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Contrasting corn acreage trends in the Midwest and Southeast: The role of yield, climate, economics, and irrigation

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ABSTRACT

The US corn area footprint has changed significantly since the 20th century, declining in the southeastern states while exhibiting an increase or stable variations in the Midwest. As harvested acreage directly impacts the total corn production, understanding the influencing factors is crucial. This study assesses the role of potential drivers on the contrasting trajectories of harvested corn acreage between midwestern and southeastern US. Profit-acreage analysis reveals that antecedent profits/losses have a statistically significant influence on corn acreage changes, with southeastern US, which experienced more loss-making years, also experiencing more frequent reductions in corn acreage. The high number of loss-making years in the Southeast is primarily attributed to the region's low corn yield, influenced by climate and other agro-environmental factors. Using a panel regression model, we find that the loss-making years in the Southeast could have reduced to fewer than 26 out of the considered 45 years, or almost similar to the average in the Midwest, by just increasing the irrigated corn area to 50 %, a realistic irrigated corn area fraction already achieved in several Georgia counties. This underscores the potential for early policy interventions like irrigation facilitation to sustain and expand cropped acreage. However, we also find that this would only be economically feasible with incentives for both the installation and sustained operation of irrigation infrastructure.

1. Introduction

Corn is the highest-produced cereal crop in the world with 1210 million metric tons in 2021 [1]. The United States (US) is the top corn-producing country followed by China and Brazil. Corn production in the US is dominated by Corn Belt states, which are mainly western Indiana, Illinois, Iowa, Missouri, eastern Nebraska, and eastern Kansas. In 2021, the US produced 383 million metric tons of corn which is 31.6 % of the global corn share [1,2], and the Corn Belt states accounted for 60 % of the US corn [2]. Notably, the spatial distribution of corn in the US has changed significantly since the early 20th century [3–6]. Although the importance of the Corn Belt states (e.g., Indiana, Iowa, Ohio, and Missouri) has remained consistent with time, with the fraction of total corn acreage remaining largely unchanged much since the late 19th century, the corn acreage in the southeastern states has shrunk but increased in midwestern states [7]. For example, between 1900 and 2020, the harvested corn area (also referred as corn area or corn acreage, henceforth) in the Great Lakes (Wisconsin, Minnesota, and Michigan) and Northern Plains (North Dakota, South Dakota, Nebraska, and Kansas) regions of the Midwest experienced an increase by around 169 % and 35 %, respectively. During the same period, corn acreage in the Appalachian region (Kentucky, Tennessee, North Carolina, Virginia, and West Virginia) of the Southeast was reduced by 68 %, while the decrease in other southeastern states (Alabama, Georgia, Florida, and South Carolina) was by around 86 %. Corn acreage decline in Southeast has been a result of overall cropland abandonment [5,8]. Notably, corn acreage was widely prevalent in the eastern corn-growing states at the beginning of the 20th century, but the footprint changed and radically moved away from the Southeast by the first half of the century [9]. This dramatic shift led to the continental centroid of corn production shifting by around 279 km towards the north and 157 km towards the west in the last 130 years [7]. To secure the future corn productivity, it is important to understand the factors that contributed to the decline in corn acreage in the Southeast and sustained it in the Midwest. This study fills this

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knowledge gap.

A large volume of literature already exists on the temporal variability of corn yield or corn production per unit area (commonly reported in bushels/acre), and the factors contributing to it. For example, earlier studies have indicated that climate variability and extreme temperature and precipitation events affect crop production [10–16]. Spatial variability of corn yield has been studied extensively as well, with climate and soil characteristics - texture, structure, and porosity - often recognized as dominant controls [17–23]. The soil characteristics regulate the soil water holding capacity, organic matter content, and crop water uptake [24,25]. Given that the total corn production is dependent both on the yield per unit area, and the acreage of it, it is crucial to also understand the corn acreage dynamics. Despite this, only a few studies have discussed the variation of corn acreage with time and the possible controls on it. Green et al. (2017) [26] examined county-level corn acreage changes in the corn belt region, however, their study focused on a relatively recent time period and did not investigate the potential factors influencing the changes in corn acreage. Hart (1986) [27] explored the historical changes in the corn belt, including the role of technological advances in machinery and seed varieties, however, a quantitative analysis of the factors driving corn acreage changes was lacking. Other studies assessed the association between the farmland acreage change –not specifically corn–and the potential factors such as urban expansion, strip mining, governmental policies and geographic and climate impediments [28,29]. Kumar et al. (2013) [4] analyzed the cropland area change in the conterminous US, and showed governmental policies, biophysical suitability, and technological advancement among the determinants of corn footprint change. Lizumi and Ramankutty (2015) [14] presented a review of studies that discussed the climate impacts on crop area, and highlighted the role of technology and farmer decision-making. Ji and Cobourn (2021) [30] provided valuable insights into the behavioral responses of farmers to weather shocks, specifically in relation to their decisions regarding planting acreage. Weersink et al. (2010) [31] also explained the impact of weather and crop yield on crop acreage decisions. Notably, the primary factors that determine crop area dynamics, as discussed in aforementioned studies, can be categorized into one of these two groups, viz. agro-environmental and economic. Agro-environmental factors include type of cultivar, meteorological and hydrological influences such as the impacts of climate, soil, and irrigation, and anthropogenic influences such as farm management practices. Factors such as the price of crop and the net cost of production, which affect profit for a given crop yield are considered economic factors.

Although previous studies have explored factors affecting cropland area changes, here we investigate the contrasting trajectories of corn acreage between the southeastern and midwestern US, and the influencing factors that likely drove this change. The objectives of the study are to-i) examine the historical changes in the corn acreage and profit received by farmers between midwestern and southeastern states during 1975–2020, ii) investigate the comparative roles and significance of agro-environmental and economic factors in driving the contrasting acreage trends, and iii) assess the role of irrigation and associated cost of production on the corn acreage. To this end, we report and explain the distinct trajectories of corn acreage between southeastern and midwestern states over the period 1975–2019 using a county-level analysis. Although the corn acreage in the Southeast has been declining since the beginning of the 20th century, we select a 45-year period for this study due to the availability of economic and ancillary data. Specifically, we consider 4 southeastern states: Alabama (AL), Georgia (GA), North Carolina (NC), Tennessee (TN), and 4 midwestern states: Minnesota (MN), Iowa (IA), Nebraska (NE), and Kansas (KS) in the study. The 8 selected states were among the top 20 corn-producing states in 1900. AL, GA, NC, and TN have had the highest declining rate of corn area while IA, MN, NE, and KS were the fastest corn-growing states based on the linear trend of corn acreage during the 45 year study period (Fig. 1). The study parses the role of economics that determines cost and price, and the agro-environmental factors which influence the corn yield, on corn acreage dynamics in these states. We also assess the potential of irrigation for mitigating declines in corn acreage. Finally, we highlight how economic incentives could potentially intervene and alter the corn acreage trajectory, thus making agriculture more resilient.

2. Methods

2.1. Data

County-level data of corn yield, and acreage and state-level price received are obtained from the United States Department of Agriculture-National Agricultural Statistics Service (USDA - NASS) [2] for 1975–2019 (https://quickstats.nass.usda.gov/). As the price data is only available at the state level, we assume that all counties within a given state received the same price. The irrigated area data is obtained from Mehta et al. (2024) [32] at 5 arcmin resolution and aggregated at county-level. The county-level total crop area dataset is downloaded

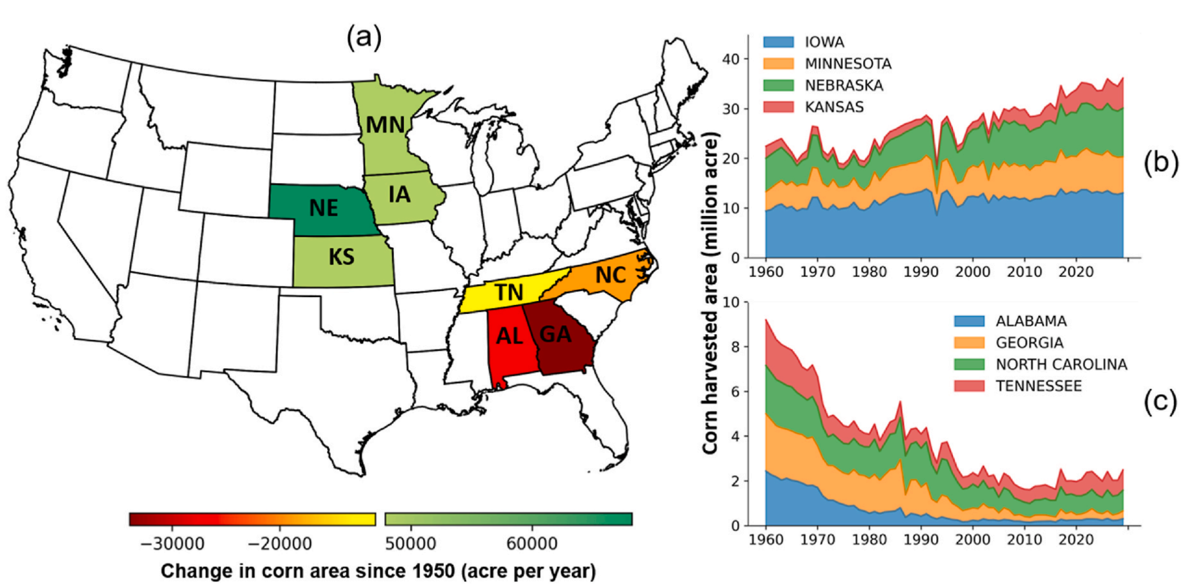

Fig. 1. Corn area trend of four highest growing and shrinking states (a), corn area of midwestern states (b), and southeastern states (c).

from Crossley et al. (2021) [33] and the irrigation fraction is calculated by dividing the irrigated area by the total crop area. The cost of corn production data is obtained from USDA Economic Research Service (ERS) [34]. The data includes the operating costs and allocated overheads, and equates to the sum of total variable cost, fixed cost, and economic cost which includes capital replacement, unpaid labor, and non-land capital. While this data is available at the farm resource region scale, all counties within a farm resource region is assumed to have the same cost (see Supplementary Fig. S1 for georeferenced cost of production). Daily climate data of temperature and precipitation is downloaded from GSWP3-W5E5 product of the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP), which is a bias-corrected reanalysis data derived using both observations and models using the WATCH Forcing Data methodology [35–37]. The dataset is obtained at a spatial resolution of 0.5° and aggregated at the county level for the development of the corn yield regression model. The growing period information is obtained from crop calendar datasets by Sacks et al. (2010) [38].

2.2. Fixed effects panel regression

Given the panel nature of our data, which includes county-level observations of corn yield and climatic variables over time, we employ a fixed effects panel regression model to estimate corn yields. This entity and time fixed effect approach allows explicit accounting of time-invariant county-specific fixed effects and time-varying location-constant fixed effects. Application of panel models is quite more prevalent in climate and crop modeling, as they account for the impact of unobservable variables that are correlated with the climatic parameters [39–43]. We use precipitation, temperature-based metrics of growing and killing degree days, and irrigated fraction as independent variables of the regression model:

$$Y_{it} = \beta_1 P_{it} + \beta_2 GDD_{it} + \beta_3 KDD_{it} + \beta_4 I_{it} + \beta_5 P_{it}^2 + \beta_6 I_{it} P_{it} + \beta_6 I_{it} GDD_{it} + \beta_7 I_{it} KDD_{it} + \alpha_i + \gamma_t + \epsilon_{it} \tag{1}$$

where Y_{it} is the corn yield, P is the precipitation, GDD is the growing degree days, KDD is the killing degree days, I is the irrigation fraction, i.e., the ratio of irrigated area to the total crop area in county *i* and year *t*. We use the linear and quadratic terms for precipitation, and irrigation interaction terms with GDD and KDD. α_i is the county fixed effect, γ_t is the year fixed effect and ϵ_{it} is the error term. County and year fixed effects are included as dummy variables where these variables take a value of 1 for the specific county or year in question and 0 for all others, allowing us to control for spatial and temporal heterogeneity in our analysis.

Daily GDD, and KDD are evaluated using maximum and minimum temperatures:

$$GDD = \min\left(\frac{T_{max} + T_{min}}{2} - T_b, T_h - T_b\right) \tag{2}$$

$$KDD = \max\,(T_{max} - T_h, 0) \tag{3}$$

where T_{max} is the maximum temperature (°C), T_{min} is the minimum temperature (°C), T_b is a baseline temperature, and T_h is an upper bound temperature. In this study, the baseline and upper bound temperatures are set to 9 °C and 29 °C, respectively, following previous studies [44, 45]. GDD is considered zero when the $0.5*(T_{max} + T_{min})$ is lower than T_b. Daily GDD (or KDD) values are then summed for the growing season.

2.3. Profit calculation

The county-level annual profit per unit area is calculated by subtracting the cost of corn production from the total production value i.e. the multiplication of yield and price of corn (eq. (4)).

$$P = Y * Pr - CoP \tag{4}$$

where P is the profit ($\$ ac^{-1}$), Y is corn yield ($bu\ ac^{-1}$), Pr is the price of corn ($\$ bu^{-1}$) and CoP is the cost of corn production ($\$ ac^{-1}$). Here ac and bu indicate Acres and Bushels of corn respectively.

3. Results

3.1. Corn yield estimation

We assess the relation between corn yield and climate variables, as well as irrigation, using a fixed-effects panel regression model for counties across 8 selected midwestern and southeastern states. The regression model is able to explain 73 % of the variation in corn yields. Precipitation, GDD, and irrigation fraction show a positive association with corn yields, while KDD exhibits a negative relation (Table 1). To examine the joint effects of irrigation and climate variables, we include interaction terms in the regression. The interaction between irrigation and GDD has a negative association with yield, while the interaction between irrigation and KDD shows a positive relation. This suggests that irrigation helps alleviate the negative impact of KDD on corn yields, a finding consistent with Zaveri and Lobell (2019) [41]. The sensitivity of yields to KDD is higher in southeastern counties (except for a few highly irrigated counties in Georgia) compared to the more heavily irrigated counties in Nebraska and Kansas, due to the mitigating effect of irrigation (Fig. S2).

The modeled corn yield is used to calculate the county-level farm profit in USD per acre. The county profit is aggregated to the state-level to determine the number of negative profit years (NPY) experienced by each state. NPY or loss making years, used interchangeably henceforth, are the number of years with negative profit. Here profit for any given year within a state is evaluated using equation (4). The modeled NPYs and the observed NPYs showed close agreement, with a root mean squared error of 2 years (Fig. S3), indicating the satisfactory performance of the NPY estimation.

3.2. Corn acreage and profit dynamics

Corn acreage in the Southeast showed a declining trend from the last midcentury while it is increasing or steady in the Midwest. The four southeastern states considered in this study lost around 2,250,000 acres of corn (a reduction of 47 %) while the four midwestern states gained around 10,330,000 acres (an increase of 40 %) from 1975 to 2019. Notably, most southeastern states also experienced a higher frequency of NPYs in them (Fig. 2a). The average NPY in southeastern states is 35.25 while for midwestern states, this value is 22.75. NC and AL experienced negative profit in almost twice the number of years than average of IA, NE and KS. For the initial 20 years from 1975, the midwestern region consistently surpassed the southeast in terms of profit. However, both regions encountered a downturn in profit over the subsequent decade. Following this decline, profits rebounded in both regions over the subsequent five years, with the midwestern states experiencing a more pronounced increase (Fig. 2b). Conspicuously, the NPY in MN is

Table 1
Fixed-effects regression analysis. P is the precipitation, GDD is the growing degree days, KDD is the killing degree days, and I is the irrigation fraction. I*P, I*GDD and I*KDD are the interaction terms of precipitation, GDD and KDD with irrigation fraction, respectively.

Predictor	Coefficient	Std. Error	p-value
P	0.0992	0.0072	0.0000
GDD	0.0638	0.0030	0.0000
KDD	−0.1851	0.0050	0.0000
I	112.59	37.727	0.0028
P^2	−7.781e-05	5.922e-06	0.0000
I.P	−0.0042	0.0095	0.6610
I.GDD	−0.0684	0.0184	0.0002
I.KDD	0.2884	0.0238	0.0000

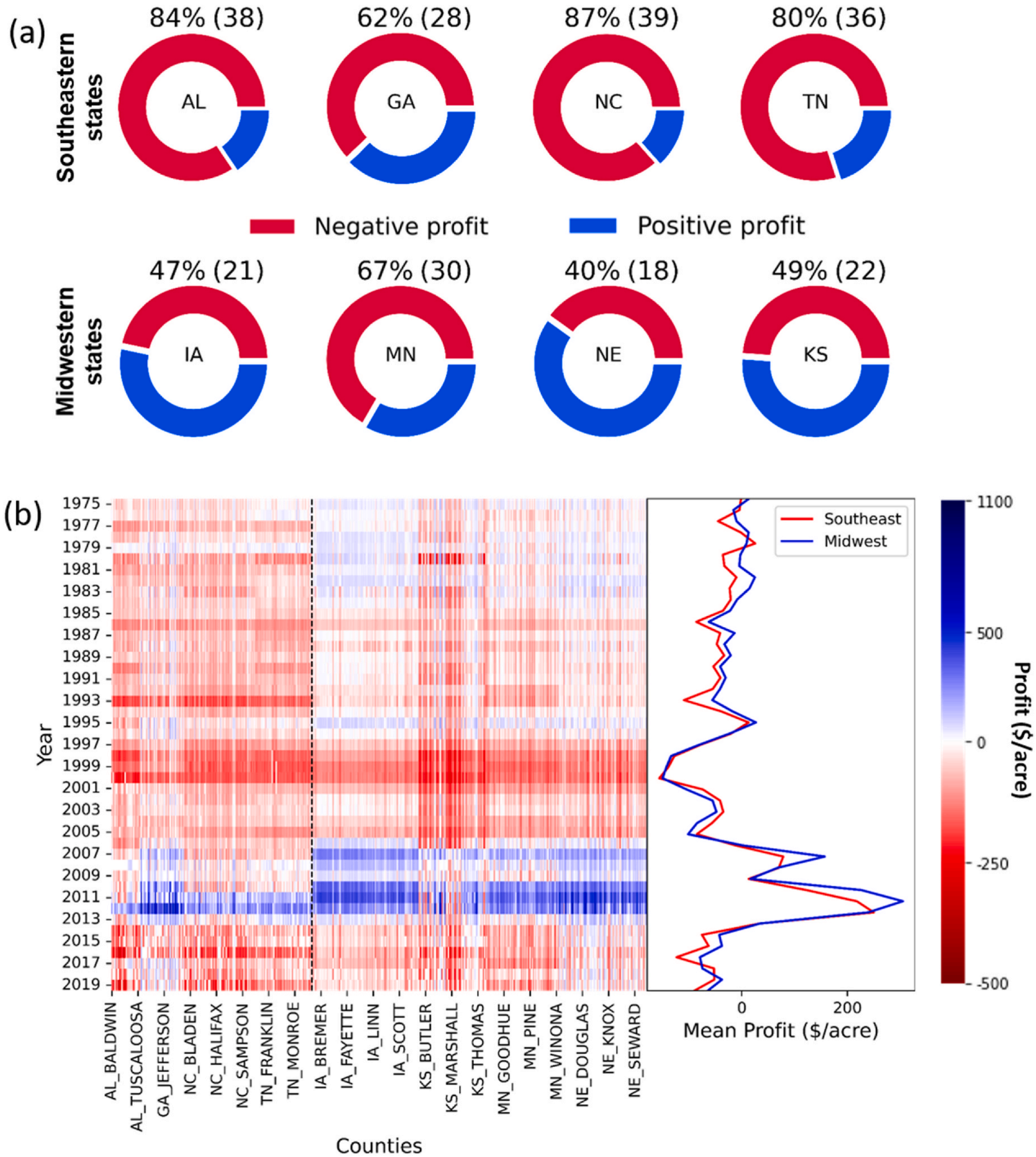

Fig. 2. (a) Fraction and the number (shown within parenthesis) of negative profit years (NPYs) in the southeastern (top) and midwestern (bottom) states. Number of analysis years is 45. Average NPY in the midwestern states is 22.75 versus 35.25 in the southeastern states. (b) Heatmap shows the county-wise profit for each year. While the x-axis includes all considered counties within the four southeastern states, to ensure readability, only a few selected counties from each state are labeled on the x-axis. Southeastern and midwestern counties are separated by dashed black line. The accompanied time series of mean profit for both the regions are shown on the right.

relatively higher than other midwestern states.

Overall, the contrasting trajectories of corn acreage between southeastern and midwestern states are associated with differences in NPYs between these two regions. This is because negative profit predisposes farmers to cut-back on the cropped area [30]. At the first glance, the acreage generally appears to decrease in the following year(s) if the farmer profit is negative, and increases or shows a steady trend when it is positive (Fig. S4). The profit per unit area soared after 2010 in all the states, which ceased the decreasing trend of the cropped area in the Southeast. In fact, the area in southeastern states either starts increasing or stops decreasing further after this period. However, it is difficult to simply quantify year-to-year variations in the corn acreage vis-a-vis profit. To understand how past years' profits impact changes in corn acreage, we perform a non-parametric Wilcoxon rank-sum test across all counties to assess the difference in the corn area changes in years following negative profits versus years following positive profits.

At a 95 % significance level ($p < 0.05$), the change in corn acreage is found to be significantly smaller (mean acreage change = −193 acres) in years following negative profits compared to years following positive profits (mean acreage change = 1331 acres). Notably, the changes remained significant when we considered the profits till the past 5 years (Fig. S5). This indicates that the recent year's profit plays a particularly important role in farmers' decisions on corn planting, compared to the profitability in older time periods. These findings align with conclusions in previous studies [30] that farmers' acreage and crop allocation decisions depend on recent crop yields. However, the response of acreage to profit may exhibit a complex non-linear delayed response relationship to both reinforcement and recency [30]. In addition, interannual variation of corn acreage is also affected by latent variables, such as offered subsidies and crop insurances [46–48]. Notably, these offerings vary both in space and time. For instance, farmers in Iowa, Minnesota, Nebraska and Kansas received around 27 % of the total farming subsidies, while Alabama, Georgia, North Carolina and Tennessee received just about 6.8 % from 1995 to 2020 [49].

Furthermore, farmer's economic status, age, land ownership type, social support, etc. may also influence the response of farmer to profit/loss. Although there is an expected positive covariation between corn acreage changes and profit in preceding years (Fig. S6) with a positive slope in most states, the correlation is not notably strong. For this reason, the analysis regarding the contrasting trajectories of corn area vs. profit is limited to the frequency of NPYs rather than the magnitude of profit.

3.3. Influence of climate contrast on NPY frequency differences between southeastern and midwestern states

To assess the extent to which the difference in climate between the two regions impacts the relative profits, and consequently NPYs, we use the statistical model of yield that was detailed in section 2.2 and subsequently implemented and validated in section 3.1. Specifically, we substitute the climate of the southeastern counties with mean climate of the midwestern states to estimate new yields for the southern counties. This substitution allows assessment of the influence of climate contrast on differences in yield between the two regions. Results indicate alterations in the yield and consequently the profit in southeastern states (Fig. 3). Climate of KS and NE generally caused much more reduction in profit than the climate of IA and MN. This makes sense as the mean precipitation of IA and MN is higher while mean KDD is lower compared to NE and KS and precipitation has a positive while KDD has a negative association with corn yield. The climate of MN reduces NPY in all the southeastern states (except for TN where it does not change). In contrast, IA climate reduces NPY in only AL, while increases in NC and TN. The climate of NE increases NPY in all the states indicating a reduction in county-level profit, in general (Table 1). Similarly, KS climate increases NPY in all southeastern states except AL.

Overall, the substitution causes both increase and reduction in the NPYs in the southeastern states, with change in NPYs ranging from −14 to 9 (Table 2). These findings highlight the influence of regional climatic differences on the profitability and productivity of corn cultivation in

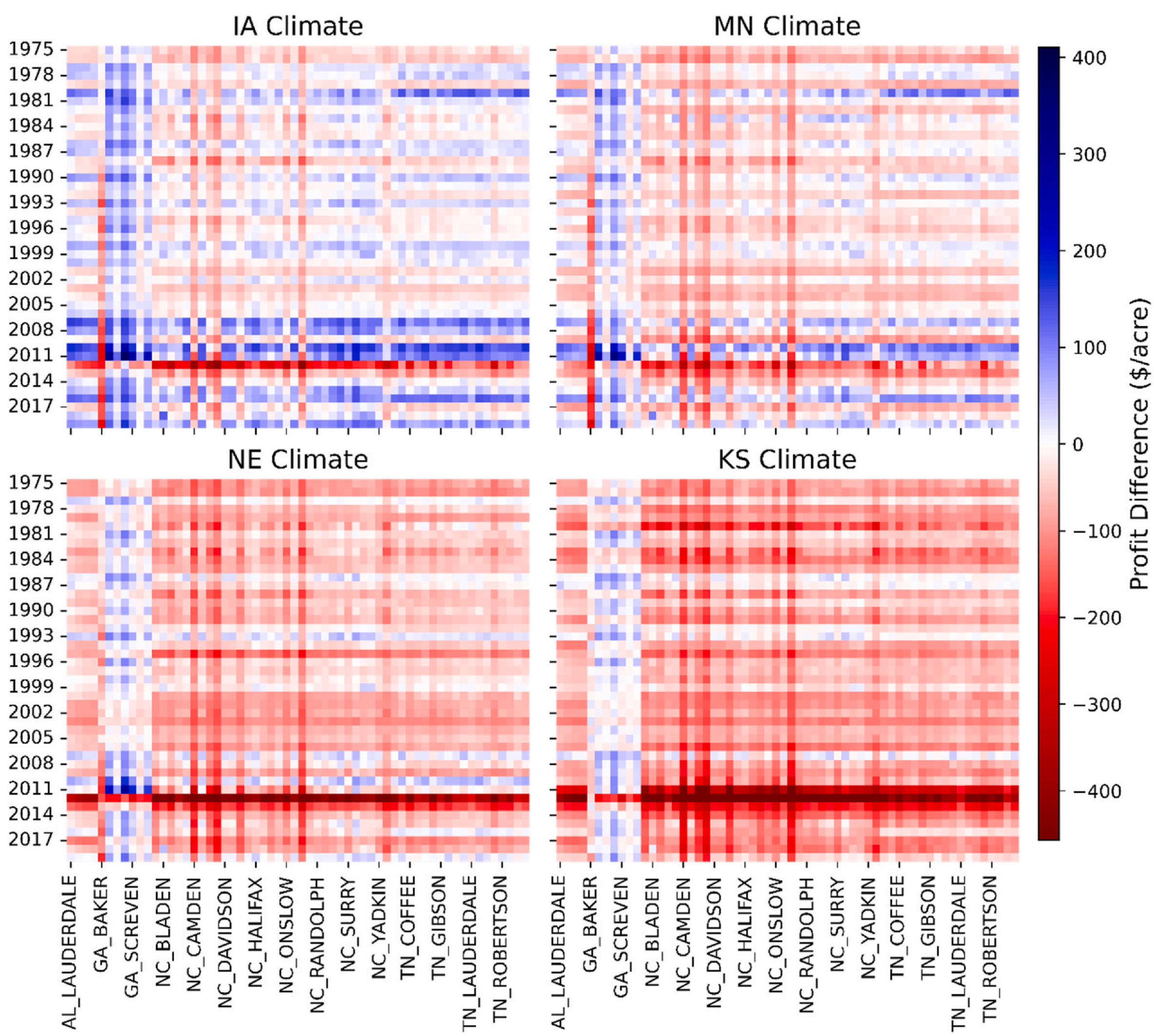

Fig. 3. Profit changes in southeastern counties when mean midwestern state climate is substituted. While the x-axis includes all considered counties within the four southeastern states, to ensure readability, only a few selected counties from each state are labeled on the x-axis. Panel headings of IA, MN, NE, and KS Climate denote substitution by the average climate of Iowa, Minnesota, Nebraska, and Kansas, respectively, in southeastern counties. AL, GA, NC, and TN followed by underscore and then county names indicate counties belonging to Alabama, Georgia, North Carolina, and Tennessee, respectively.

Table 2
Change in the number of negative profit years (NPY) in southeastern states (in columns) after substituting climate, corn yield and, cost of production and price of midwestern states (in rows). Negative change means reduction in NPYs indicating increase in profitable years after climate substitution.

	Alabama	Georgia	North Carolina	Tennessee
Climate replacement				
Iowa	−3	2	3	6
Minnesota	−14	−6	0	0
Nebraska	2	3	5	6
Kansas	−1	4	6	9
Yield replacement				
Iowa	−33	−30	−34	−24
Minnesota	−24	−19	−24	−13
Nebraska	−36	−31	−37	−26
Kansas	−26	−19	−22	−18
Cost of production and price replacement				
Iowa	5	5	3	2
Minnesota	11	11	10	7
Nebraska	4	4	3	3
Kansas	5	6	5	4

the southeastern and midwestern states. However, it is to be noted that the reduction in NPYs over southeastern states is relatively modest, and does not fully explain the significant difference in the NPYs between southeastern and midwestern states. It is likely that other agro-environmental and/or economic factors, such as soil properties, fertilizer input, crop management, crop price and cost of production, and irrigation practices are additional driving controls on contrasting trajectories.

3.4. Impact of economic factors and yield on contrasting corn acreage trajectories

Profit from corn production (see Eqn. (4)) is a function of price and cost, and yield. Corn prices vary from state to state based on the interaction between supply and demand while the cost of production depends on the farm inputs – chemicals, fertilizers and seeds, machinery, rent, labor, taxes, etc. To assess the role of economic factors such as price and cost, and agro-environmental factors that determine the yield on contrasting corn area trajectories, two scenario simulations are performed. Scenario 1 involves substituting the mean corn yield of the midwestern states for the profit calculation of the southeastern states. Since corn yield is a result of agro-environmental forcings, this scenario captures the profit in southeastern states if they have these settings identical to that in the midwestern states. Scenario 2 involves the evaluation of profit under the assumption that the price (Pr) and cost of production (CoP) of southeastern states are identical to that in the midwestern states.

The profit increases and the trajectory shifts upwards in scenario 1. Our analysis shows that substitution of corn yield increases profit in majority of southeastern counties, whereas substitution of cost and price reduces the profit (Fig. 4). Midwestern corn yields increase profit in almost all southeastern counties, except for a few in GA. The replacement of KS yield reduces the profit in the last decade. In the case where cost and price of Midwest are used for the Southeast, the profit in southeastern counties generally, though not always, reduces. The substitution of economic terms increases the frequency of NPYs by a few years in all southeastern states, however, the substitution of the yield reduces NPYs significantly (Table 2). This shows that if the southeastern states had yields similar to the midwestern states, the number of NPYs would have been significantly lower. The largest change occurs in North Carolina where the NPY reduces by 37 years when the yield of Nebraska is substituted. The change in NPY is in general higher when the yield of either Iowa or Nebraska is substituted in the profit models of southeastern states.

These results highlight that agro-environment makeup of the Midwest is crucial in reducing the frequency of NPYs. Overall, higher corn yield in the Midwest is likely facilitated by better climate, agro-environmental factors such as soil fertility, management practices, and water-retaining property of soil of the Corn Belt region, and the accessibility to irrigation water [50–53].

3.5. Impact of irrigation expansion and incentives on NPYs

Next, we examine whether a greater extent of irrigated agriculture in the Southeast can significantly alter the frequency of NPYs. To assess this, we consider scenarios with varying minimum irrigation area fractions (10 %–100 % of total crop area). For counties with existing irrigation exceeding a scenario's fraction, the current irrigated area is

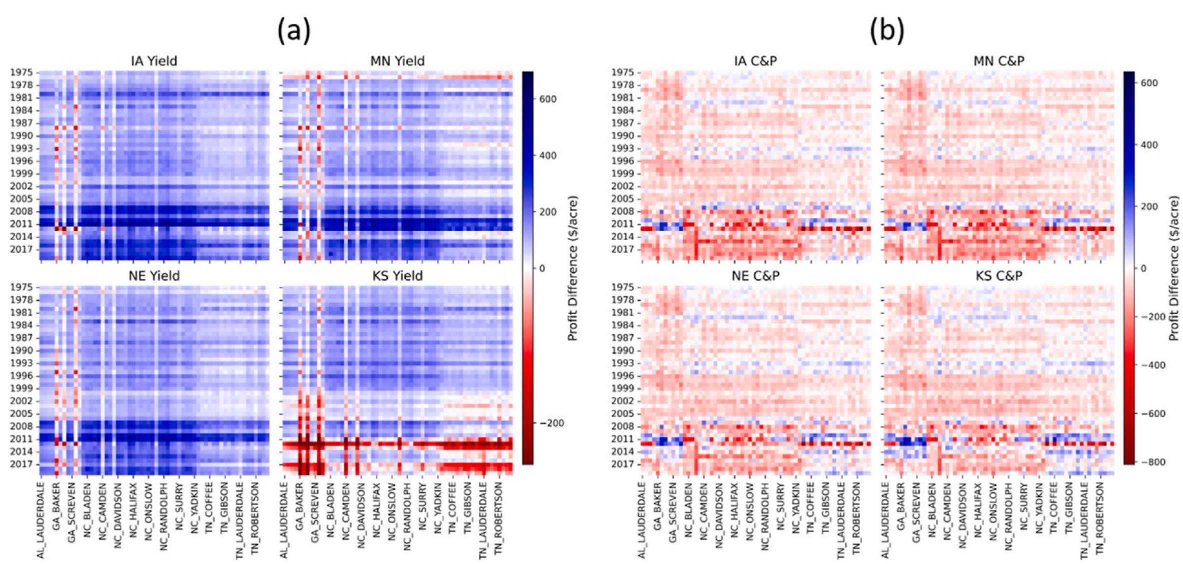

Fig. 4. Profit difference when mean (a) corn yield, and (b) cost of production and price of midwestern states are substituted to southeastern states. While the x-axis includes all considered counties within the four southeastern states, to ensure readability, only a few selected counties from each state are labeled on the x-axis. Panel headings of IA, MN, NE, and KS Yield (C&P) in the left (right) panel denote substitution by the average yield (cost of production and price) of Iowa, Minnesota, Nebraska, and Kansas, respectively, in southeastern counties. AL, GA, NC, and TN followed by underscore and then county names indicate counties belonging to Alabama, Georgia, North Carolina, and Tennessee, respectively. C&P stands for cost of production and price.

maintained. These new irrigation fractions are used within the partial regression model (see model details in section 2.2 and validation in section 3.1) to obtain revised estimates of yield. The cost of production (see Eq. (4)) increase due to irrigation expansion is also taken into consideration in the analysis. Based on the available literature and data [54,55], the irrigation cost (including pumping, maintenance, and water purchase costs only) can range between $50 and $150 per acre. Therefore, irrigation can increase the cost of corn production by 10%–50 %, although the exact increase depends on factors such as the type of irrigation system, farm size, energy source, and location. Including installation costs would further increase the overall cost. Our scenario analysis assumes a 0 %, 15 %, 30 %, 45 %, 60 %, and 75 % increase in the cost of production due to irrigation. Unsurprisingly, the corn yield increased in all irrigation expansion scenarios, however, the NPYs variation is found to depend on both yield and the cost. When no increase in cost of production is associated with the irrigation expansion, the NPYs reduce for all states (Fig. 5). The rate of reduction reduces with an increase in cost. Notably, the NPY starts to increase for NC at 45 % increase in cost of irrigated for lower magnitudes of minimum irrigation expansion fraction. At 45 % cost increase, the NPY reduces to 26, 5, 34, and 32 for AL, GA, NC and TN, respectively for irrigated corn area fraction equal to one. Higher NPY reduction for GA can be attributed to the initial high irrigation percentage in the state. Notably, more than 25 % of counties growing corn in GA have at least 0.5 irrigated area fraction. Over the four selected southeastern states, irrigated corn area fraction of 0.5 reduces the mean NPY from 35.25 to 12.75, 18.50, 25.50, 29.50, 32, and 34.50 for 0 %, 15 %, 30 %, 45 %, 60 % and 75 % cost increase scenarios, respectively. In other words, a 15 %–30 % increase in production costs due to irrigation expansion—for an irrigation area fraction of 0.5, a realistic figure already achieved in several Georgia counties—could reduce NPY similar to those in the Midwest. These results suggest that irrigation expansion could be a viable strategy to reduce NPYs and counteract the decline in corn acreage in the Southeast. However, to make this feasible, economic incentives such as tax breaks and loans may be necessary to lower irrigation costs and keep production costs for irrigated agriculture preferably below 130 % of rain-fed agriculture. Notably, the installation costs of irrigation infrastructure could make the transition from rain-fed to irrigation-fed agriculture even more economically prohibitive.

4. Discussion

Southeastern states have faced a significant loss in corn acreage over the last century which has affected their economy as the rural population is greatly dependent on agriculture. For example, in 1950, Alabama had around 2 % share of the value of crop production and ranked 18th while Iowa had 3.7 % and ranked 6th in the US. This has now changed to 1.3 % and 28th rank and 6.2 % and 3rd rank in 2020 for Alabama and Iowa, respectively [56]. A similar scenario has unfolded in other southeastern states too. Notably, such drastic change has happened despite the fact that the Southeast receives abundant water availability through precipitation with an average annual rainfall of 1200 mm [57] and other suitable climatic conditions for crop growth [58]. To make crop production and associated markets more resilient in the future, and to possibly devise strategies to stem or even invert large scale decreasing trends in crop acreage, this study quantified the relative roles of economic and agro-environmental factors on this trend.

Our analysis of the 8 states indicates that the farmer's decision about planting corn depends on the profit. Corn profit in southeastern states has been lower than the Midwest, which led to the declining corn area trajectory there. Results also highlight that instead of the economic factors such as cost and price, it was the contrast in yield that majorly determined the divergence in profitability in the two regions. These yield differences could be due to a range of agro-environmental factors, including differences in climate, soil properties (e.g. organic content, pH, sodicity) [59], management practices such as hybrid seed adaptation, crop rotation, fertilizer application, increasing plant density, etc. [60,61], and irrigation. We find that if the southeastern states were provided with irrigation assistance, it could have significantly reduced NPYs. For example, increasing irrigation to a minimum of 50 % of corn area in each county within the southeastern states reduced average NPY to 25.5 from 35.25, for scenario where irrigated agriculture production cost is 30 % higher than that of rain-fed. This could have in turn possibly stemmed or reduced the corn acreage decrease. The same strategy can be used in future as well to ensure resilience of corn acreage. However, as noted earlier, the strategy would be feasible only if appropriate economic incentives such as tax breaks and loans may be provided both for installation and sustained operation of irrigation infrastructure. Notably, just because rain-fed to irrigation-fed transition can yield increased profits, does not always mean that farmers will partake in such a transition. Facilitating such transition may also depend on other factors such education, persuasion, training, and enablement through legislations [62]. While each state may encounter unique physical and political obstacles, the rapid shift from rain-fed to irrigation-fed agriculture in Georgia during the latter part of the previous century [63], a transformation attributed to i) the implementation of high-capacity center-pivot irrigation systems in the abundant Floridian aquifers with high water availability at an affordable cost, ii) a series of agricultural droughts that heightened farmers' awareness of the benefits of irrigation for improving crop resilience and yields, and iii) substantial support

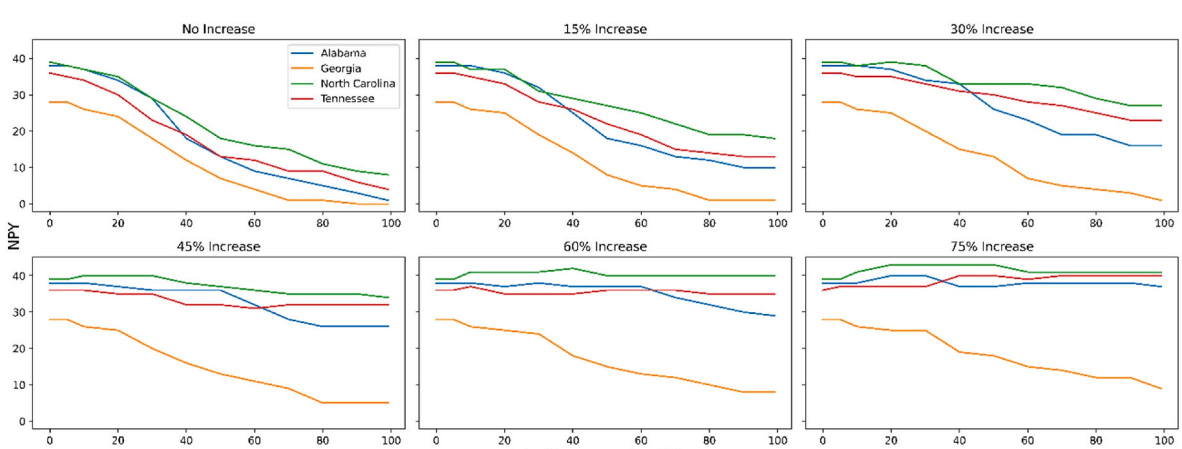

Fig. 5. Change in the number of negative profit years (NPYs) with increasing irrigated corn area fraction (i.e., irrigated corn acreage/total corn acreage) for various magnitudes of production cost differences between irrigated and rain-fed agriculture. A 0 % cost increase scenario indicates no increase in cost with irrigation expansion, whereas, a 75 % increase scenario indicates the cost of production of irrigated agriculture to be 1.75 times that of rain-fed.

from agricultural extension organizations, remains a potential template.

It is to be noted that in scenarios exploring the impact of irrigation expansion on yield, there is a likelihood of reduction in corn price because of surplus production [64,65]. This has not been explicitly considered in our analysis. It is expected that the feedback of increased production on reduced costs will likely alter NPYs, however the extent of it is difficult to quantify due to concomitant changes in market conditions that it may bring. Despite these simplifications, overall, the results show that expansion of irrigated land has the potential to not only enhance corn yield and acreage in the region, but also to strengthen the nationwide corn productivity by promoting a more distributed growing center, making it more resilient to extreme weather conditions.

It is to be noted that while irrigation aids in buffering against the adverse climate stress, thereby making corn yield relatively more resilient compared to rainfed settings [10,66–73], additional irrigation may exert pressure on local water resources, impact streamflow, or exacerbate water scarcity [74–81] and deteriorate water quality [82]. Therefore, large scale facilitation of irrigation expansion should be executed with an understanding of its impact on local and inter-basin water resources. Notably, the relationship between corn acreage and farmer profit is a complex one, with various factors influencing the decision-making process of farmers. While the profit is a significant factor in determining overall corn acreage trajectories, it cannot fully explain the interannual corn area dynamics. Some of the controls on corn acreage dynamics, such as the price and costs, can be volatile or responsive to the national or international macro-economic environment, accounting for such risks is also needed while making long term decisions to favorably alter the crop acreage dynamics [83]. For example, the 1980s farm crisis resulted in high debt loads and a reduction in land prices, which significantly affected prices and costs for US farmers. Similarly, increased demand for corn for bioenergy production due to the biofuel mandates also had an effect on economics. An additional factor that may need consideration is large scale socio-economic transitions. For example, the rural population is on the decline overall [84]. Also, the average age of farmers has been increasing in the last four decades [85]. These changes, coupled with the changes in climate and advances in biotechnological interventions are likely to also impact the agro-environmental and economic controls on corn acreage dynamics.

5. Conclusions

This study highlights the contrasting trends in corn acreage between the southeastern and midwestern US states during 1975–2020. Despite favorable climatic conditions in the Southeast, lower corn profits in these states compared to the Midwest are found to have driven this contrast. Yield differences influenced by agro-environmental factors and management practices, rather than differences in just climate or production costs, play a crucial role in this profitability gap. Irrigation emerges as a potential strategy to reduce negative net profit years and stabilize or increase corn acreage in southeastern states. However, our analysis indicates that the economically feasible implementation of irrigation expansion would likely require financial incentives and ancillary supporting measures. While expanding irrigation can enhance corn productivity, it must be approached with caution to avoid adverse impacts on water resources and quality. Overall, the relationship between corn acreage and farmer profit is multifaceted, influenced by various socio-economic and policy-related factors. Addressing these complexities is essential for developing effective strategies to sustain and enhance corn production in the face of changing environmental and economic conditions.

Data availability statement

All the datasets used in this study are freely available. Corn yield, acreage, and irrigation information are obtained from USDA-NASS (https://quickstats.nass.usda.gov/), cost of production data are obtained from USDA-ERS (https://www.ers.usda.gov/data-products/commodity-costs-and-returns), climate data are obtained from ISIMIP (https://data.isimip.org/).

CRediT authorship contribution statement

Lokendra S. Rathore: Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Mukesh Kumar:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization. **Richard T. McNider:** Writing – review & editing, Methodology. **Nicholas Magliocca:** Writing – review & editing, Methodology. **Walter Ellenburg:** Writing – review & editing.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Mukesh Kumar reports financial support was provided by the United States National Science Foundation Division of Earth Sciences and Office of Integrative Activities. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jafr.2024.101373.

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