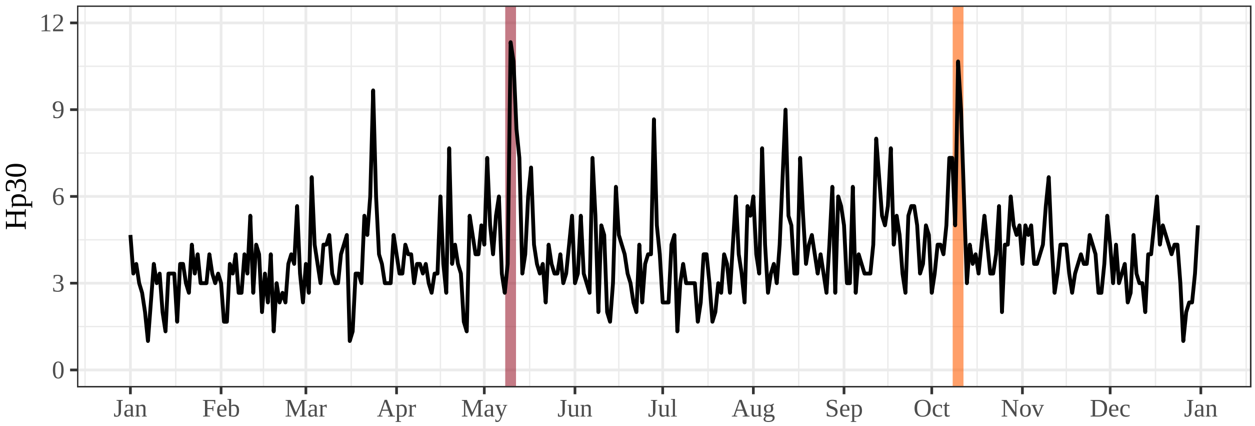


Figure 3: daily maximum of geomagnetic disturbances as Hp30, 2024

While such storm indices provide a general view of the disturbance level, they are global in nature and neither sector-specific nor able to account for the degree of sector-preparedness to mitigate storm effects. The North American power sector has been developing severe-storm mitigation plans for nearly 35 years; the grid fared reasonably well during the Gannon Storm (NERC, 2024). However, sectors relying on space infrastructure, such as spacecraft operating in low Earth orbit (LEO), and sectors relying on precise navigation and timing (PNT) (US DOT, 2024) signals reported more significant impacts during the Gannon Storm. The effects of the strong variations in Global Navigation Satellite System (GNSS) phase measurements used in agricultural applications of GNSS-enabled guidance technologies in the upper Midwestern United States are evaluated.

GNSS in Agriculture

Most technology referred to as precision agriculture was commercialized during the 1990s and 2000s (Figure 10) (Ofori et al., 2020). The commercialization of these technologies coincided with GNSS becoming available for civilian use and Selective Availability being deactivated (NOAA, 2024). Agricultural GNSS-enabled guidance technologies rely on differential correction (dGNSS) to improve relative pass-to-pass accuracy within a few hours and absolute accuracy repeatable months afterward. Differential correction are available from Satellite-Based Augmentation Systems (SBAS) (EU SPA, 2024), local single-tower base stations, and a network of base stations including cellular towers (Teunissen & Montenbruck, 2017). Wide Area Augmentation System (WAAS) is a SBAS developed by the US Federal Aviation Administration for aviation and available for other civilian uses since 2003 (Elrod et al., 2019a, 2019b, 2019c; US DOT, 2023). The free-to-use WAAS-corrected agricultural receivers are used for mapping and guidance for fertilizer applications. Proprietary SBAS correction systems developed specifically for agriculture provide greater accuracy than WAAS, but usually have an activation and/or periodic subscription fee.

Tasks requiring repeatable sub-inch absolute accuracy necessitates real-time kinematic (RTK) capability. The Continuously Operating Reference Station (CORS) system, managed by NOAA's National Geodetic Survey (Stone, 2000), improves accuracy of GNSS. The Virtual Reference Station (VRS) uses existing CORS network to imitate a single-station RTK system. RTK-type systems (e.g. RTK, CORS, VRS) allow both relative and absolute accuracy and have been adopted for agricultural activities requiring sub-inch accuracy such as planter guidance, especially when subsequent in-season applications or harvest operations rely upon known location. Radio RTK systems have a single base station potentially owned by the farmer or otherwise subscribed to for the signal. Proprietary SBAS alternatives include StarFire (SF) SF2 and SF3 from Deere, OmniSTARXP, OmniSTARHP, AFS2 and AFS3 from Case IH, and RangePoint RTX and ViewPoint RTX from Trimble. Network RTK includes SFRTK from Deere, CenterPoint RTK from Trimble, CenterPoint VRS from Trimble, and AFS-RTK+ from Case IH. Deere's receivers are produced by wholly owned NavCom. CIH are produced by NovAtel. OmniSTAR capable receivers are available from a number of manufacturers such as Autofarm, Geneq, Hemisphere GPS, NovAtel, Topcon, Trimble, and Raven. Four GNSS constellations providing global coverage, and in particular for American agricultural purposes, include BeiDou from China, Galileo from the European Union, the Global Position Systems (GPS) from the United States, and GLONASS from Russia (Guo et al., 2018; Teunissen & Montenbruck, 2017).

Regarding accessing more than one GNSS constellation, latitude and masking angle plays an important role in a receiver's ability to access more than one GNSS constellation. Starting at about 35 degrees latitude, inaccuracy increases as latitude increases because of the increasing number of GNSS satellites that appear closer to the horizon. This phenomenon is a consequence of the orbital inclinations of GNSS satellites, which greatly impacts Geometric Dilution of Precision (GDOP) at higher latitudes. For example, Langley et al. (1999) found that at New Brunswick Canada (at a latitude of 46.57 degrees with a masking angle above 15 degrees) GDOP was impacted severely near 0000 UTC time. During this time, the GNSS satellites were nearly aligned and GDOP increased to over 12. Thus, higher latitude operations are more prone to degraded GDOP, increasing the risk for inaccuracies (Langley et al., 1999).

The most recent precision agriculture adoption statistics reported 72% of US planted acreage used automated guidance (McFadden et al., 2023) (Figure 11). Automated guidance systems on harvesters, sprayers, and tractors allow parallel passes such that the equipment operator is not required to make manual adjustments with the steering wheel while traveling through the field, although must turn the equipment around at field boundaries and to avoid in-field obstacles. Integrated GNSS-enabled guidance systems have become standard on new row crop equipment. Automated section control was commercialized after automated guidance and is relevant to liquid boom sections or individual nozzles on sprayers and row shut-offs on planters (Runge et al., 2014; Velandia et al., 2013). Control sections automatically shut off portions of equipment that are in specific sub-field areas that do not need inputs or have already received inputs while remaining sections continue operating on areas where input applications are intended. Although automated guidance reduces reliance on the human operator while mimicking how a human could operate equipment under near-ideal conditions, automated section control performs tasks that are infeasible for humans. Without GNSS, automated section control is inoperative even if planters are able to continue with manual guidance. Given the cost of seed and crop protection chemicals, some farmers may wait until cost saving automated section control technology becomes operational. Larger planters that were able to plant seed into the ground were susceptible to wide and narrow middles, e.g. adjacent equipment passes deviated from the intended row spacing tolerance of $\pm$ a few inches. Straight crop rows without wide and narrow middles have become expected such that social capital in rural farming communities and landowner relations may be adversely affected when expectations are not met.

Agricultural Benefits of GNSS and Implications of GNSS degradation

Some crop-specific production systems benefit more than others from agricultural technology. Automated guidance allows planting row crops such as corn, cotton, and sorghum without physical row markers and therefore provides opportunity for wider equipment use. For underground crops such as peanuts (Roberson & Jordan, 2014) and sugarbeets, matching planting and harvest operations is important for quality and yield. For sugarbeets, RTK is used for planting so that mid-season crop protection chemicals can be accurately applied in the row. For peanuts, RTK automated guidance is used for planting followed by digging during the first phase of harvest. In the past, when manual steering was used instead of automated guidance for digging, yield was reduced by 11% (Roberson & Jordan, 2014). Cereal grains such as wheat and rice may be able to compensate for wide and narrow middles via tillering. Therefore these crops are not evaluated in this study. Although many farms were able to continue planting seeds such that there were no delayed acreage during the Gannon Storm, automated section control was inoperative without GNSS.

The notion of a regional GNSS outage has been considered with respect to agriculture (Bishop et al., 2022; T. W. Griffin, 2010; O'Connor et al., 2019). T. W. Griffin (2010) reported the summation of farm losses across the Midwestern USA could reduce revenues by $500M due to a season-long GNSS outage. Their estimates were based on reversing incremental benefits of adopting automated guidance (T. W. Griffin et al., 2005) using adoption rates and relative profitability during that time. Today, however, the benefits of adopting automated guidance can no longer be modeled as the simple addition of the technology to existing farms but rather as an integral component such that disabling the technology does not simply revert efficiency back to pre-adoption levels. An outage may halt many farming activities such as planting, application of inputs, and possibly harvest especially with respect to georeferencing logged sensor data. O'Connor et al. (2019) reported the agricultural sector benefited by more than $5.8B due to precision agriculture up through 2017; with an estimated $8.5B revenue loss if GNSS failed during corn planting or $15B for all six evaluated crops. They estimated the absence of GNSS would cost $1B per day with 50% additional impacts if the outage occurred during the planting season for summer crops (O'Connor et al., 2019). They listed space weather as one of several potential sources of a GNSS outage. Bishop et al. (2022) explicitly focused on how space weather may adversely affect precision agricultural systems and offered suggestions on nowcasts.

Data and Analysis

US corn production for select Midwestern states is the focus of this report. For illustrative purposes, details for Illinois are provided to demonstrate calculations applied to all pertinent states. In Illinois, farmers planted 10.8M acres of corn in 2024 (Table 15) (USDA NASS, 2025). In 2023, Illinois farmers produced 2.3B bushels of corn valued at $10.8B (USDA NASS, 2025). A bushel is a volumetric unit that weighs 56 pounds for corn. Across the US, corn for grain was valued at $73.9B in 2023.

Corn is grown in all 50 states but is concentrated across the Midwestern USA (Figure 4). Of the 94.6M acres of corn, 78M (83%) are planted in these 12 states. Production per acre, e.g., yield, varies across the US due to climatic factors, latitude, and inherent soil productivity; therefore, state-wise analysis is conducted due to likelihood of degradation affecting locations differently rather than uniformly across the entire Continental United States (CONUS). Rather than presenting results for each state individually, specifics for Illinois are presented as an example of the logic being applied across the remaining Midwestern states.

Agricultural Situation prior to and during the Gannon Storm

For context, many Midwestern states were already behind planting schedule prior to the onset of the Gannon Storm. In Illinois, days suitable for fieldwork during the three weeks leading up to the Gannon Storm were at or near the 25^{th} percentile and below the median for an additional 3 weeks (Figure 6). A day suitable for fieldwork is defined as a day "where weather and field conditions allowed producers to work in fields a major portion of that day" (USDA NASS, 2018). Fieldwork days are applicable to all crops grown in the respective state for any within-field activity during that time, e.g., tillage, planting, spraying, harvesting. Modeling agricultural processes usually requires evaluating events occurring during specific weeks of the year. In 2024, May 10 fell during week number 19 that ended on Sunday 12 May 2024. Since suitable days for planting are a function of precipitation deviation from the normal, reduced fieldwork days led to delayed planting progress relative to the 5-year average (Figure 8). Percentage progress relate to acreage of field activities (USDA NASS, 2018).

Given that planting progress was behind schedule by Week 19 (Figure 8), any anticipated excess equipment capacity had already been exhausted. Under these conditions, additional downtime led to late planting that is associated with lower crop yields. Although corn planting progress caught up to long-term averages by week 21 ending Sunday 26 May 2024, some amount of acreage had been delayed from 10 May to individual farm's final day of planting.

Most states were behind average progress during Week 18; the exception being Missouri that was 1% ahead (Table 1). On average, the 12 states were at 32% planting completion, 11 percentage points behind the average. Over the last 25 years, 2024 ranked 15th with respect to planting progress. In Illinois, corn planting progress was ranked 18th and Nebraska was ranked 22 out of 25 years. In Illinois, corn planting progress averaged 57% by end of Week 18 since 2000; but was only 32% complete in 2024. Relative to Week 18, planting progress was further behind by end of Week 19 (Table 2). Not all states were behind planting

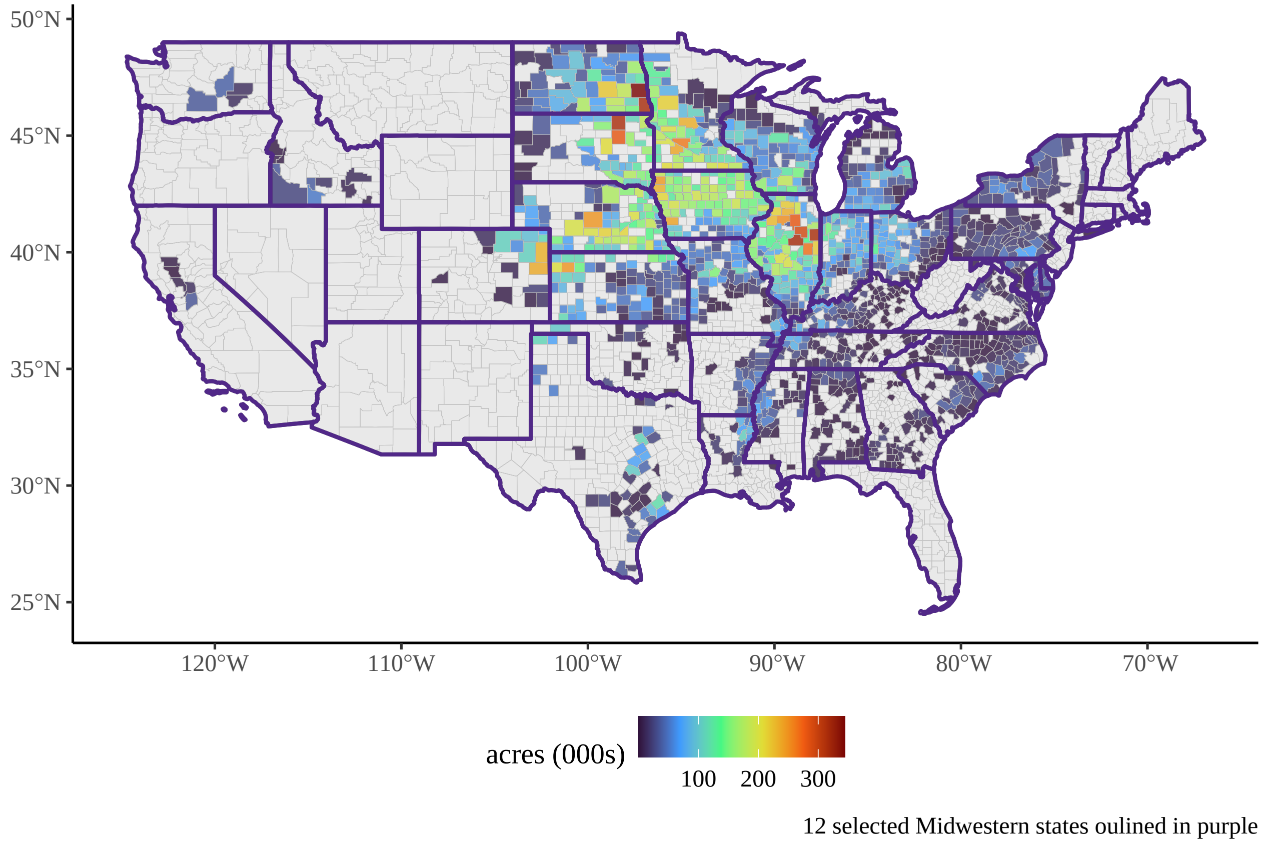


Figure 4: corn planted acres by county, 2023

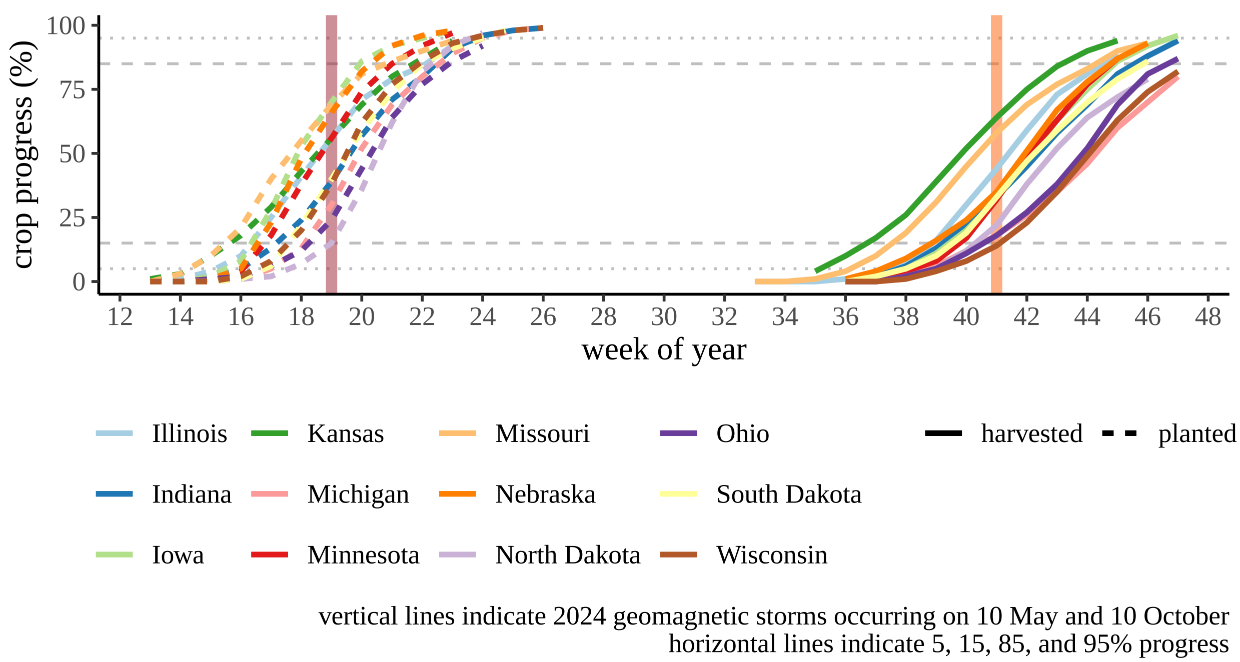


Figure 5: corn planting and harvest progress, 5-year average

schedule. Illinois, Iowa, and Nebraska were behind the 5-year average but Kansas, Missouri, North Dakota, and Ohio may have been slightly ahead of schedule (Figure 9). Planting progress in Indiana, Michigan, and Wisconsin were similar to respective 5-year averages.

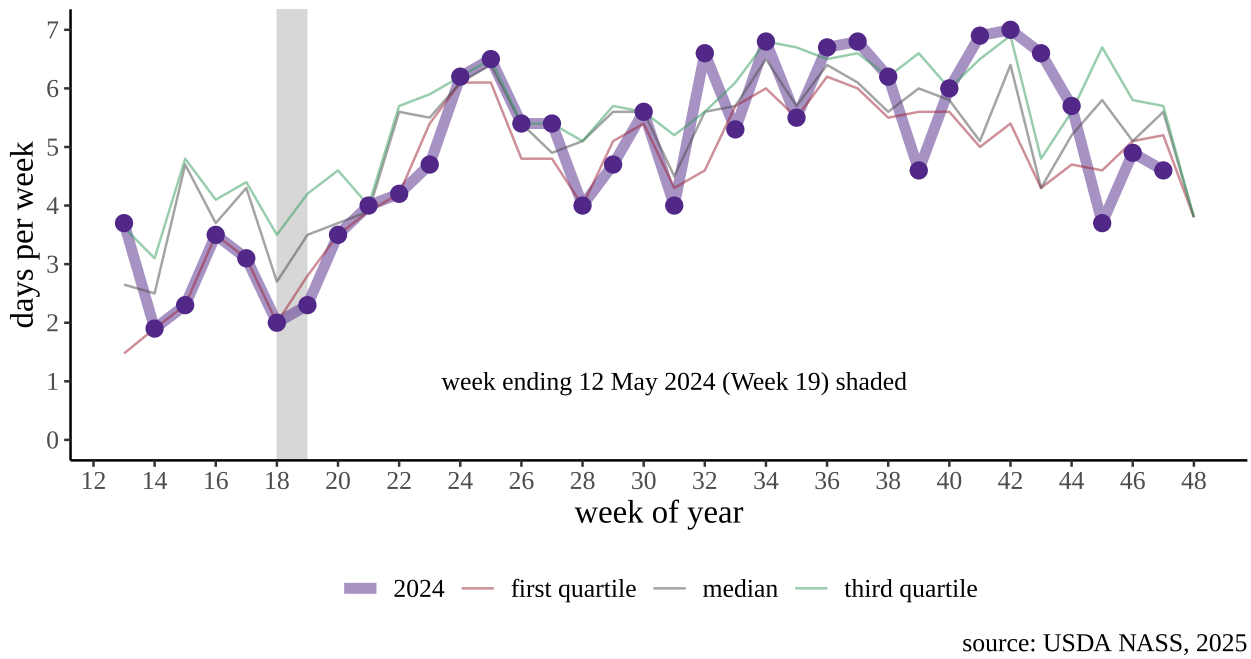


Figure 6: fieldwork days, long-term probabilities versus 2024, Illinois

Days suitable for fieldwork were not impacted by GNSS signal degradation given that equipment were able to enter the field to conduct fieldwork. Conversely, planting progress statistics may have been affected by GNSS degradation. The Gannon Storm occurred during peak corn planting time for many states (Figure 5). Although GNSS degradation occurred in the middle of corn planting, sufficient time may not have been available to plant the displaced acreage without additional yield penalties associated with delayed planting. Even though the acreage intended to be planted on 10 May 2024 may have been planted later that week, some equivalent displaced acreage was planted after anticipated times and possibly during a week with more severe penalties.

The susceptibility of automated guidance to GNSS signal degradation may have been associated with the source of differential correction. Radio RTK and WAAS were reported to be more susceptible than proprietary subscription-fee SBAS and network RTK systems (Paulson et al., 2024). Network-based RTK systems have many ground-based stations that were anecdotally reported to be less susceptible than single-tower radio RTK. Although pass-to-pass accuracy was degraded on 10 May 2024, some SBAS remained within operational criteria for planting operations. Receivers able to access more than one GNSS constellation may have been less susceptible during signal degradation (Biswas & Paul, 2021; Paul et al., 2017).

Farmers across several states reported GNSS degradation beyond acceptable limits, effectively manifesting as an outage, on the afternoon of 10 May 2024 with lingering effects into the following two days. Some planters that were intended to be used with GNSS-enabled guidance could still plant seeds into the soil, albeit with crooked rows or increased variability of wide or narrow middles, however, automated section control technology such as row shut-offs were inoperative without precise location information. Eyewitness accounts by farmers are consistent with geomagnetic monitoring. The timing and locations of these eyewitness reports coincided with the observed auroral oval and were consistent with the risk of scintillation (Foster et al., 2024). The first GNSS-outage reports began about 20:00 UTC (3 pm central daylight time Chicago) from North Dakota with later reports from states further south (Paulson et al., 2024). GNSS signal degradation as far south as Georgia were reported. Farms reported experiencing approximately four hours of GNSS signal degradation during the afternoon and evening of 10 May.

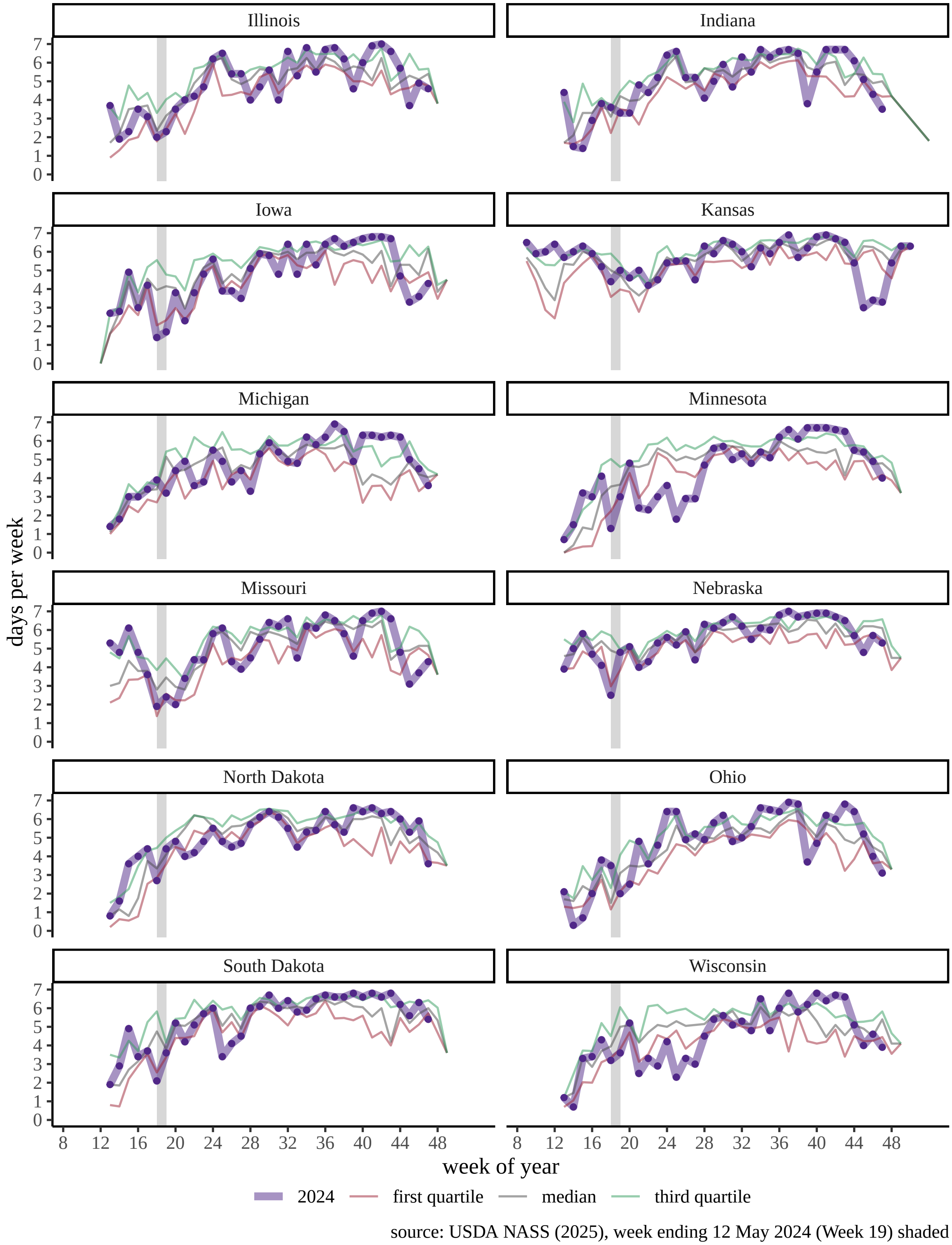


Figure 7: fieldwork days, long-term probabilities versus 2024, select states

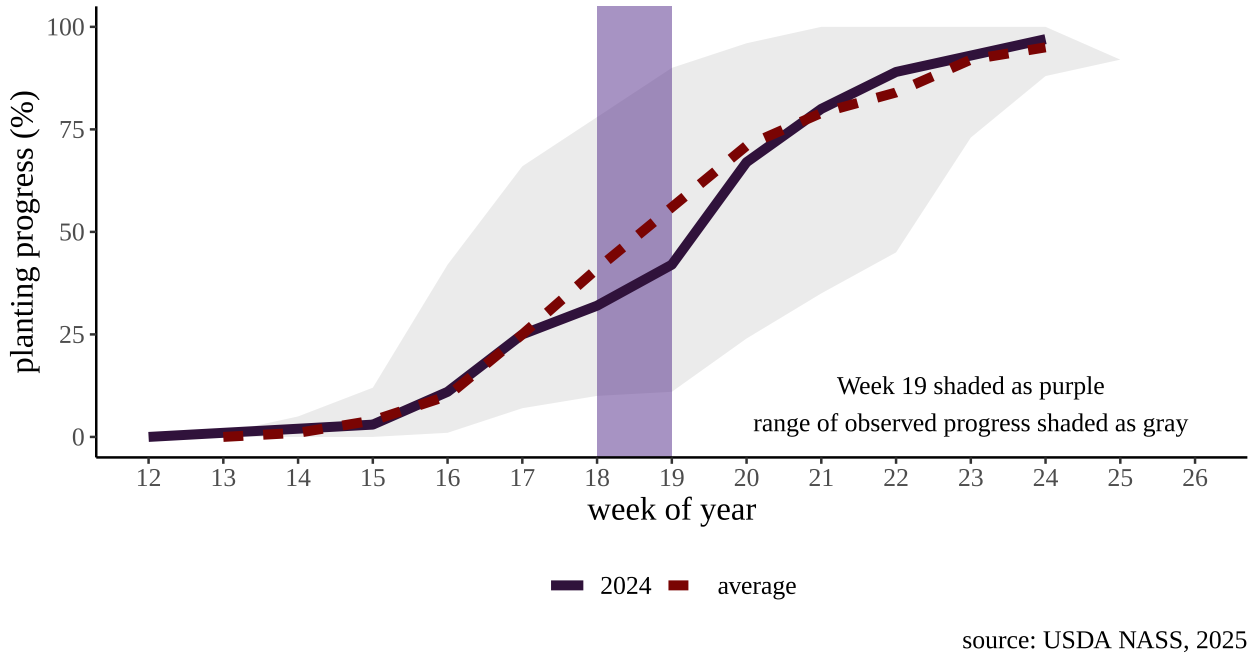


Figure 8: corn planting progress, 5-year average versus 2024, Illinois

Table 1: corn planting progress summary statistics, 2000 to 2024, Week 18

	planting progress (%)					current year		
state	**min**	Q_1	**mean**	Q_3	**max**	**2024**	**MD**	**rank**
Illinois	10	38	54	74	78	32	-9	9
Indiana	3	20	29	40	51	20	-4	8
Iowa	14	38	54	74	86	47	-6	7
Kansas	41	46	49	52	63	51	8	5
Michigan	3	5	15	17	46	16	3	4
Minnesota	6	9	44	80	89	42	4	5
Missouri	32	55	66	78	94	67	12	6
Nebraska	31	40	49	56	71	31	-17	11
North Dakota	0	2	17	30	51	11	4	5
Ohio	2	10	18	26	46	26	14	4
South Dakota	0	14	28	38	66	18	-4	8
Wisconsin	2	10	24	38	56	22	2	5
mean	**12**	**24**	**37**	**50**	**66**	**32**	**1**	**6**

data source: USDA NASS 2025

MD is mean deviation, as difference from mean

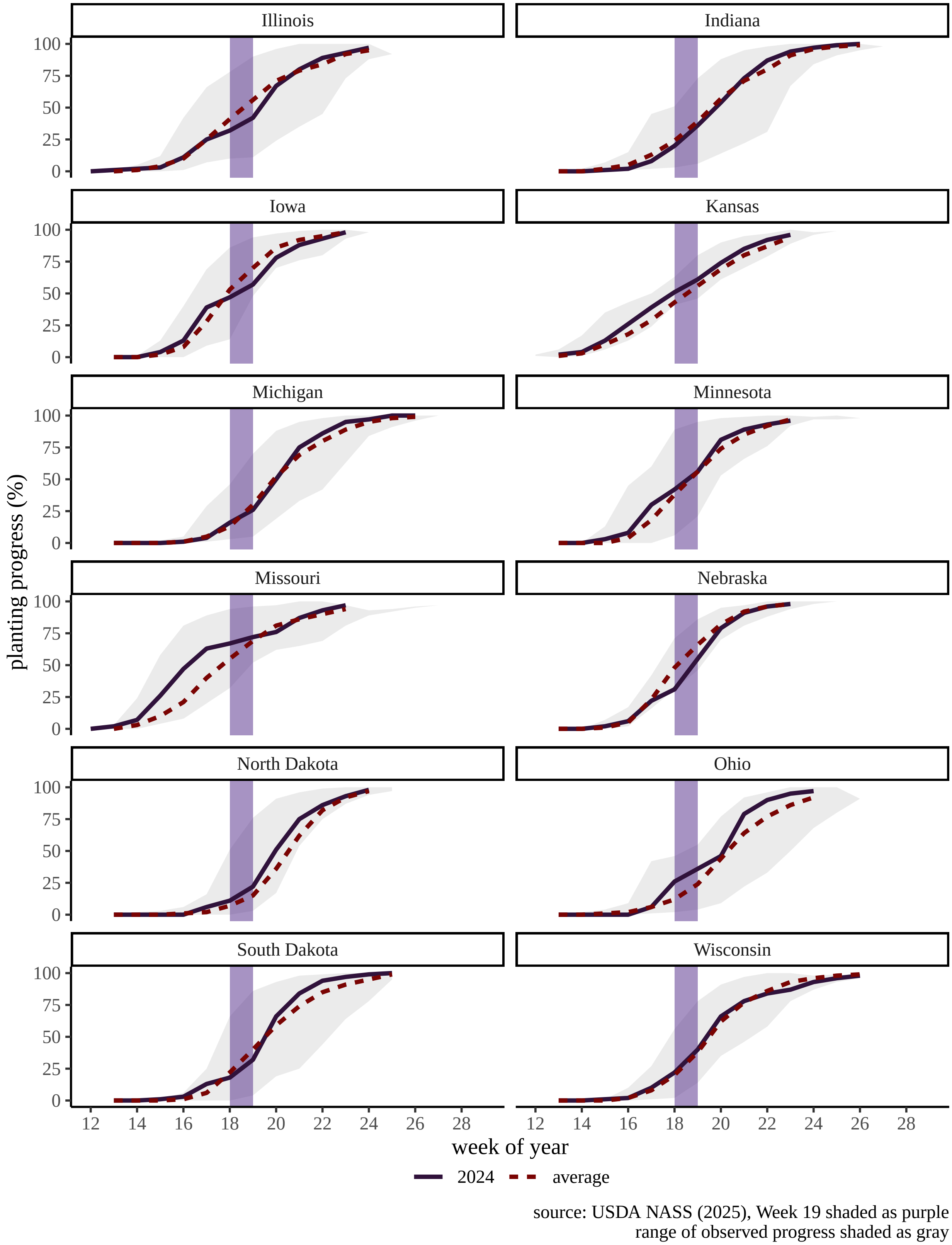


Figure 9: corn planting progress, 5-year average versus 2024, select states

Table 2: corn planting progress summary statistics, 2000 to 2024, Week 19

	planting progress (%)					current year		
state	**min**	Q_1	**mean**	Q_3	**max**	**2024**	**MD**	**rank**
Illinois	11	62	69	85	90	42	-14	10
Indiana	6	42	49	58	73	36	-3	10
Iowa	48	61	75	87	94	57	-13	9
Kansas	46	60	64	68	80	61	5	6
Michigan	5	28	34	36	70	26	-4	9
Minnesota	21	38	64	91	95	56	0	7
Missouri	52	70	79	89	96	72	3	8
Nebraska	46	67	71	78	86	55	-11	10
North Dakota	3	6	32	60	76	22	7	6
Ohio	4	32	36	44	55	36	12	6
South Dakota	4	32	49	69	86	32	-8	8
Wisconsin	14	32	46	64	78	40	2	6
mean	**22**	**44**	**56**	**69**	**82**	**45**	**-2**	**8**

data source: USDA NASS 2025

MD is mean deviation, as difference from mean

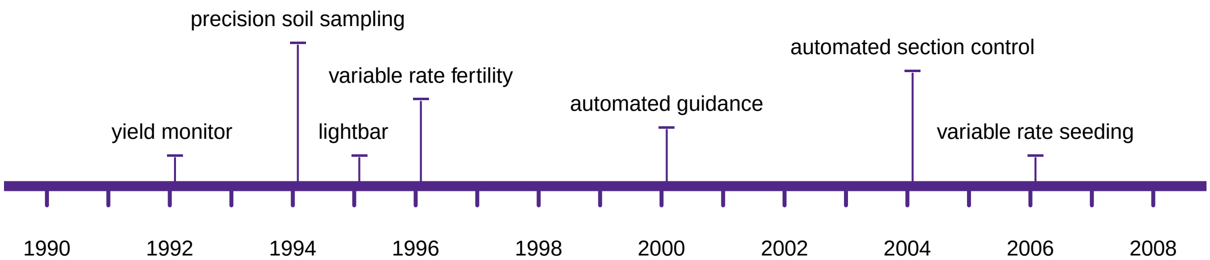


Figure 10: commercialization dates of agricultural technology

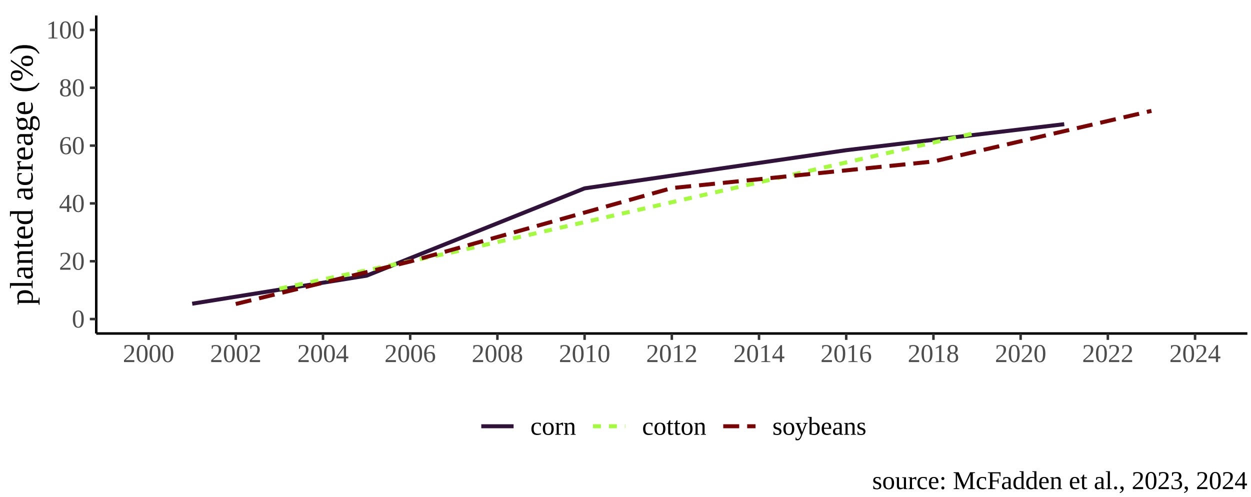


Figure 11: GNSS-enabled automated guidance adoption

Data and Analysis: Equations and Logic of Thought Processes

Acreage affected by the GNSS signal degradation was calculated for a representative farm in each state then extrapolated across the Midwestern USA. The first step was to calculate the number of foregone bushels due to delayed planting on the representative farm. This requires an estimate of the yield penalty for each displaced acre, acreage displaced per hour, and the duration of the outage (Equation 1).

$$\frac{bu}{ac} \times \frac{ac}{hr} \times \frac{hr}{\text{outage}} = \frac{bu}{farm} \tag{1}$$

where bu are bushels, ac is acres, and hr is hours. Once foregone bushels for the representative farm were estimated, the number of adversely affected farms, $farms_a$, were calculated. Even by 2024, GNSS-guidance was not ubiquitous for planting systems; therefore the subset of farms that adopted agricultural technology were taken into account (Equation 2).

$$\text{farms}_t \times \%\ \text{adoption} = \text{farms}_p \tag{2}$$

where farms_t are total farms, % adoption is percent of farms with GNSS-guidance, and farms_p are precision farms with agricultural technologies. Some GNSS-guidance systems were more susceptible during the outage, therefore the proportion of precision farms with vulnerable differential correction systems, % dGNSS, were considered to be adversely affected, farms_a (Equation 3).

$$\text{farms}_p \times \%\ \text{dGNSS} = \text{farms}_a \tag{3}$$

Once foregone bushels for each representative farm and the number of adversely affected farms were estimated, total foregone bushels were summed for each state (Equation 4).

$$\frac{bu}{farm} \times \frac{farms_a}{state} = \frac{bu}{state} \tag{4}$$

The value of foregone production was calculated by multiplying by the sales price, $\$\ bu^{-1}$ (Equation 5).

$$\text{bu} \times \$\ \text{bu}^{-1} = \text{total}\ \$ \tag{5}$$

Yield Potential by Planting Date

Dates when farmers plant and harvest crops differ slightly between states due to local climatic attributes (USDA NASS, 2010). Consider the most active dates for corn planting progress that span only a few weeks (Figure 5). Potential yield differs by planting and harvest timing, geographic location, climatic factors, and local management practices. For long-run planning purposes, usually three to five years or longer, potential yield percentages are useful to model yield expectations. Whole-farm planning models (Boehlje & Eidman, 1984) have relied upon potential yield percentages (Doster et al., 2010, p. 43; T. W. Griffin & Robertson, 2024) and have been reported by Doster et al. (2006) for the Eastern corn belt (Table 3).

When corn is late-planted during Week 21 instead of Week 19, fewer weeks are available for harvest, e.g., Week 40 and Week 41 are no longer economically feasible to harvest if planted after Week 20 (Table 3). Fewer feasible harvest weeks during early fall increases strain on equipment capacity. Most Midwestern farms produce multiple field crops such that competition for planters and harvesters exist within the farm gates.

According to Doster et al. (2006), corn planted in Week 19 has 98% potential harvestable yield if harvested between weeks 42 to 44 (Table 3). Acreage displaced from Week 19 may be planted potentially as soon as Week 20 but more likely Week 21 or Week 22 given delayed planting progress in 2024. Corn planted during

Table 3: potential corn yield percentages by planting and harvest week

planting week	harvest week 39	40	41	42	43	44	45	46	47	48	49
17	90	96	96	94	94	94	90	90	85	85	85
18	0	100	100	98	98	98	94	94	89	89	89
19	0	95	95	98	98	98	94	94	89	89	89
20	0	92	92	94	94	94	90	90	85	85	85
21	0	0	0	84	84	84	84	84	79	79	79
22	0	0	0	74	74	74	74	74	69	69	69
23	0	0	0	0	0	0	0	0	56	56	56

source: Doster et al., 2006, page 43

Week 20, Week 21, and Week 22 had 94%, 84%, and 74% potential harvestable yield, respectively, when harvested Week 42 through Week 44 (Table 3). If offset acreage were able to be planted during Week 19, no penalty was expected; but for acreage that was delayed to later weeks between 4% (98% - 94% = 4%) and 24% (98% - 74% = 24%) yield penalty was expected.

In Illinois, Nafziger (2020) reported similar yield penalties as Doster et al. (2006); suggesting that mid-April planted corn had the maximum yield potential while mid-June planted corn had 20% yield penalty. For 10 May, the maximum yield percentage was 95% while May 31 (Week 22) maximum yield percentage was 85% for a 10% yield difference (95% − 85% = 10%) (Nafziger, 2020). T. Griffin (2024) referred to the yield penalties reported by Nafziger (2020) to calculate production and revenue penalty a few days after the Gannon Storm. The range of yield penalty percentages could vary from 10% (Nafziger, 2020) to 24% (Doster et al., 2006); however, Doster et al. (2006) took into account the ability to harvest while Nafziger (2020) considered planting activities without accompanying harvest capacity constraints.

The 4-year average corn yield in Illinois is 203 bushels per acre (Table 16). Acreage planted during week ending 12 May 2024 were expected to yield 199 bushels per acre (203 bu × 98% = 198.9 bu) if harvested between Week 42 and Week 44. If the delayed acreage was planted in Week 22, expected yield of 150 bushels may be harvested (203 bu × 74% = 150.2 bu). The 48.72 bu per acre deviation (198.9 bu - 150.2 bu = 48.72 bu) is the yield penalty when acreage displaced during Week 19 were planted in Week 22. Some farms were more constrained for time than others, therefore calculations based on delayed planting are presented in all three weeks to represent a range of equipment capacity to acreage ratios.

Delayed Planted Acreage on Affected Precision Farms

The next step in determining the number of bushels foregone by the representative farm is to calculate the number of acres displaced during the GNSS-outage. Foregone production is a function of how many acres were displaced per hour. Effective field capacity, e.g., acres planted per hour (ac hr^{-1}), is a function of equipment speed (mph), width (ft), and field efficiency (%) (Equation 6). Typical planters range from 4 to 48 rows wide (Table 4); however, larger equipment exists. Prior to widespread adoption of automated guidance, Schnitkey (2004) reported that the least cost planters for 800 to 1,200 acre farms were 12-row and 1,600 to 2,000 acre farms was 16-row planters using 2004 price ratios. Effective field capacity of planters (Equation 6) is calculated as:

$$\frac{\text{speed (mph)} \times \text{width (ft)} \times \text{field efficiency (\%)}}{\text{constant (8.25)}} = \text{ac hr}^{-1} \tag{6}$$

Larger acreage farms tend to have more agricultural technology than smaller acreage farms (Lim et al., 2024; McFadden et al., 2023; McFadden et al., 2024) and are likely to have wider and/or multiple units of planters. Because of GNSS-enabled technology, planters and seeding equipment became much wider in part due to physical row markers no longer required for visual guidance (Bishop et al., 2022). Planter widths and

Table 4: equipment parameters, planters

planter	rows	width (ft)	capacity (ac/hr)
4R-30	4	10	5.3
6R-30	6	15	8.0
8R-30	8	20	10.6
12R-30	12	30	15.9
16R-30	16	40	21.2
24R-30	24	60	31.8
36R-30	32	80	42.6
36R-30	36	90	47.9
48R-30	48	120	63.6

30-in spacing, 6.25 mph
70% field efficiency

reliance on GNSS are directly proportional. As planter widths increased, additional reliance was placed on GNSS instead of visual markers for navigation. The representative farm is assumed to have planter capacity equivalent to between the 12-row 30-foot-wide and the 16-row 40-foot-wide planter. A 12-row 30-foot-wide planter operating at 6.25 mph with 70% field efficiency plants 15.9 acres per hour (Table 4 and Equation 7).

$$\frac{6.25 \text{ mph} \times 30 \text{ ft} \times 70\%}{8.25} = 15.9 \text{ ac hr}^{-1} \tag{7}$$

A 16-row 40-foot-wide planter operating at the same speed and field efficiency has an effective field capacity of 21.2 acres per hour (Table 4 and Equation 8).

$$\frac{6.25 \text{ mph} \times 40 \text{ ft} \times 70\%}{8.25} = 21.2 \text{ ac hr}^{-1} \tag{8}$$

For every hour of downtime, between 15.9 to 21.2 acres are displaced then equivalent acreage delayed until the end of the planting season. Assuming four hours of downtime during Week 19, between 63.6 (15.9 ac hr^{-1} $\times$ 4 hr = 63.6 ac) and 84.8 (21.2 ac hr^{-1} $\times$ 4 hr = 84.8 ac) acres were displaced into Week 20, Week 21, or Week 22.

Yield and Revenue Penalties on the Representative Farm

The yield penalty for late-planted acreage depends on location and duration of the delay, and how many acres would have been planted given the effective field capacity. Some regions may be less sensitive to delayed planting than others. The ratio of acreage to equipment capacity is specific to individual farms and some farms were further behind planting schedule than others. Representative farms vulnerable to GNSS signal degradation were modeled using effective field capacity for both 12-row and 16-row planter equivalents in each state.

Assuming an average effective field capacity of 15.9 acres per hour (12-row 30-foot planter) across representative Illinois farms and GNSS signal degradation duration of 4 hours, 63.6 acres per form were displaced from being planted during Week 19. If acreage intended to be planted during Week 19 were delayed until Week 20, 516 bushels would be foregone (Table 5). If acreage intended to be planted during Week 19 were delayed until Week 22, 3,099 bushels worth \$12,394 would be foregone for each vulnerable farm.

Table 5: representative farm penalties, delayed planting, 12-row

state	mean yield (bu/ac)	bushels per farm			revenue per farm		
		foregone value when displaced acreage planted during					
		Week 20	**Week 21**	**Week 22**	**Week 20**	**Week 21**	**Week 22**
Illinois	203	516	1,808	3,099	2,066	7,230	12,394
Indiana	194	494	1,727	2,961	1,974	6,910	11,845
Iowa	196	499	1,745	2,992	1,994	6,981	11,967
Kansas	127	323	1,131	1,938	1,292	4,523	7,754
Michigan	166	422	1,478	2,534	1,689	5,912	10,135
Minnesota	187	476	1,665	2,854	1,903	6,660	11,418
Missouri	161	410	1,434	2,458	1,638	5,734	9,830
Nebraska	180	458	1,603	2,748	1,832	6,411	10,990
North Dakota	129	328	1,149	1,969	1,313	4,594	7,876
Ohio	187	476	1,665	2,854	1,903	6,660	11,418
South Dakota	145	369	1,291	2,213	1,476	5,164	8,853
Wisconsin	177	450	1,576	2,702	1,801	6,304	10,807

12-row planter, 4-hour GNSS signal degradation, \$4 per bushel, delay relative to planting Week 19

Assuming an average effective field capacity of 21.2 acres per hour (16-row 40-foot planter) across representative farms and GNSS signal degradation duration of 4 hours, 84.8 acres per farm (21.2 ac hr^{-1} $\times$ 4 hrs = 84.8 ac) were displaced from being planted during Week 19. Penalties were calculated assuming displaced acreage from Week 19 was planted either during Week 20, Week 21, or Week 22 (Table 6). If acreage intended to be planted during Week 19 were delayed to Week 20, 689 bushels (203 bu $\times$ (98% $-$ 94%) $\times$ 84.8 acres = 689 bu) would be foregone for the representative Illinois farm.

If acreage intended to be planted during Week 19 were delayed to Week 22, a 48.72 bushel per acre reduction in yield potential may result (203 bu$\times$(98%$-$74%) = 48.72 bu). Due to delayed planting, the representative farm has 4,132 fewer bushels (84.8 ac $\times$ 48.72 bu $= 4,132$ bu) to harvest than if the outage had not occurred (Table 6). Assuming an average corn price of \$4 per bushel (USDA NASS, 2025), each GNSS-reliant farm in Illinois experienced \$16,526 in foregone revenue ($4,132$ bu $\times$ \$4 bu^{-1} = $\$16,526$) (Table 6).

Table 6: representative farm penalties, delayed planting, 16-row

state	mean yield (bu/ac)	bushels foregone per farm			revenue foregone per farm		
		Week 20	**Week 21**	**Week 22**	**Week 20**	**Week 21**	**Week 22**
Illinois	203	689	2,410	4,132	2,754	9,640	16,526
Indiana	194	658	2,303	3,948	2,632	9,213	15,793
Iowa	196	665	2,327	3,989	2,659	9,308	15,956
Kansas	127	431	1,508	2,585	1,723	6,031	10,339
Michigan	166	563	1,971	3,378	2,252	7,883	13,514
Minnesota	187	634	2,220	3,806	2,537	8,880	15,223
Missouri	161	546	1,911	3,277	2,184	7,646	13,107
Nebraska	180	611	2,137	3,663	2,442	8,548	14,654
North Dakota	129	438	1,532	2,625	1,750	6,126	10,502
Ohio	187	634	2,220	3,806	2,537	8,880	15,223
South Dakota	145	492	1,721	2,951	1,967	6,886	11,804
Wisconsin	177	600	2,101	3,602	2,402	8,405	14,409

16-row planter, 4-hour GNSS signal degradation, \$4 per bushel, delay relative to planting Week 19

Number of Total Farms, Precision Farms, and Advsersly Affected Farms Relying upon GNSS

The Census of Agriculture reported that there were 71,123 farms in Illinois in 2022 (Table 17) (USDA NASS, 2024, 2025). Many but not all farmers use precision agricultural technology such as GNSS-enabled guidance. McFadden et al. (2023) reported state-level adoption uptake rates of GNSS-enabled guidance technology (Table 17). Applying the state-level GNSS-enabled guidance adoption statistics (McFadden et al., 2023) to the number of farms in Illinois (USDA NASS, 2024), the number of precision farms adopting GNSS guidance was calculated (Table 17). In Illinois, there were 24,054 precision farms or 33.82% of the 71,123 total farms (Equation 9).

$$71{,}123 \text{ farms}_t \times 33.82\% = 24{,}054 \text{ farms}_p \tag{9}$$

Not all precision farms were adversely affected during the Gannon Storm. One variable associated with vulnerability was the source of differential correction used during planting activities. The proportion of farms using radio RTK, satellite correction, and WAAS for differential correction on planter tractors, e.g., market share, is unknown. Given the uncertainty of the proportion of vulnerable farms, the interquartile range, 25% to 75%, was evaluated as a sensitivity analysis for the lower and upper bound of adversely affected precision farms. For Illinois, the assumed number of affected vulnerable farms ranged from 6,014 to 18,040 out of the 24,054 precision farms (Table 17).

Of the 211,671 American farms using GNSS-enabled guidance in 2022, 158,315 were in Illinois, Indiana, Iowa, Kansas, Michigan, Minnesota, Missouri, Nebraska, North Dakota, Ohio, South Dakota, and Wisconsin. Of the 158,315 farms using GNSS across the Midwest, between 39,580 to 118,735, e.g., 25% to 75% of adopters, were assumed to be adversely affected by the GNSS-outage (Table 17).

Sales Price Data

Corn prices fluctuate due to market forces and varies over time (Figure 12). Average monthly nominal prices received for corn (USDA NASS, 2025) from 2015 to 2020 remained between $3 and $4 per bushel. The annual average price increased to $5.40 in 2021 then to $6.76 in 2022. During 2023, average monthly corn price fell to slightly below $6 per bushel. During the first 10 months of 2024, average monthly corn price was $4.28 per bushel. A conservative corn price of $4 per bushel was chosen for this analysis. If the reader wanted to use $5 per bushel instead of $4, simply add 25% to final foregone revenue estimates.

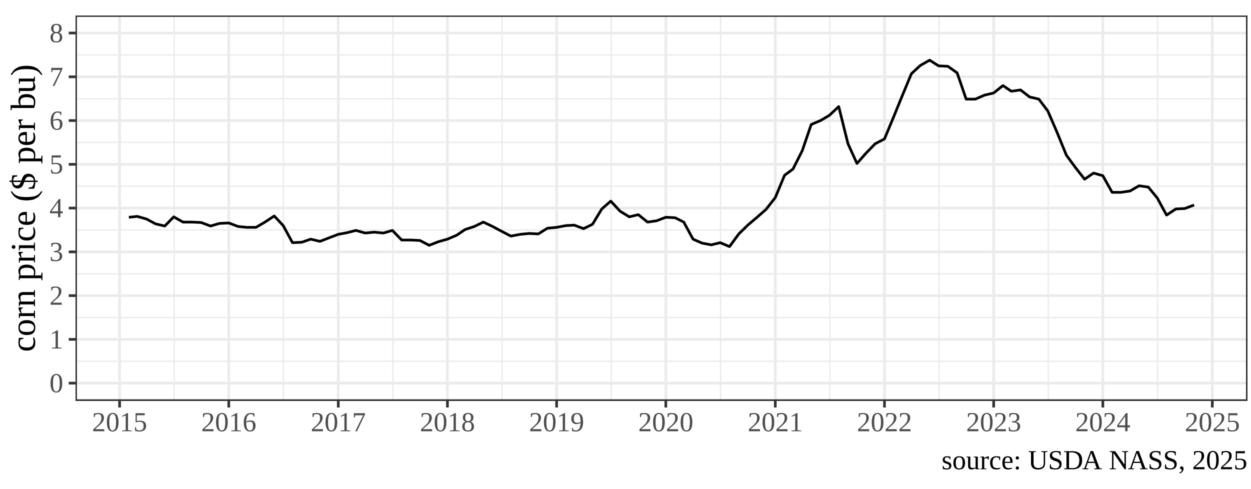


Figure 12: nominal corn prices received by month

Results

Yield and revenue losses for farms with equivalent planter capacity of 12-row and 16-row for both lower (25%) and upper (75%) bounds of precision farms being vulnerable to GNSS signal degradation are presented. The lower bound of 25% of precision farms with 12-row planter capacity are presented in Table 7. In Illinois, 6,014 farms were assumed to have been adversely affected by the GNSS outage (Table 7). If these farms delayed planting for one week into Week 20, 3.1M bushels may have been forfeited due to production losses valued at $12.4M. If Illinois farms were delayed from Week 19 into Week 22, 18.6M bushels worth $74M would have been lost. Across the 12 Midwestern states, 39,580 farms were assumed to have been affected. If these farms were delayed by one week, 17.4M bushels worth $69.6M would have been foregone (Table 7). When considering delaying planting from Week 19 to Week 22, the 105.9M bushels equates to about 1.2 bushels per corn acre, a negligible penalty.

Table 7: losses, delayed planted, lower bound of precision farms, 12-row planter

		foregone bushels (millions)			**foregone revenue ($ millions)**		
state	**farms**	**Week 20**	**Week 21**	**Week 22**	**Week 20**	**Week 21**	**Week 22**
Illinois	6,014	3.1	10.9	18.6	12.4	43.6	74.4
Indiana	2,057	1.0	3.6	6.1	4.0	14.4	24.4
Iowa	6,716	3.3	11.7	20.1	13.2	46.8	80.4
Kansas	3,790	1.2	4.3	7.3	4.8	17.2	29.2
Michigan	971	0.4	1.4	2.5	1.6	5.6	10.0
Minnesota	4,289	2.0	7.1	12.2	8.0	28.4	48.8
Missouri	1,815	0.7	2.6	4.5	2.8	10.4	18.0
Nebraska	3,793	1.7	6.1	10.4	6.8	24.4	41.6
North Dakota	3,730	1.2	4.3	7.3	4.8	17.2	29.2
Ohio	2,930	1.4	4.9	8.4	5.6	19.6	33.6
South Dakota	1,861	0.7	2.4	4.1	2.8	9.6	16.4
Wisconsin	1,614	0.7	2.5	4.4	2.8	10.0	17.6
Total	**39,580**	**17.4**	**61.8**	**105.9**	**69.6**	**247.2**	**423.6**

12-row planter, 4-hour GNSS signal degradation, $4 per bushel, 25% of precision farms vulnerable
select Midwestern corn producing states, relative to planting Week 19

Assuming the lower bound of affected precision farms but with the larger 16-row planter capacity, the 6,014 Illinois farms may have experienced a 24.8M bushel loss valued at $99.2M. Across the Midwest, 39,580 farms may have lost 141.2M bushels valued at $565M. On average, 1.5 bushels per acre were lost across the Midwest (Table 8).

Table 8: losses, delayed planted, lower bound of precision farms, 16-row planter

		foregone bushels (millions)			**foregone revenue ($ millions)**		
state	**farms**	**Week 20**	**Week 21**	**Week 22**	**Week 20**	**Week 21**	**Week 22**
Illinois	6,014	4.1	14.5	24.8	16.4	58.0	99.2
Indiana	2,057	1.4	4.7	8.1	5.6	18.8	32.4
Iowa	6,716	4.5	15.6	26.8	18.0	62.4	107.2
Kansas	3,790	1.6	5.7	9.8	6.4	22.8	39.2
Michigan	971	0.5	1.9	3.3	2.0	7.6	13.2
Minnesota	4,289	2.7	9.5	16.3	10.8	38.0	65.2
Missouri	1,815	1.0	3.5	5.9	4.0	14.0	23.6
Nebraska	3,793	2.3	8.1	13.9	9.2	32.4	55.6
North Dakota	3,730	1.6	5.7	9.8	6.4	22.8	39.2
Ohio	2,930	1.9	6.5	11.2	7.6	26.0	44.8
South Dakota	1,861	0.9	3.2	5.5	3.6	12.8	22.0
Wisconsin	1,614	1.0	3.4	5.8	4.0	13.6	23.2
Total	**39,580**	**23.5**	**82.3**	**141.2**	**94.0**	**329.2**	**564.8**

16-row planter, 4-hour GNSS signal degradation, $4 per bushel, 25% of precision farms vulnerable
select Midwestern corn producing states, delay relative to planting Week 19

Table 9: losses, delayed planted, upper bound of precision farms, 12-row planter

		foregone bushels (millions)			**foregone revenue ($ millions)**		
state	**farms**	**Week 20**	**Week 21**	**Week 22**	**Week 20**	**Week 21**	**Week 22**
Illinois	18,040	9.3	32.6	55.9	37.2	130.4	223.6
Indiana	6,170	3.0	10.7	18.3	12.0	42.8	73.2
Iowa	20,148	10.0	35.2	60.3	40.0	140.8	241.2
Kansas	11,370	3.7	12.9	22.0	14.8	51.6	88.0
Michigan	2,913	1.2	4.3	7.4	4.8	17.2	29.6
Minnesota	12,867	6.1	21.4	36.7	24.4	85.6	146.8
Missouri	5,444	2.2	7.8	13.4	8.8	31.2	53.6
Nebraska	11,379	5.2	18.2	31.3	20.8	72.8	125.2
North Dakota	11,190	3.7	12.9	22.0	14.8	51.6	88.0
Ohio	8,791	4.2	14.6	25.1	16.8	58.4	100.4
South Dakota	5,582	2.1	7.2	12.4	8.4	28.8	49.6
Wisconsin	4,841	2.2	7.6	13.1	8.8	30.4	52.4
Total	**118,735**	**52.9**	**185.4**	**317.9**	**211.6**	**741.6**	**1,271.6**

12-row planter, 4-hour GNSS signal degradation, $4 per bushel, 75% of precision farms vulnerable
select Midwestern corn producing states, delay relative to planting Week 19

Summing across the 18,040 affected precision farms in Illinois (assuming 75% of GNSS-enabled planters were affected from Table 10 and Table 17), state-level production decreased by 74,541,280 bushels ($4,132$ bu $\times$ $18,040$ farms $= 74,541,280$ bu) and $298,165,120 ($16,528 $\times$ $18,040$ farms $=$ $298,165,120) in foregone value of production (Table 10). If displaced acreage were planted the week following the Gannon Storm, 70.6M bushels valued at $282M of lost corn production would have been realized in these twelve states assuming effective planting capacity equivalent to the 16-row planter (Table 10). If the delay took two weeks such that displaced acreage was planted during Week 21, 247M bushels valued at $988M would have been lost (Table 10). Assuming the displaced acreage were planted in Week 22, American farms would have foregone 424M bushels valued at $1.7B due to the GNSS-outage associated with the Gannon Storm (Table 10).

Table 10: losses, delayed planted, upper bound of precision farms, 16-row planter

state	farms	foregone bushels (millions)			foregone revenue ($ millions)		
		Week 20	Week 21	Week 22	Week 20	Week 21	Week 22
Illinois	18,040	12.4	43.5	74.5	49.6	174.0	298.0
Indiana	6,170	4.1	14.2	24.4	16.4	56.8	97.6
Iowa	20,148	13.4	46.9	80.4	53.6	187.6	321.6
Kansas	11,370	4.9	17.1	29.4	19.6	68.4	117.6
Michigan	2,913	1.6	5.7	9.8	6.4	22.8	39.2
Minnesota	12,867	8.2	28.6	49.0	32.8	114.4	196.0
Missouri	5,444	3.0	10.4	17.8	12.0	41.6	71.2
Nebraska	11,379	6.9	24.3	41.7	27.6	97.2	166.8
North Dakota	11,190	4.9	17.1	29.4	19.6	68.4	117.6
Ohio	8,791	5.6	19.5	33.5	22.4	78.0	134.0
South Dakota	5,582	2.7	9.6	16.5	10.8	38.4	66.0
Wisconsin	4,841	2.9	10.2	17.4	11.6	40.8	69.6
Total	**118,735**	**70.6**	**247.1**	**423.8**	**282.4**	**988.4**	**1,695.2**

16-row planter, 4-hour GNSS signal degradation, $4 per bushel, 75% of precision farms vulnerable
select Midwestern corn producing states, delay relative to planting Week 19

Discussion

Estimated losses indicate relatively large financial penalties for reliance upon GNSS systems especially during peak farming activities. Modest farm-level losses sum to substantial amounts given the vast corn acreage in the USA. Early warning of GNSS-outages may be useful for many practitioners, but not likely sufficient to prevent production yield losses due to the complex timing with respect to the biological and climatic implications of agricultural systems. In limited situations, an early warning of impending GNSS signal degradation may prompt some precision farmers to plant additional acreage per day before the impending geomagnetic disturbance; however, many farms already operate at near-maximum capacity during peak planting times such that no additional acreage can be planted without increased equipment capacity. Acquiring additional planter capacity may be possible, albeit difficult to secure with only a few days notice in situations with demand surges. Spoofing and jamming may have similar adverse economic impacts on agricultural production as space weather.

Development of guidance technologies that do not solely rely upon GNSS may be possible. Many autonomous systems depend upon GNSS for navigation, but alternatives are being considered such as machine vision and deep learning (T. Griffin et al., 2024). For high-value crops, semi-permanent terrestrial-based triangulation systems may be integrated, especially for swarms of small autonomous robots that have central operations base replete with local charging stations.

Economic losses on corn farms due to the Gannon Storm were similar to the estimates that T. W. Griffin (2010) reported for a hypothetical season-long GNSS-outage and O'Connor et al. (2019) reported similar penalties for a daily outage during peak activities. In light of the Gannon Storm impacts assessed in this study, it is clear that the penalties of GNSS outages have become more severe than in the past. These penalties are due to changes in the value of production, but even more importantly is how automated guidance systems have become so integrated into farming systems, that rather than simply adding efficiency to an existing system, they can cripple a farming system when GNSS reception is degraded or non-existent. Even for GNSS-enabled planters that are able to continue planting under degraded GNSS performance, wide and narrow middles and crooked rows may cause farm management issues, including landowner relations being adversely affected in the competition for farmland leasing. Social capital has been known to be an important aspect within farming communities.

Results may be adjusted by setting specific states to plant displaced acres in Week 19, some in Week 20, some in Week 21, and others during Week 22. It is not necessary to assume that all states or farms within a state have the same duration of delayed planting. States that were behind schedule with respect to crop progress may have been assigned a delay from Week 19 to Week 22 while states that were ahead of schedule may have been assigned to Week 20 and so on.

What to Expect for Agriculture Moving Forward

The GNSS-outage associated with the Gannon Storm was unprecedented with respect to within the precision agricultural era. However, this extreme storm is unlikely to be a once-in-a-lifetime event. The Gannon Storm occurred in the spring, coinciding with peak on-farm use of GNSS. Solar cycles have been tracked since 1750 (Hathaway, 2015) but GNSS has been available for civilian use only during the three most recent solar cycles since the 1990s (Figure 13). GNSS became fully operational for civilian use during the declining phase of Solar Cycle 22, however, agricultural guidance technology were not commercialized until well into the declining phase of Solar Cycle 23. This meant the first real tests of GNSS-enabled agricultural technology in a solar maximum space weather environment occurred during the maxima of Solar Cycle 24 and 25 (Figure 13). Both GNSS and Low Earth Orbit (LEO) satellites came online during the relatively mild solar cycles (Parker & Linares, 2024). Given that Solar Cycle 24 was a relatively mild cycle with few strong geomagnetic disturbances (see Table 13), only anecdotal impacts to GNSS-enabled equipment were reported, which were easily dismissed.

Solar Cycle 25 has been the only solar cycle in the precision agricultural era with near-average sunspot counts (Clette & Lefèvre, 2016). Thus, geomagnetic disturbances during Solar Cycle 25 may be the first readily observed events replete with adverse effects on GNSS-enabled agricultural technology. At least two extreme geomagnetic storms (G5-level) have affected GNSS thus far, and the cycle is far from over. One barrier to understanding the impacts of space weather on GNSS-intensive precision agricultural operations has been the relatively few well-documented observations during high solar activity periods. Although reports of GNSS impacts on agricultural technology during Solar Cycle 24 exist, they have been sparse and only anecdotally reported.

Data from the Geomagnetic Observatory Niemegk, GFZ German Research Centre for Geosciences at Potsdam (Matzka, Stolle, et al., 2021; Matzka, Bronkalla, et al., 2021) were analyzed to determine the frequency of geomagnetic disturbances that could affect agricultural production due to increased risk of GNSS signal degradation, especially during peak production activities. Geomagnetic disturbances measured as 3-hour intervals with $Kp \geq 7$ were evaluated.

Although the commercialization of automated guidance preceded the deactivation of Selective Availability on 1 May 2000 (NOAA, 2024), adoption rates were not measured until afterwards. The Agricultural Resource Management Survey conducted by USDA (McFadden et al., 2023) first reported non-zero adoption rates for automated guidance at 5.3% for corn in 2001, a year after Selective Availability was deactivated (Figure 11). Since Selective Availability was deactivated, 112 days with a geomagnetic disturbance of $Kp \geq 7$ have occurred (Table 11 and Figure 13). The vertical lines in Figure 13 show the distribution of active days from Solar Cycle 17 to the present day. The sparsity of these lines throughout Cycle 24 indicates the dearth of geomagnetic disturbances during the precision agriculture era. Since 2013, when automated guidance adoption reached 50% of planted acreage, only 33 days have had a geomagnetic disturbance of $Kp \geq 7$. When considering geomagnetic disturbances of $Kp \geq 8.5$, 14 have occurred since Selective Availability was deactivated. However, none of those days occurred during Solar Cycle 24 when the adoption of agricultural guidance technology was on the rise.

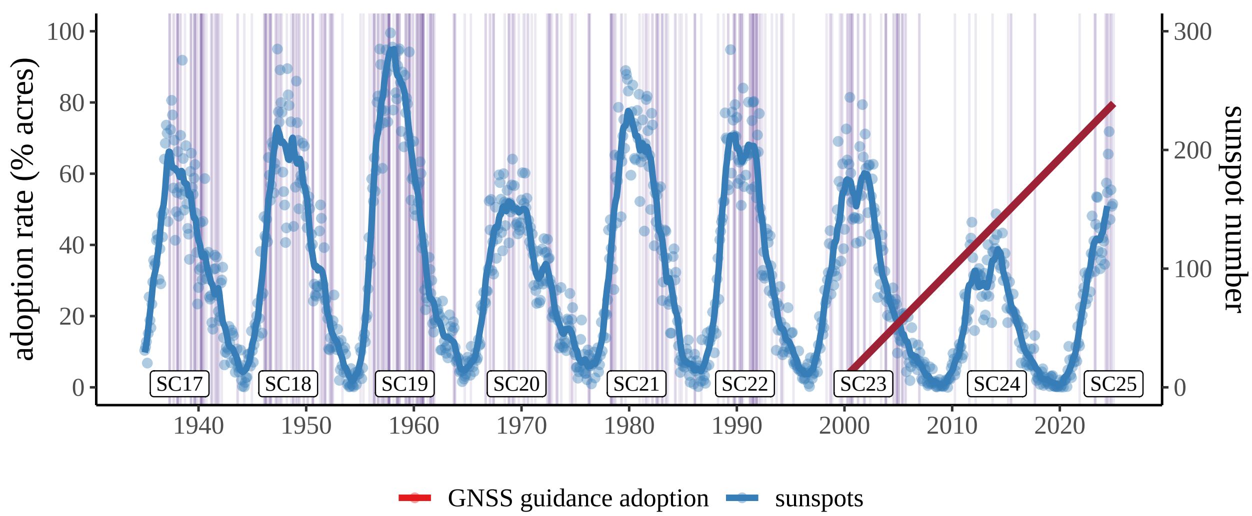
By contrast, Solar Cycle 25 has already amassed 3 days of $Kp \geq 8.5$. These have occurred in a single year, during the maximum of solar activity in 2024 (Table 11). Comparing sunspot numbers between Cycle 24 and 25 during activity maximums in Figure 13, it is clear the current cycle is much larger than its predecessor. This comparison is indicative of how different solar cycles can have different activity levels. Thus, the mild impacts to GNSS in Solar Cycle 24, are not reliable indicators of the number and severity of potential GNSS outages possible in the current cycle.

Table 11: frequency of days during GNSS era with geomagnetic disturbances

	days since		
Kp ≥	**2000**	**2013**	**2024**
6.0	288	94	22
6.5	145	42	14
7.0	112	33	13
7.5	55	18	7
8.0	37	12	6
8.5	14	3	3
9.0	4	1	1

source: Matzka et al. 2021
Selective Availability, 2000
50% guidance adoption, 2013

When specifically considering the subset of days containing the most active period of corn planting, from March to May (see Figure 16), there were 9 days with a geomagnetic disturbance. Looking more closely at this subset, one-third of those days occurred during 2024. Limiting this selection further to geomagnetic disturbances of Kp ≥ 8 (G4 to G5 level), there was only 6 days that occurred during peak planting times. Four of those days occurred in 2005, when GNSS-enabled automated guidance technology was used on less than 20% of planted acreage. The other two days occurred during the Gannon Storm from 10-12 May 2024.



vertical purple lines indicate days with a geomagnetic disturbance Kp>=7.5
agricultural technology adoption data source: adapted from McFadden et al. 2024
sunspot number data source: NOAA Space Weather Prediction Center
Kp data source: Matzka et al. 2021

Figure 13: GNSS era relative to solar cycles and geomagnetic disturbances, 1935 to present

Due to the Russell–McPherron (R–M) effect (Cortie, 1912; Russell & McPherron, 1973), the chances of GNSS outages associated with geomagnetic disturbances are enhanced during earlier portions of planting and harvest times than during non-peak times given the proximity of peak agricultural activities to the equinoxes. The Russell-McPherron effect is the increased geomagnetic disturbances corresponding to Earth equinoxes and decreased activity during solstices (Katsavrias et al., 2021; McPherron et al., 2009; Meziane et al., 2022; Wang et al., 2024; Zhao & Zong, 2012). If the Russell-McPherron effect holds with increased geomagnetic disturbances continuing to occur near equinox, weeks of intense precision agriculture usage during pre-plant, planting, late-season, and harvest times may be at increased risk of GNSS outages.

Rather than visualize individual days with geomagnetic disturbances, days were charted monthly. The monthly frequency of geomagnetic disturbances since 1932 indicate bi-modal distribution with increased activity occurring near the equinoxes (Figure 14). Superimposing the Midwestern corn progress (Figure 5) onto the monthly distribution of geomagnetic disturbances (Figure 14) yields Figure 15. Peak planting and harvest activities for many field crops typically correspond to within a few weeks after spring equinox and during autumn equinox, respectively (Figure 16), therefore the chances of geomagnetic disturbances may be expected to be slightly higher during times when farmers are actively relying upon GNSS-enabled automated guidance especially during harvest. On average, the 12 Midwestern states actively planted corn during the 4 weeks from Week 18 to Week 21 and harvested corn during the 4 weeks from Week 40 to Week 43 (Table 12). Corn fields in lower latitudes are planted earlier in the spring than in the Midwestern US. other crops have different planting harvest dates due to biology and location where grown (Figure 16). Planting and harvest dates do not perfectly align with equinox for corn (Figure 15) or the other summer crops (Figure 16), however other GNSS-reliant activities such as tillage and application of crop protection chemicals may be affected.

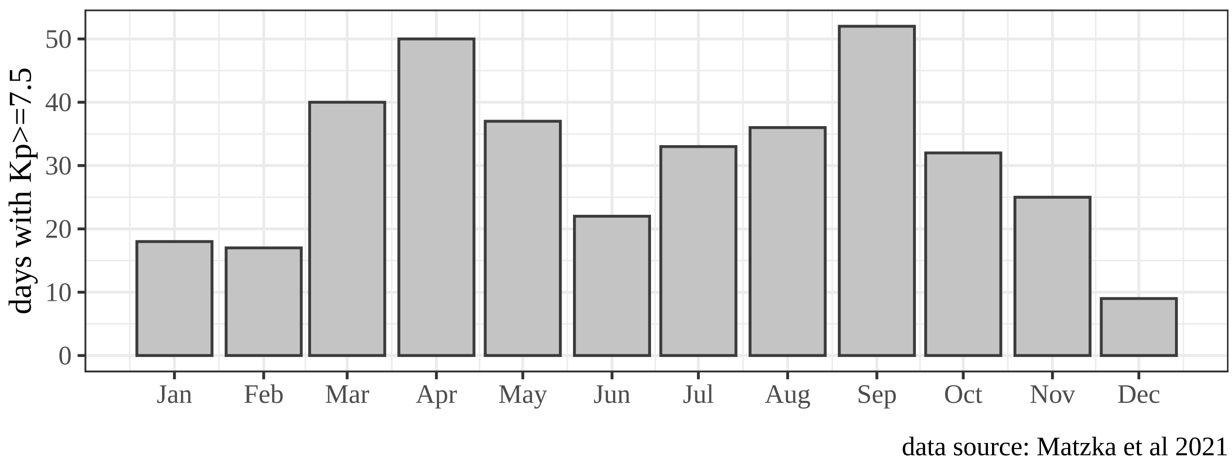


Figure 14: geomagnetic disturbances by month, 1932 to present

Ascending and Descending Phases of Solar Cycles

Within each Solar Cycle, the frequency of geomagnetic disturbances events were partitioned into the rising and declining phases of the solar cycle (before and after sunspot maximum, respectively) to demonstrate the likelihood of geomagnetic disturbances during each phase (Figure 17). The rising and declining phases of sunspot cycles are not of equal duration. On average, the rise from sunspot (solar) minimum to sunspot (solar) maximum takes an average of four years while the decline from maximum back to minimum occurs over the remaining seven years of the 11-year solar cycle (Hathaway, 2015). On average, the frequency and strength of geomagnetic disturbances usually peak one to two years after sunspot maximum (Leamon et al., 2022; Leamon & McIntosh, 2022; McIntosh & Leamon, 2024).

Since 1932, 356 days with geomagnetic disturbances of $Kp \geq 7.5$ have occurred with two-thirds (70%) of those during the decline phase (Table 13). The relatively more frequent geomagnetic disturbances during the decline phase can partially be explained by longer duration, e.g., 7 years versus 4 years, however disturbances typically occur within a few years of solar sunspot maximum. Most disturbances (86%) occur during non-peak weeks of the year, however between 6 and 8% of disturbances occurred during most active corn harvesting and planting times, respectively. Although corn planting and harvest loosely coincide with equinox and R-M, no correlation was expected with respect to rise and decline of solar maximums. During most active planting and harvest dates, geomagnetic disturbances occurred more frequently during descending than ascending phase (Figure 17).

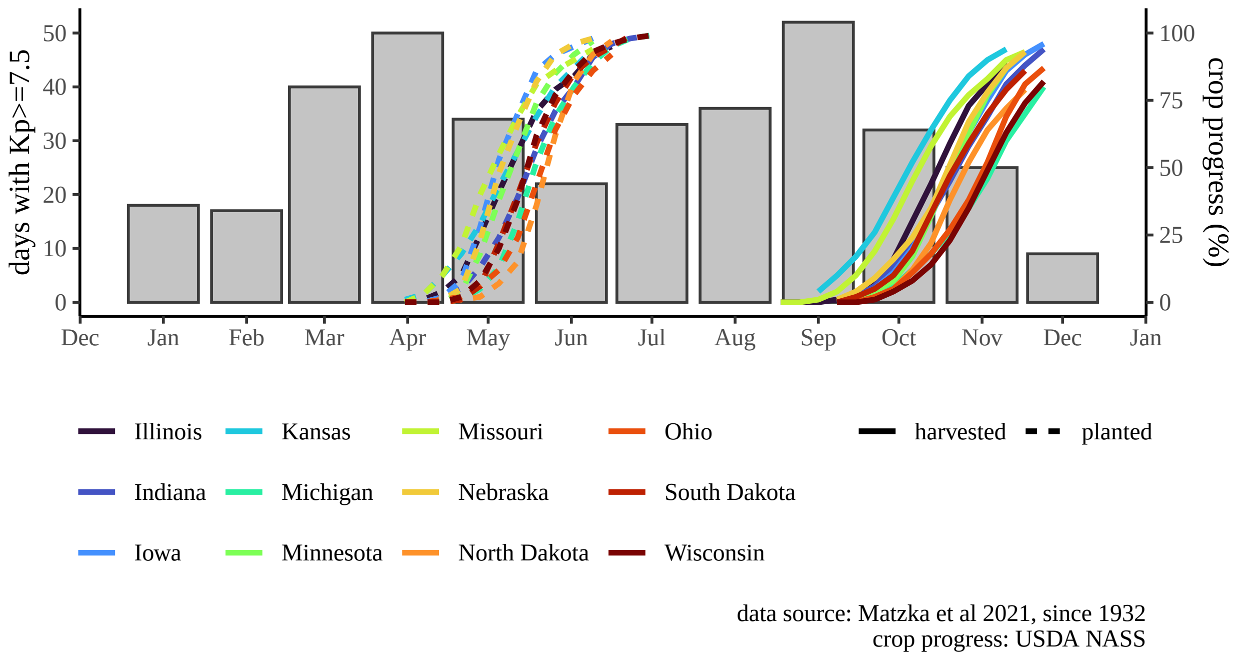


Figure 15: geomagnetic distubrances versus corn progress by month for select states

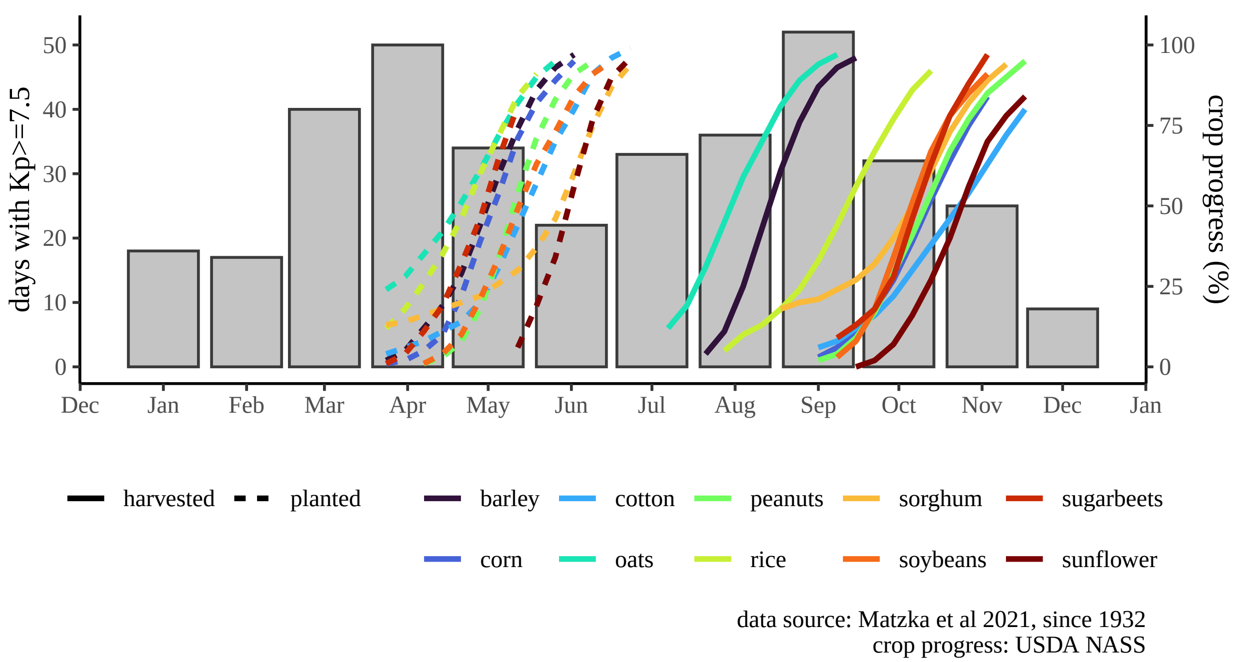


Figure 16: geomagnetic distubrances versus field crop progress by month for select states

Table 12: most active corn planting and harvest weeks of the year

	planting		**harvest**	
state	**begin**	**end**	**begin**	**end**
Illinois	17	22	40	44
Indiana	18	22	36	45
Iowa	17	19	40	44
Kansas	17	21	38	43
Michigan	19	22	41	47
Minnesota	18	21	41	39
Missouri	16	20	39	44
Nebraska	18	20	40	44
North Dakota	20	22	41	46
Ohio	19	22	42	39
South Dakota	19	22	41	45
Wisconsin	19	21	42	41
mean	**18**	**21**	**40**	**43**

data source: USDA NASS 2010
dates are from 15th to 85th percentile

NOAA assigns a geomagnetic storm rating of G1 through G5, with G5 being considered extreme. [1] The probability of a G5 geomagnetic storm is 4 days per cycle (NOAA SWPC, 2024b). Springtime during 2025 and 2026 may have geomagnetic disturbances affecting GNSS accuracy and therefore planting of summer crops. The next wide-spread GNSS-outage may occur during the declining phase of Solar Cycle 25 then again in about a decade during Solar Cycle 26. The timing of the next space-weather-induced GNSS outage remains unknown, but when it occurs agriculture will likely be affected with possibly delayed field activities or precluding georeferencing of sensor data. Given that the date of solar maximum of Solar Cycle 25 was not definitively known as of this writing, springtime planting during 2025 and 2026 may experience additional and potentially more several geomagnetic disturbances (McIntosh et al., in preparation). Events similar to Gannon Storm are likely to occur in 2025 and maybe 2026 then again in about 11 years during the next solar cycle maximum. Although the exact timing and geographic location of the next GNSS outage remains unknown, preparations for geomagnetic disturbances, potentially impacting GNSS and precision agriculture must be made to mitigate downside risks.

[1] NOAA also assigns R1 through R5 for severity of X-ray emission from the sun ('Radio Blackouts') and S1 through S5 for energetic particles ('Solar Radiation Storms'), but these solar effects are less relevant to GNSS degradation than the G-scale.

Table 13: days with geomagnetic disburbances during corn planting and harvest by solar cycle

	ascending						**descending**										
	planting		**harvest**		**non-peak**		**planting**		**harvest**		**non-peak**		**ascending**		**descending**		
SC	**days**	**(%)**	**days**	**(%)**	**days**	**(%)**	**days**	**(%)**	**days**	**(%)**	**days**	**(%)**	**days**	**(%)**	**days**	**(%)**	**total**
17	0	0	0	0	0	0	2	4	3	7	41	89	0	0	46	100	46
18	0	0	0	0	18	33	4	7	6	11	26	48	18	33	36	67	54
19	1	1	0	0	27	33	3	4	4	5	46	57	28	35	53	65	81
20	2	5	0	0	10	26	3	8	1	3	22	58	12	32	26	68	38
21	5	12	0	0	11	26	1	2	1	2	25	58	16	37	27	63	43
22	0	0	3	7	5	12	1	2	0	0	33	79	8	19	34	81	42
23	2	5	3	7	15	35	3	7	0	0	20	47	20	47	23	53	43
24	0	0	1	11	3	33	0	0	0	0	5	56	4	44	5	56	9
all	**10**	**3**	**7**	**2**	**89**	**25**	**17**	**5**	**15**	**4**	**218**	**61**	**106**	**30**	**250**	**70**	**356**

Kp data source: Matzka et al 2021, crop progress data source: USDA NASS 2025

most active planting dates are Week 18 to Week 21 and most active harvest dates are Week 40 to Week 43

geomagnetic disburances defined as Kp>=7.5, SC is Solar Cycle number

Table 14: days with geomagnetic disburbances during corn planting and harvest by Hale Cycle numbering

	ascending						**descending**										
	planting		**harvest**		**non-peak**		**planting**		**harvest**		**non-peak**		**ascending**		**descending**		
SC	**days**	**(%)**	**days**	**(%)**	**days**	**(%)**	**days**	**(%)**	**days**	**(%)**	**days**	**(%)**	**days**	**(%)**	**days**	**(%)**	**total**
17	0	0	0	0	18	28	2	3	3	5	41	64	18	28	46	72	64
18	1	2	0	0	27	42	4	6	6	9	26	41	28	44	36	56	64
19	2	3	0	0	10	15	3	5	4	6	46	71	12	18	53	82	65
20	5	12	0	0	11	26	3	7	1	2	22	52	16	38	26	62	42
21	0	0	3	9	5	14	1	3	1	3	25	71	8	23	27	77	35
22	2	4	3	6	15	28	1	2	0	0	33	61	20	37	34	63	54
23	0	0	1	4	3	11	3	11	0	0	20	74	4	15	23	85	27
24	2	17	0	0	5	42	0	0	0	0	5	42	7	58	5	42	12
all	**12**	**3**	**7**	**2**	**94**	**26**	**17**	**5**	**15**	**4**	**218**	**60**	**113**	**31**	**250**	**69**	**363**

Kp data source: Matzka et al 2021, crop progress data source: USDA NASS 2025

most active planting dates are Week 18 to Week 21 and most active harvest dates are Week 40 to Week 43

geomagnetic disburances defined as Kp>=7.5

SC is Solar Cycle number as odd is from solar maximum of odd numbered SC to solar maximum of even numbered SC

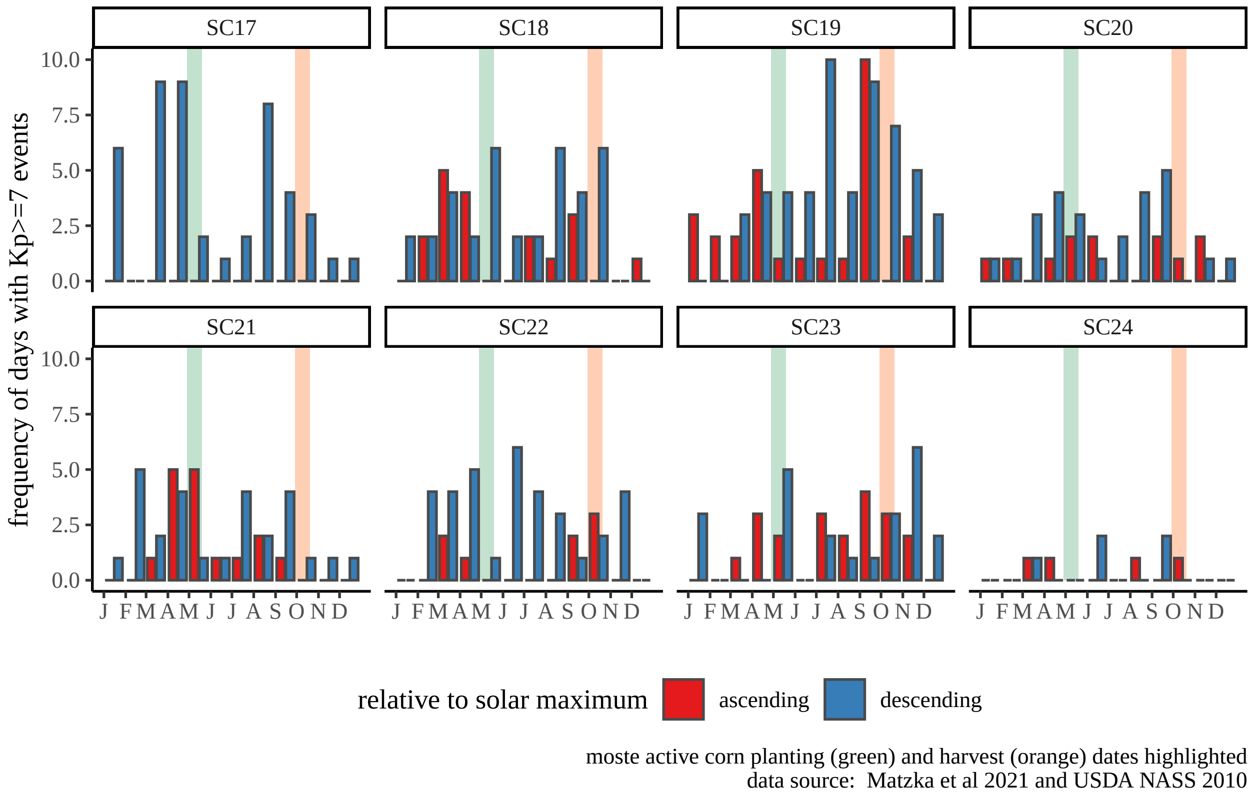


Figure 17: geomagnetic activity relative to corn planting and harvest dates by Solar Cycle

The number of days with geomagnetic disturbances occurred more frequently during odd numbered solar cycles during the descending phase and more frequently during even numbered solar cycles during ascending phase (Figure 19 and Figure 20). The number of days for both ascending and descending phases being higher in the odd solar cycles occurred only in March and December. The number of days for both ascending and descending phases being higher in even solar cycles occurred only in February and May. The remaining months had divergent ascending and descending phases with one occurring more frequently during odd or even solar cycles. April, July, September, and November had nearly equal divergence but in opposite directions. Springtime farming activities during 2025 will occur during the descending phase of an odd numbered solar cycle, Solar Cycle 25; therefore increased prevalence of days with geomagnetic disturbances are affected therefore increased probability of space weather related GNSS signal degradation.

Summary of Assumptions

- one source of uncertainty with respect to chosen variable values was percentage of planter tractors adversely affected by GNSS outage, e.g., differential correction source. Differential correction systems were affected differently, WAAS and single-tower radio RTK may have been most susceptible followed by subscription SBAS, e.g., SF2 and SF3 correction, OmnistarXP, and OmnistarHP, and network RTK. In the absence of market share, a lower and upper bound of adversely affected precision farms using susceptible dGNSS were assumed to be 25% to 75% of GNSS adopters.
- another source of uncertainty was size of planter by farmsize class, e.g. effective field capacity. Each farmsize acreage class likely has distinct average planter capacity, but overall average effective planter capacity were assumed to be either 12-row 30-foot at 15.9 ac hr^{-1} or 16-row 40-foot planter at 21.2 ac hr^{-1} for calculations; smaller acreage farms with smaller equipment, e.g., 4-row to 8-row planters possibly with physical row markers, may not be as reliant upon GNSS as larger acreage farms with wider planters.

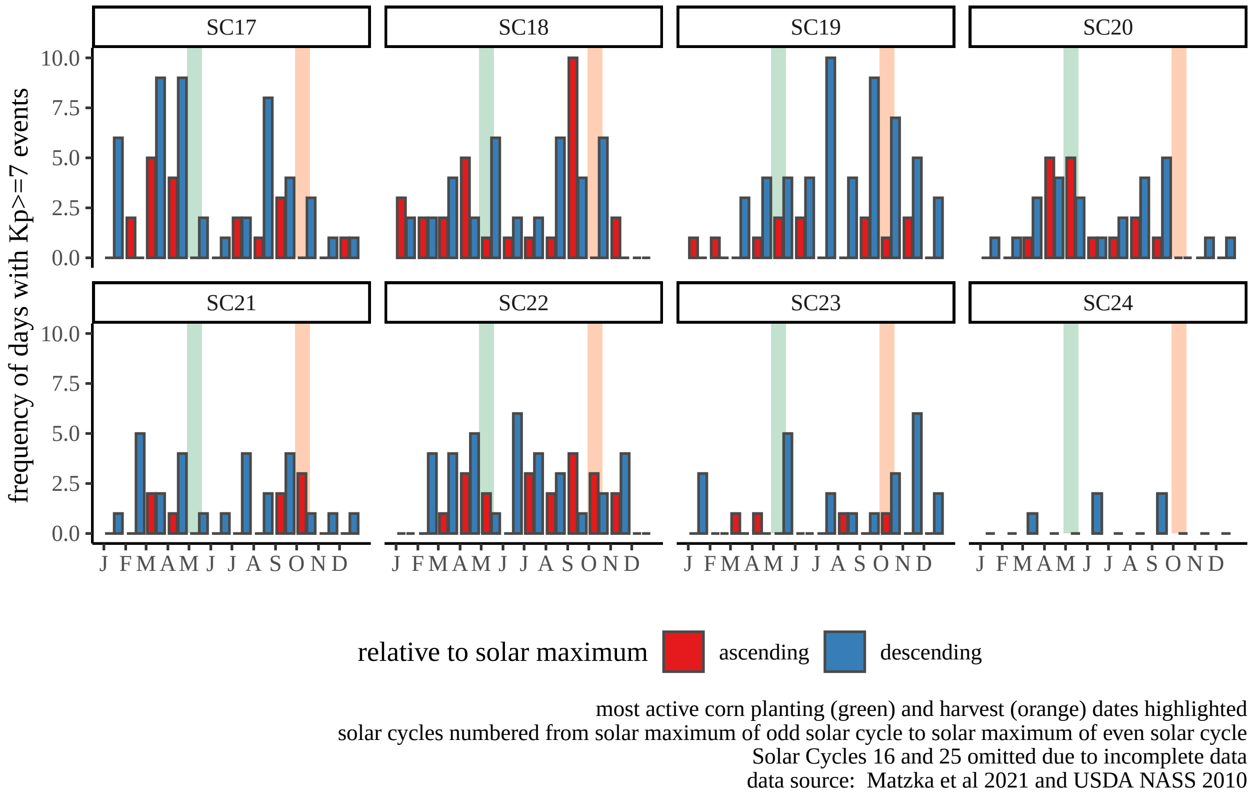


Figure 18: geomagnetic activity relative to corn planting and harvest dates by odd Solar Cycle

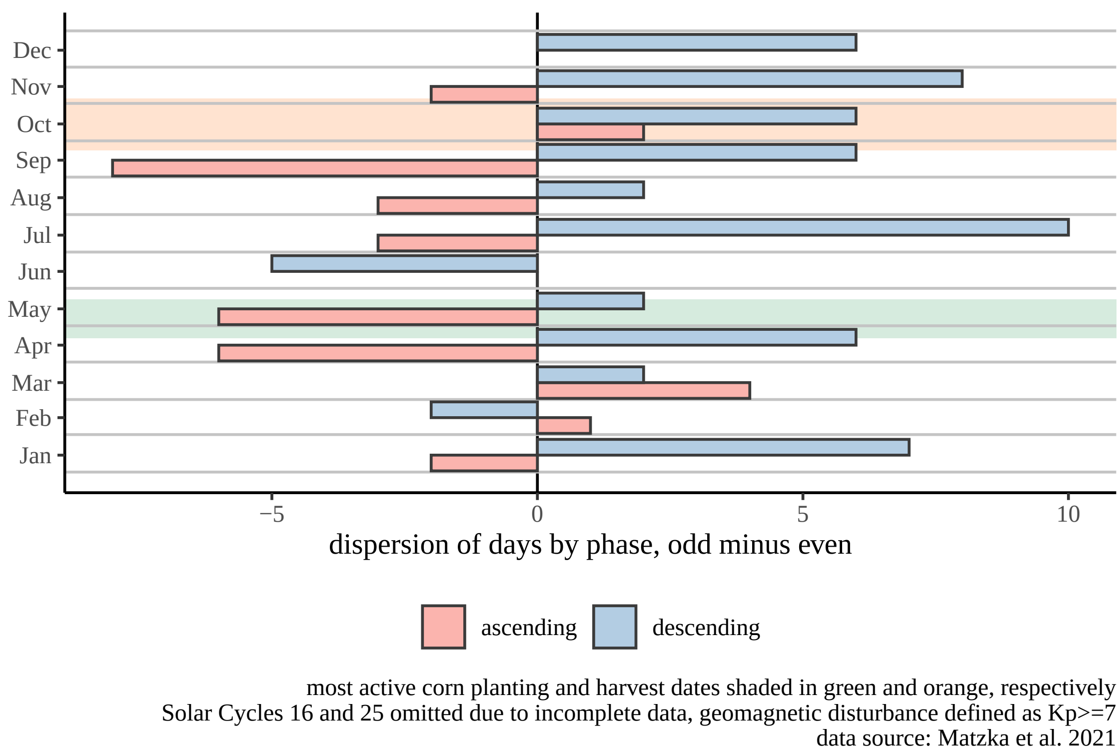


Figure 19: geomagnetic disturbances by phase during Hale Cycles

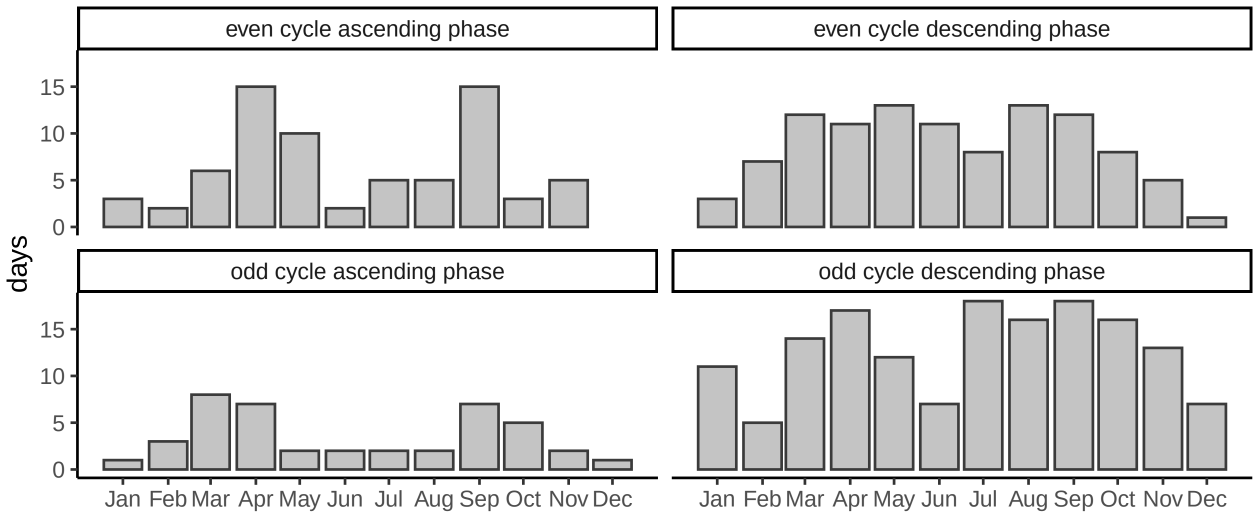


Figure 20: days with geomagnetic disturbances grouped by Hale Cycle and phase

- expected yield for each state was 4-year average from 2020 to 2023 of respective state
- corn price was constant at $4 per bushel
- displaced acreage from Week 19 were planted during Week 20, Week 21, or Week 22
- farms using GNSS-enabled guidance use wider planters such that physical row markers may not be feasible

Limitations and Future Work

Many farmers and equipment operators felt frustration especially if they were unaware of the GNSS-outage; and initially assuming the culprit was a local hardware issue. Frustration can be a non-monetary cost that is difficult to quantify although applies to the benefit cost analysis. Alerts indicating local GNSS signal degradation, e.g., nowcasts, may be useful (Bishop et al., 2022), especially to prevent frustration, redirect from assumption of local hardware malfunction, and ultimately mitigate downside risk.

Farm data is more difficult to valuate than physical goods such as bushels of corn. Changes in the benefit-cost analysis are more difficult to estimate with respect to foregone farm data than production losses associated with delayed planting. The inability to georeference sensor and as-applied farm data has agronomic and economic implications beyond the current growing season. The 10 May 2024 event was not the only geomagnetic storm affecting farmers' use of GNSS in 2024. Degradation of GNSS signals on 11 October 2024 occurred during harvest of several summer crops; although equipment continued harvesting even with potentially inoperative guidance technology, georeferencing yield and other sensor data may have been compromised. Harvest-time GNSS outages preclude georeferencing sensor data that ultimately negates the ability to create spatial maps of yields, analyze on-farm experiments, negotiate farmland leases with landowners, or participate in third-party data services. Gaps in data collection anytime during the growing season may adversely impact ability to analyze data from on-farm experiments. Geo-referenced as-applied data from planters and sprayers were not likely logged during the Gannon Storm even if the equipment were performing respective tasks without automated guidance. Absence of data may impede farm-level decision making beyond 2024 especially with respect to on-farm experimentation and big data community analysis. The lack of geo-referenced yield monitor data was not included in estimates of economic impacts. Geo-referencing sensor and as-applied data are not currently possible without GNSS.

Production and revenue losses reported here were for corn. Other crops such as cotton, peanuts, soybeans, and sugarbeets may also have been affected but were omitted from this report. Crops such as peanuts may have planting dates that align more closely with equinox and therefore more likely to be affected by geomagnetic disturbances due to the Russell-McPherron effect. For peanuts, precise guidance during harvest may be as important as planting; Roberson & Jordan (2014) reported 11% yield reduction if RTK GNSS was not used for digging peanuts.

Crop prices are a function of demand and supply. When production is below expectations, the market reacts by pushing prices upward such that drastic yield penalties from farm-level downtime could cause prices to increase. However, these elasticities were not modeled. Economic losses were considered only within the farm gates such that commodity traders and supply chain entities were not modeled.

Calculations presented here were simplified but realistic. Sophisticated analyses that evaluate whole-farm acreage, multiple crops in rotation, fieldwork probabilities, and equipment capacity inventory would provide more precise estimates. Whole-farm modeling including linear programming (Dantzig, 1949, 1963) could be applied to these scenarios similar to how T. W. Griffin et al. (2014) evaluated equipment downtime, T. W. Griffin et al. (2005) estimated the value of adding GNSS to existing farms and Bishop et al. (2022) discussed with respect to space weather impact on precision agriculture. The cotton harvest dashboard had a GNSS signal degradation tab inspired by space weather (T. Griffin et al., 2024).

In some climatic regions, yield penalties associated with late planting may be less severe than those assumed for the eastern corn belt. Some farms employing GNSS-enabled technology were not behind planting schedule during Week 19, therefore less likely to be adversely affected.

The time frame and geographic footprint of the 10 May 2024 GNSS-outage is currently unknown. Additional information regarding when specific US counties were affected will improve precision of these analyses. More accurate production loss estimates may be calculated once GNSS signal degradation footprint is known. RINEX (Teunissen & Montenbruck, 2017) and smartphone TEC data (Smith et al., 2024) may be useful to evaluate the impact of signal degradation (Demyanov & Yasyukevich, 2021; Romaniuc et al., 2024).

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Table 15: acreage planted by state and crop, 2023

	planted acreage (thousands)							
state	**corn**	**cotton**	**peanut**	**rice**	**sorghum**	**soybean**	**sugarbeet**	**wheat**
Alabama	280	800	190			360		220
Arizona	70	220						118
Arkansas	500	1,300	45	2,902		3,050		260
California	440	318		976			23	630
Colorado	1,460				520		25	4,200
Connecticut	24							
Delaware	165					155		140
Florida	85	172	170					
Georgia	375	2,200	850			170		290
Idaho	380						174	2,420
Illinois	10,800					10,800		1,540
Indiana	5,200					5,800		620
Iowa	12,900					10,050		
Kansas	6,300	260			3,000	4,530		15,200
Kentucky	1,370					2,050		1,120
Louisiana	470	310		950		1,100		
Maine	30							
Maryland	440					495		650
Massachusetts	14							
Michigan	2,250					2,190	135	800
Minnesota	8,200					7,400	412	2,440
Mississippi	490	1,040	26	314		2,300		120
Missouri	3,450	800	23	440		5,900		1,340
Montana	135						24	10,560
Nebraska	10,100				290	5,300	47	2,000
Nevada	20							
New Hampshire	12							
New Jersey	71					105		
New Mexico	105	110						740
New York	1,010					370		270
North Carolina	890	820	130			1,630		820
North Dakota	3,950					6,650	216	13,150
Ohio	3,400					5,050		1,040
Oklahoma	450	870	18		370	505		8,700
Oregon	95						10	1,480
Pennsylvania	990					610		480
Rhode Island	2							
South Carolina	345	450	83			390		160
South Dakota	5,900				420	5,450		3,040
Tennessee	700	530				1,830		760
Texas	2,200	11,966	240	298	1,700	100		11,000
Utah	75							210
Vermont	94							
Virginia	460	182	30			610		300
Washington	170						2	4,590
West Virginia	41							
Wisconsin	3,750					2,150		530
Wyoming	90						32	220

source: USDA NASS, 2025

Table 16: corn yield and 4-year average by state, 2020 to 2023

state	corn yield (bu/ac)				
	2020	**2021**	**2022**	**2023**	**mean**
Alabama	158	163	118	164	151
Arizona	202	181	220	206	202
Arkansas	184	184	173	183	181
California	187	188	177	178	182
Colorado	116	129	121	122	122
Delaware	160	184	170	189	176
Florida	138	176	164	158	159
Georgia	180	182	175	174	178
Idaho	199	210	216	203	207
Illinois	191	202	214	206	203
Indiana	187	195	190	203	194
Iowa	177	204	200	201	196
Kansas	134	139	115	119	127
Kentucky	184	192	156	187	180
Louisiana	181	183	170	175	177
Maryland	155	175	165	165	165
Michigan	153	174	168	168	166
Minnesota	191	177	195	185	187
Mississippi	180	181	165	181	177
Missouri	170	159	161	153	161
Montana	109	100	112	129	112
Nebraska	180	194	165	182	180
New Jersey	156	163	114	168	150
New Mexico	195	184	149	155	171
New York	157	167	142	159	156
North Carolina	113	149	126	147	134
North Dakota	139	105	130	143	129
Ohio	171	193	187	198	187
Oklahoma	135	150	122	149	139
Oregon	241	240	237	214	233
Pennsylvania	138	169	140	157	151
South Carolina	132	139	122	150	136
South Dakota	162	134	132	152	145
Tennessee	170	170	130	173	161
Texas	128	128	95	122	118
Utah	149	179	165	185	170
Virginia	122	160	167	157	152
Washington	228	248	220	240	234
West Virginia	144	144	168	145	150
Wisconsin	173	180	180	176	177
Wyoming	122	132	153	153	140

source: USDA NASS, 2025

Table 17: number of totalm precision, and affected farms

state	adopters (%)	farming operations			
		total	**precision**	**lower**	**upper**
Alabama	1.18	37,362	441	110	331
Arizona	0.33	16,710	55	14	41
Arkansas	4.59	37,756	1,733	433	1,300
California	5.96	63,134	3,763	941	2,822
Colorado	7.62	36,056	2,747	687	2,060
Florida	1.31	44,703	586	146	440
Georgia	5.52	39,264	2,167	542	1,625
Idaho	21.46	22,877	4,909	1,227	3,682
Illinois	33.82	71,123	24,054	6,014	18,040
Indiana	15.35	53,599	8,227	2,057	6,170
Iowa	30.91	86,911	26,864	6,716	20,148
Kansas	27.20	55,734	15,160	3,790	11,370
Kentucky	2.24	69,425	1,555	389	1,166
Louisiana	6.55	25,006	1,638	410	1,228
Michigan	8.52	45,581	3,884	971	2,913
Minnesota	26.18	65,531	17,156	4,289	12,867
Mississippi	7.23	31,290	2,262	566	1,696
Missouri	8.26	87,887	7,259	1,815	5,444
Montana	19.32	24,266	4,688	1,172	3,516
Nebraska	34.11	44,479	15,172	3,793	11,379
New York	6.92	30,650	2,121	530	1,591
North Carolina	5.45	42,817	2,334	584	1,750
North Dakota	59.52	25,068	14,920	3,730	11,190
Ohio	15.42	76,009	11,721	2,930	8,791
Oklahoma	5.90	70,378	4,152	1,038	3,114
Oregon	1.97	35,547	700	175	525
Pennsylvania	3.09	49,053	1,516	379	1,137
South Carolina	2.78	22,633	629	157	472
South Dakota	26.30	28,299	7,443	1,861	5,582
Tennessee	1.73	63,105	1,092	273	819
Texas	4.60	230,662	10,610	2,652	7,958
Utah	0.30	17,386	52	13	39
Virginia	0.66	38,995	257	64	193
Washington	8.29	32,076	2,659	665	1,994
West Virginia	1.12	22,787	255	64	191
Wisconsin	11.03	58,521	6,455	1,614	4,841
Wyoming	4.13	10,544	435	109	326
Total		**1,813,224**	**211,671**	**52,920**	**158,751**

source: USDA NASS, 2025; McFadden et al., 2023