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Crop management and phenology trends in the U.S. Corn Belt: Impacts on yields, evapotranspiration and energy balance

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ABSTRACT

Crop yields are affected by many factors, related to breeding, management and climate. Understanding these factors, and their relative contributions to historical yield increases, is important to help ensure that these yield increases can continue in the future. Two important factors that can affect yields are planting dates and the crop's growing degree day (GDD) requirements. We analyzed 25 years of data collected by the USDA in order to document trends in planting dates, lengths of the vegetative and reproductive growth periods, and the length of time between maturity and harvest for corn and soybeans across the United States. We then drove the Agro-IBIS agroecosystem model with these observations to investigate the effects of changing planting dates and crop GDD requirements on crop yields and fluxes of water and energy. Averaged across the U.S., corn planting dates advanced about 10 days from 1981 to 2005, and soybean planting dates about 12 days. For both crops, but especially for corn, this was accompanied by a lengthening of the growth period. The period from corn planting to maturity was about 12 days longer around 2005 than it was around 1981. A large driver of this change was a 14% increase in the number of GDD needed for corn to progress through the reproductive period, probably reflecting an adoption of longer season cultivars. If these changes in cultivars had not occurred, yields around 2005 would have been 12.6 bu ac^{-1} lower across the U.S. Corn Belt, erasing 26% of the yield increase from 1981 to 2005. These changes in crop phenology, together with a shortening of the time from maturity to harvest, have also modified the surface water and energy balance. Earlier planting has led to an increase in the latent heat flux and a decrease in the sensible heat flux in June, while a shorter time from maturity to harvest has meant an increase in net radiation in October.

1. Introduction

Over the next few decades, the world's farmers will face increasing pressure to grow more food on less land. Growing population, rising per-capita consumption, and the use of agricultural products as biofuels will all demand increasing crop yields. In the U.S., yields of two major crops, corn and soybeans, have steadily increased since the mid-20th century (Duvick, 2005; Egli, 2008; Kucharik and Ramankutty, 2005). For corn, these yield increases have been attributed ~40–50% to improved management and ~50–60% to breeding (Duvick, 2005; Lee and Tollenaar, 2007). Management factors that have contributed to this yield increase include increasing applications of fertilizer, irrigation and herbicides, higher plant densities, and increasing mechanization (Egli, 2008). Breeding factors include improved stay-green characteristics during the grainfill period, increased stress tolerance, and tolerance to high plant populations through more upright leaves and reduced lodging (Duvick, 2005; Duvick and Cassman, 1999; Egli, 2008). Climatic changes, such as a longer growing period, lower summer temperatures and higher summer precipitation rates may also have contributed to these yield increases (Andresen et al., 2001; Lobell and Asner, 2003; Twine and Kucharik, 2009). A better understanding of the factors responsible for these historical yield increases would help ensure that yields can continue to increase in the future. However, since many factors have been changing simultaneously, it is difficult to separate their effects.

Two factors that may have contributed to historical yield increases are the adoption of cultivars with a longer grainfill period and a shift to earlier planting dates (Bruns and Abbas, 2006;

Abbreviations: ET, evapotranspiration; G, soil heat flux; GDD, growing degree days; GDD$_{\mathrm{mat}}$, GDD between planting and maturity; GDD$_{\mathrm{reprod}}$, GDD between R1 and maturity; GDD$_{\mathrm{veg}}$, GDD between planting and R1; H, sensible heat flux; LAI, leaf area index; LE, latent heat flux; NASS, National Agricultural Statistics Service; R1, start of the reproductive period; R_{net}, net radiation; USDA, U.S. Department of Agriculture.

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Duvick, 2005; Egli, 2004; Egli and Cornelius, 2009; Howell et al., 1998; Kucharik, 2008; Lauer et al., 1999; Lee and Tollenaar, 2007; Norwood, 2001). A longer grainfill period increases the length of time devoted to yield accumulation. Earlier planting can increase yields by increasing the length of the vegetative period, and possibly the grainfill period (Bastidas et al., 2008; Nielsen et al., 2002; Robinson and Wilcox, 1998; Wilcox and Frankenberger, 1987). A longer vegetative period generally means higher leaf area, which in turn means faster dry matter fixation.

In addition to their importance for crop yield, changes in crop phenology can also affect the surface water and energy balance (Twine et al., 2004). Changes in the timing and duration of when the surface is vegetated vs. bare can alter the surface albedo, the longwave radiation budget, and the partitioning of net radiation (R_{net}) into sensible (H) and latent (LE) heat fluxes (Foley et al., 2003). These changes, in turn, can affect climate regionally and perhaps even globally (Betts et al., 2007; Lobell et al., 2006). Thus, knowledge of how crop phenology has changed in the past and what this has meant for fluxes of water and energy can help us understand historical climatic patterns and better predict future changes.

Across the U.S. Corn Belt, corn planting dates have been getting earlier over the last few decades (Kucharik, 2006). This seems to be an extension of a trend going back to the mid-20th century or earlier (Duvick, 1989; McGarrahan and Dale, 1984). A trend to earlier soybean planting has also been documented for a few states (Conley and Santini, 2007; Irwin et al., 2008), but this has not been analyzed comprehensively. Along with these trends to earlier planting, trends to a longer grainfill period in corn and soybeans have been documented based both on studies of particular cultivars (Duvick, 2005; Egli, 2004) and on analyses of state-level statistics of crop growth periods (McGarrahan and Dale, 1984). However, there has been no comprehensive documentation of these trends to a longer grainfill period across the U.S., or of trends in the length of the vegetative growth period. Furthermore, there have been no regional analyses of the contribution of longer season cultivars to crop yields and the surface water and energy balance.

For this study, we analyzed weekly crop progress observations for corn and soybeans from 1981 to 2005, collected by the U.S. Department of Agriculture (USDA). We document trends in planting dates, lengths of the vegetative and reproductive growth periods, and the length of time between maturity and harvest. These analyses cover 15 states that comprise over 80% of the nationwide growing areas of these crops. We then combined these observations with gridded temperature data to determine how the number of growing degree days (GDD) between corn development stages has changed over the last few decades, as a measure of changes in crop cultivars. In addition, for corn, we used these observations to drive the Agro-IBIS agroecosystem model, performing a regional analysis of the effects of these observed trends on crop yields. By using a process-based model, we can isolate the effects of changing planting dates and crop GDD requirements, and estimate how much of the observed yield increase over the last few decades is attributable to these factors. Finally, we also used the model to investigate how surface water and energy fluxes have changed as a result of these changes in crop management and phenology.

2. Methods

2.1. Analysis of crop progress data

We determined the timing of crop development stages using weekly, state-level crop progress observations collected by the USDA's National Agricultural Statistics Service (NASS). These observations report the fractional acreage in each state that has reached or passed a given development stage by the end of the week. NASS collects county-level estimates from over 5000 observers across the U.S., and weights these estimates by crop acreage to derive state-level averages. These data are distributed via the USDA's Weekly Weather and Crop Bulletins (USDA-OCE, 2010), and also via NASS's Quick Stats service starting in 1985 (USDA-NASS, 2010). We used data from 1981 to 2005; 1981 was the first year for which we could obtain continuous records of all variables of interest, and 2005 was the last year for which we had climate data.

We analyzed corn and soybean data for planting, harvest and two intermediate development stages: the start of the reproductive period (hereafter referred to as R1) and physiological maturity. For corn, we used the silking and maturity progress reported by NASS to characterize these stages; for soybeans we used blooming and dropping leaves (definitions of these terms are in USDA-NASS, 2009). We refer to the period from planting to R1 as the vegetative period, from R1 to maturity as the reproductive period, and from planting to maturity as the growth period. Note that both the vegetative period and the growth period include the period from planting to emergence. For corn, we use "grainfill period" interchangeably with "reproductive period"; we use the former especially when discussing model results, for consistency with how Agro-IBIS defines this period.

For corn, our analyses encompassed the 12 major Corn Belt states (IL, IN, IA, KS, KY, MI, MN, MO, NE, OH, SD, and WI, accounting for 85% of the national harvested area). For soybeans, we used the 13 states with continuous data over the analysis period (AR, IL, IN, IA, KS, KY, LA, MI, MN, MO, NE, OH, and TN, accounting for 81% of the national harvested area).

We interpolated the weekly crop progress observations using the PCHIP (Piecewise Cubic Hermite Interpolating Polynomial) method available through the "signal" package in the R statistical package (www.r-project.org/). PCHIP is a non-linear interpolation method that maintains the monotonicity of the data. Based on this interpolation, we determined the day at which planting, R1, maturity and harvest were 50% complete for each crop–state–year combination. In this paper, references to the planting date, R1, maturity or harvest date denote 50% completion. Occasionally, data collection ended before progress was 50% complete, or began after progress had already reached 50%. In these cases, we estimated the date of 50% completion using dates of 25% or 75% completion (or 10% or 90% completion if the 25% or 75% dates were not available) and the average time between the dates of, for example, 25% completion and 50% completion for that crop in that state.

We then derived a weighted average interpolated record for the U.S. as a whole: for each day, we computed the weighted average percent progress across the 12 (corn) or 13 (soybean) states. The weighting was based on the crop's average harvested area in each state, across the years 1981–2005 (from NASS's Quick Stats: USDA-NASS, 2010). Thus, we used the same weights in each year to eliminate the possible effects of shifting cultivation areas on the trends in planting date and development times (although our analyses could still be slightly influenced by shifting cultivation areas within a state).

Finally, we determined linear trends and P-values of the trends for planting, R1, maturity and harvest dates, as well as for the number of days between these development stages. To be considered statistically significant, trends had to differ from zero at $P < 0.05$.

2.2. Calculation of GDD between corn development stages

We combined these crop progress data with gridded temperature data to calculate the GDD between development stages for each state–year combination. We restricted these analyses – as well as the modeling analyses described below – to corn, because of the complex interactions between temperature and photoperiod that affect soybean development (e.g., Setiyono et al., 2007).

To compute GDD, we used minimum and maximum daily temperatures derived from the same climate dataset used to drive the Agro-IBIS model (see Section 2.3.1). We used these gridded data to compute weighted average climate variables for each state. The weighting of each grid cell was based on the harvested area of corn in that grid cell, according to the dataset of Monfreda et al. (2008). This weighting ensures that the climate averages apply to the area in which corn is actually grown.

For each state and each year, we computed the accumulated GDD between planting and R1 ($\mathrm{GDD}_{\mathrm{veg}}$), between R1 and maturity ($\mathrm{GDD}_{\mathrm{reprod}}$), and between planting and maturity ($\mathrm{GDD}_{\mathrm{mat}}$), using the Modified GDD equation:

$$\mathrm{GDD} = \sum_{i} \left(T_i^{\mathrm{adjusted}} - 10^{\circ}\mathrm{C} \right), \tag{1}$$

where T_i^{adjusted} is the adjusted mean temperature on day i (°C), which is calculated by (1) imposing a maximum of 30 °C and a minimum of 10 °C on the daily minimum and maximum temperatures, and (2) taking the average of these adjusted minimum and maximum temperatures. We then computed linear trends in these state-level GDD values.

2.3. The Agro-IBIS model

2.3.1. Model overview

We used the observational analyses described above to drive the Agro-IBIS model, in order to investigate the effects of changing planting dates and cultivars on crop yields and fluxes of water and energy. In this sub-section, we describe the existing Agro-IBIS model, with a focus on its simulation of crop phenology. In Section 2.3.2, we describe changes that we made to the model for this study. We focus on the model's simulation of corn, since that was the crop used for all of our simulations.

Agro-IBIS is a process-based ecosystem model adapted from the Integrated Biosphere Simulator (IBIS; Foley et al., 1996; Kucharik et al., 2000). The Agro-IBIS version adds the simulation of Midwest U.S. corn, soybean and wheat cropping systems (Donner and Kucharik, 2003; Kucharik, 2003; Kucharik and Brye, 2003). The model accounts for agricultural management, such as planting dates and irrigation, and environmental effects on crop development (e.g., solar radiation, temperature and available soil water). Agro-IBIS simulates fast response processes that vary hourly such as energy, water, carbon and momentum balance of the canopy and soil, processes that vary daily such as leaf growth, and slow response processes like soil carbon storage and turnover. Net primary productivity is calculated at each time step on a grid cell basis according to physiologically based formulations of leaf-level photosynthesis (Farquhar et al., 1980), stomatal conductance (Collatz et al., 1991; Collatz et al., 1992) and respiration (Ryan, 1991). Total ET from the land surface is the sum of three fluxes: evaporation from the soil surface, evaporation of canopy-intercepted water, and canopy transpiration; transpiration rates are linked to photosynthetic rates through the modeling of stomatal conductance (Collatz et al., 1991; Collatz et al., 1992; Kucharik et al., 2000). For this study, soil moisture was simulated using 11 soil layers, with a total depth of 2.5 m. Agro-IBIS has previously been validated for the simulation of crop yields as well as water and energy balance (Kucharik, 2003; Kucharik and Brye, 2003; Kucharik and Twine, 2007; Twine and Kucharik, 2008).

Agro-IBIS simulates the timing of emergence, grainfill initiation and physiological maturity based on accumulated GDD since planting (Equation (1)). The time from planting to grainfill initiation corresponds to the vegetative period described in Section 2.1, and the time from grainfill initiation to maturity corresponds to the reproductive period (although see Section 2.4.1 for a discussion of some minor differences). In each grid cell, the crop requires a certain number of GDD to progress from planting to maturity ($\mathrm{GDD}_{\mathrm{mat}}$) (see Section 2.4.1 for how this was specified). Emergence occurs when accumulated GDD reaches 3% of $\mathrm{GDD}_{\mathrm{mat}}$, and grainfill initiation when accumulated GDD reaches a given fraction of $\mathrm{GDD}_{\mathrm{mat}}$, typically between 55% and 60% (the "grainfill initiation fraction"; see Section 2.4.1 for how this was specified). Soil temperatures are used for the emergence trigger, and air temperatures for the grainfill and maturity triggers. Maturity can be reached prematurely due to either (1) a number of days threshold (165 days since planting), or (2) a cold trigger that simulates fall frost damage. The latter occurs if there have been three consecutive nights with minimum temperatures below −2.2 °C. In reality, a corn plant can be damaged if there is a single night with temperatures below −2.2 °C (Carter and Hesterman, 1990). The three-night requirement in the model adjusts for problems that arise when trying to simulate this effect on the regional scale, since in reality frost damage tends to be a microscale phenomenon. However, these triggers for premature maturity were only activated occasionally in our simulations: in general, the GDD-based trigger was used.

Time-varying parameters determine carbon allocation to specific pools (leaf, stem, root and grain). These parameters vary gradually throughout the season based on GDD accumulation since planting, but there are two major changes at grainfill initiation. First, leaf area index (LAI) shifts from an accumulation phase to a decline phase. During the vegetative period, LAI is calculated using the accumulated leaf biomass and the specific leaf area (but with a prescribed maximum LAI of 5.0). During grainfill, LAI declines, slowly at first but more rapidly as maturity approaches. Second, allocation to the grain begins at this time; this eventually determines crop yield. Agro-IBIS does not simulate the remobilization of existing dry matter to the grain (Tollenaar & Dwyer, 1999).

After maturity, there is no more crop growth, but the crop remains in the field for about one month before being harvested (see Sections 2.3.2 and 2.4.1 for more details). After harvest, the grid cell is reset to bare ground; there is no simulation of crop residues remaining after harvest.

Climate inputs required at each time step include solar radiation, air temperature, precipitation, relative humidity and wind speed. We derived these inputs from a combination of monthly climatic observations and daily, reanalyzed meteorological data. Monthly averages were specified using data from the Climatic Research Unit, University of East Anglia (CRU TS3.0; Mitchell and Jones, 2005), at a 0.5° × 0.5° latitude/longitude resolution. We combined these with daily anomalies from the National Centers for Environmental Prediction-National Center for Atmospheric Research (NCEP/NCAR) meteorological reanalysis dataset (Kalnay et al., 1996) to produce daily values in each grid cell. Finally, hourly variations in these variables were simulated through empirical formulations (Campbell and Norman, 1998). Temperature in the input data was specified as mean daily temperature and the diurnal temperature range. Minimum and maximum daily temperatures (e.g., to compute GDD) were then estimated by assuming an equal distribution around the daily mean. We ran the model at 0.5° × 0.5° resolution, corresponding to the resolution of the climate drivers.

2.3.2. Modifications made for this study

Because this study focuses on changes in crop phenology, we modified Agro-IBIS to improve the realism of its simulated phenological processes in corn. First, we modified the model to take advantage of observed rather than simulated values of four phenological variables: planting date, $\mathrm{GDD}_{\mathrm{mat}}$, the grainfill initiation fraction, and the number of days between maturity and harvest. These variables can vary from grid cell to grid cell, and from year to year. Section 2.4.1 describes how we specified these variables for our simulations.

Table 1
Model runs performed for this study.

Name	Description	Planting date	GDD_{mat}	Grainfill initiation fraction	Days from maturity to harvest
CONTROL	No trends in planting dates or cultivars	Detrended observations	Fixed	Fixed	Fixed
PLANT	Trends in planting dates only	Observed timeseries	Fixed	Fixed	Fixed
CULT	Trends in cultivars only	Detrended observations	Linearized observations	Linearized observations	Linearized observations
PLANT + CULT	Trends in both planting dates and cultivars	Observed timeseries	Linearized observations	Linearized observations	Linearized observations

Second, we modified the GDD function that triggers the grainfill period and maturity to agree with Equation (1). This included changing the base for GDD accumulation for these two periods and emergence from 8 °C to 10 °C, since 10 °C is the more commonly used value for corn. Note that, since we specify GDD_{mat} from observations, the details of the GDD scheme are less important than the fact that we are consistent between the way GDD are calculated in the model and the data analyses.

Third, we added a gradual decline in the greenness fraction of leaves after the crop reaches the grainfill period. The original version of Agro-IBIS often had issues with leaf senescence in the later growth stages, leading to higher than observed values of green leaf area (Kucharik and Twine, 2007); this change was meant to improve realism. The original model assumed that all leaves remained green until maturity; the LAI decline during grainfill (described in Section 2.3.1) was meant to simulate a decrease in total leaf area. In reality, though, corn leaves gradually die and turn brown after the vegetative period. Based on measured rates of leaf senescence in newer hybrids (Valentinuz and Tollenaar, 2004), we specified a decline in the greenness fraction – and a corresponding increase in the brown fraction – of 0.25% per day for the first half of the grainfill period and 1.4% per day for the second half of grainfill. These values typically lead to a greenness fraction of ~50% at maturity. After maturity, the greenness fraction declines more rapidly, at 4% per day, until all leaves are brown. We left in place the original LAI decline function, only modifying the fraction of leaves that are green vs. brown. Brown leaves do not photosynthesize or transpire. Furthermore, brown leaves have different optical properties from green leaves, leading to higher albedo. Green leaves have a visible reflectance of 0.10, a near-infrared reflectance of 0.58, a visible leaf transmittance of 0.07 and a near-infrared transmittance of 0.25. Brown leaves have a visible reflectance of 0.36, a near-infrared reflectance of 0.58, a visible leaf transmittance of 0.22 and a near-infrared transmittance of 0.38 (Twine et al., 2004).

Finally, we added a period between maturity and harvest, when corn is left in the field to dry. Although the model does not simulate this drying process, we included this period because it can affect the surface water and energy balance. After maturity, there is no photosynthesis or transpiration, even for green leaves. In addition, LAI declines linearly to a value of 1.0 at harvest. Finally, the greenness fraction declines more rapidly, as described above.

2.4. *Description of modeling experiments*

2.4.1. *Specification of planting date and cultivar*

We performed four simulations to examine the effects of changes in planting date and cultivar choice on corn yields and water and energy fluxes. These simulations differed in how we specified planting dates, GDD_{mat}, the grainfill initiation fraction, and the number of days between maturity and harvest (Table 1). We divided these variables into two sets: planting date, and the three other variables, which we call the “cultivar” variables. The four simulations then encompassed the different possible combinations of fixed vs. transient management for these two sets of variables. The PLANT + CULT run represents actual, historical management changes in planting dates and cultivar choice. The CONTROL run represents what would have happened if, throughout the period 1981–2005, planting dates and cultivar choice remained constant at their average values over this period. The other two runs represent some combination of these two, to separate the effects of changing planting dates and changing cultivars.

We defined a cultivar in terms of the number of GDD to maturity, rather than the number of days, because the former tends to be a more fixed characteristic of a given cultivar. Thus, we viewed changes in cultivar choice as being equivalent to changes in the number of GDD required for the crop to progress from one stage to the next. This meant that the number of days between development stages could vary from year to year even in the CONTROL and PLANT simulations, due to variability in climate or planting date. We also treated the number of days between maturity and harvest as a fixed property of a given cultivar—namely, the number days required for that cultivar to dry sufficiently in the field. In reality, this is partly a function of climate (e.g., humidity) and partly a function of cultivar (Duvick, 2005). Since this version of Agro-IBIS does not simulate the climatic determinants of drying time, we assume that these climatic determinants have remained roughly constant over the simulation period, so that long-term trends have been driven by changes in cultivars or other management factors. Although we talk about changes in the length of this period in terms of changes in cultivar choice, in reality they could also be partly due to changes in management (e.g., allowing less field drying), but that distinction would not affect our results. We ignored other changes in cultivars that have occurred over this period, focusing only on these phenology-related variables. Also, note that we allowed for changes in the length of the green period via changes in GDD_{mat}, but other than this did not explicitly simulate an increasing “stay-green” period due to delayed senescence, as has been reported for newer corn hybrids (Tollenaar, 1991).

In the runs with transient planting dates (PLANT and PLANT + CULT), we used the actual, observed state-level timeseries of the 50% planted date. Thus, every grid cell in a given state had the same planting date for a particular year. In the runs with “fixed” planting dates (CONTROL and CULT), we used the observed timeseries with the state-level linear trends removed. The average planting dates over the period 1981–2005 were the same in all runs. Even in the runs with fixed management, there was still some year-to-year variability in planting dates. This mostly represents the response of farmers to weather variability. We allowed this interannual variability because we are interested just in the effects of long-term management trends. However, note that, because of the detrending, the simulated farmers were not allowed to adjust planting dates in response to long-term climatic trends in the CONTROL and CULT runs.

We treated the three cultivar variables slightly differently. In the runs with transient cultivars (CULT and PLANT + CULT), we used the linearized values of the timeseries, removing any interannual variability around this trend line. In the runs with fixed cultivars (CONTROL and PLANT), we used values fixed at the average over the period 1981–2005. We removed interannual variability from these variables to try to just capture true management changes. We assumed that, for the most part, farmers choose which cultivars to plant before knowing what the weather will be in a given year. We further assumed that changes in cultivar choice would be gradual—there would not be large variations from year to year, at least when averaged over a state. Based on these assumptions, most of the interannual variability in these variables appears due to observational errors or errors in assuming that development is based on GDD accumulation, and is not representative of actual management changes.

In contrast to planting dates, we allowed GDD_{mat} and the grainfill initiation fraction to vary within a state. This was to allow the planting of shorter season cultivars in cooler parts of a state; without this, northern grid cells in each state can take much too long to reach maturity. However, we ensured that the trends of these variables were identical for all grid cells in a state. To create this spatial variability in GDD_{mat} and the grainfill initiation fraction, we assumed that the number of days between development stages is roughly constant across a state in a particular year. First, for each grid cell and each year, we calculated GDD_{veg} and GDD_{reprod} using the state-level crop progress data, the gridded climate data described in Section 2.3.1, and Equation (1). Second, for each grid cell, we calculated the average values of these two variables over the years 1981–2005. These averages were used to specify cultivars in the CONTROL and PLANT simulations. Third, we applied the state-level linear trends in GDD_{veg} and GDD_{reprod} (described in Section 2.2) to each grid cell in a state. The resulting time-varying values were used to specify cultivars in the CULT and PLANT + CULT simulations. For both fixed and transient cultivars, we then calculated GDD_{mat} (as $GDD_{veg} + GDD_{reprod}$) and the grainfill initiation fraction. The latter was basically equal to GDD_{veg}/GDD_{mat}, but we applied a small correction factor (~0.04) to account for the fact that grainfill initiation in Agro-IBIS is defined as starting slightly after silking. For the remainder of the paper, we ignore this slight distinction, referring to R1 (silking) and grainfill initiation in the model interchangeably. For the number of days between maturity and harvest, unlike these other two cultivar variables, we used the same value for every grid cell in a state for a particular year.

2.4.2. Other details of the simulations and analyses of the results

We ran the model from 1976 to 2005. The first five years were discarded as spin-up, needed to bring the soil water balance into rough equilibrium; we drove those five years with average planting dates and cultivars. The results presented here are based on the simulated years 1981–2005, the years for which we had crop progress observations. Atmospheric CO_2 was set constant at 360 ppm in all runs. Simulations assumed that N was not a limiting factor to plant growth. Finally, we allowed irrigation in grid cells where at least 50% of the corn-growing area is irrigated, according to the MIRCA2000 dataset (Portmann et al., 2010). Thus, 11% of the corn area in our domain was irrigated, mostly in NE and KS. Irrigation in Agro-IBIS is performed by adding enough water to bring plant available water up to field capacity when this value falls below 50% of field capacity.

To calculate differences between the runs, we first averaged the results over each state or the entire region. We computed weighted averages over each state based on the harvested area of corn in each grid cell in the state, according to the dataset of Monfreda et al. (2008). To compute regional averages, we weighted these state-level averages based on the average corn harvested area in each state, across the years 1981–2005 (USDA-NASS, 2010), as we did for the crop progress data (Section 2.1). We then examined linear trends of the differences between each experimental run and the CONTROL run. To be considered significant, trends had to differ from zero at $P < 0.05$. Since the differences in all forcing variables between the different runs were essentially linear in time (Table 1), it makes sense to look at the differences in model output in terms of linear trends as well. However, since the forcing variables were linearized, it is reasonable to expect the modeled differences to be more linear than the original observations. Finally, in some cases we present total changes from 1981 to 2005. These were derived simply by multiplying the trends by 24 years.

Note that all runs allowed for changes in climate, but by looking at the differences between the experimental runs and the CONTROL run, we remove any effects that are due solely to climatic changes. However, we still allow for interactive effects of changes in climate with changes in planting dates or cultivars.

3. Results & discussion

3.1. Planting date trends

Corn planting dates have advanced 0.40 days per year from 1981 to 2005, averaged over the U.S. (Fig. 1A; Table 2). Thus, corn planting was 10 days earlier around 2005 than it was around 1981. This trend has been fairly consistent across the 12 states included in this study; with the exception of MI, statewide planting date trends have been within a factor of two of the national average. The trend is significantly different from zero in seven of the 12 states (Table 2). This trend has not been entirely monotonic, however, probably because of interannual weather variability. For example, corn was planted much later in 1993 and 1995 than in the preceding or following years.

Soybean planting dates have followed a trend similar to that of corn, advancing 0.49 days per year from 1981 to 2005 (Fig. 1A; Table 2). The trend is significantly different from zero in seven of the 13 states included in this study. Three states – AR, KS and LA – have seen particularly large changes in soybean planting dates. In LA and AR, these changes reflect an adoption of the Early Soybean Production System in the southern U.S., which helps soybean growers avoid drought stress (Egli and Cornelius, 2009).

The main factors allowing earlier corn planting seem to have been technological, although springtime warming may have contributed in some states, especially KS, MO and NE (Kucharik, 2006). Some of the technological changes that allow for earlier corn planting have been the adoption of fall tillage and conservation tillage, the use of more efficient equipment, and new crop varieties that are more resistant to cold temperatures, pests and diseases (Lauer, 2001; Kucharik, 2006). In the U.S. Midwest, soybeans are often planted after corn planting is complete. Thus, earlier corn planting has allowed for earlier soybean planting as well (Irwin et al., 2008).

3.2. Trends in other crop development stages

Trends in R1 dates have generally followed planting date trends, but with a smaller magnitude, leading to an increase in the length of the vegetative period (Fig. 1B; Tables 2 and 3). Across the U.S., corn R1 (silking) dates have advanced by 0.15 days per year from 1981 to 2005, 37% of the planting date trend; however, this trend does not differ significantly from zero. Thus, the vegetative period has been growing longer by 0.25 days per year (Table 3). Soybean R1 (blooming) date has followed a pattern similar to corn: soybean R1 dates have advanced by 0.27 days per year from 1981 to 2005 on average, 56% of the planting date trend; however, as for corn, this trend does not differ significantly from zero. The vegetative period in soybeans has generally been getting longer, although this is not statistically significant for the U.S. as a whole. But AR and LA have

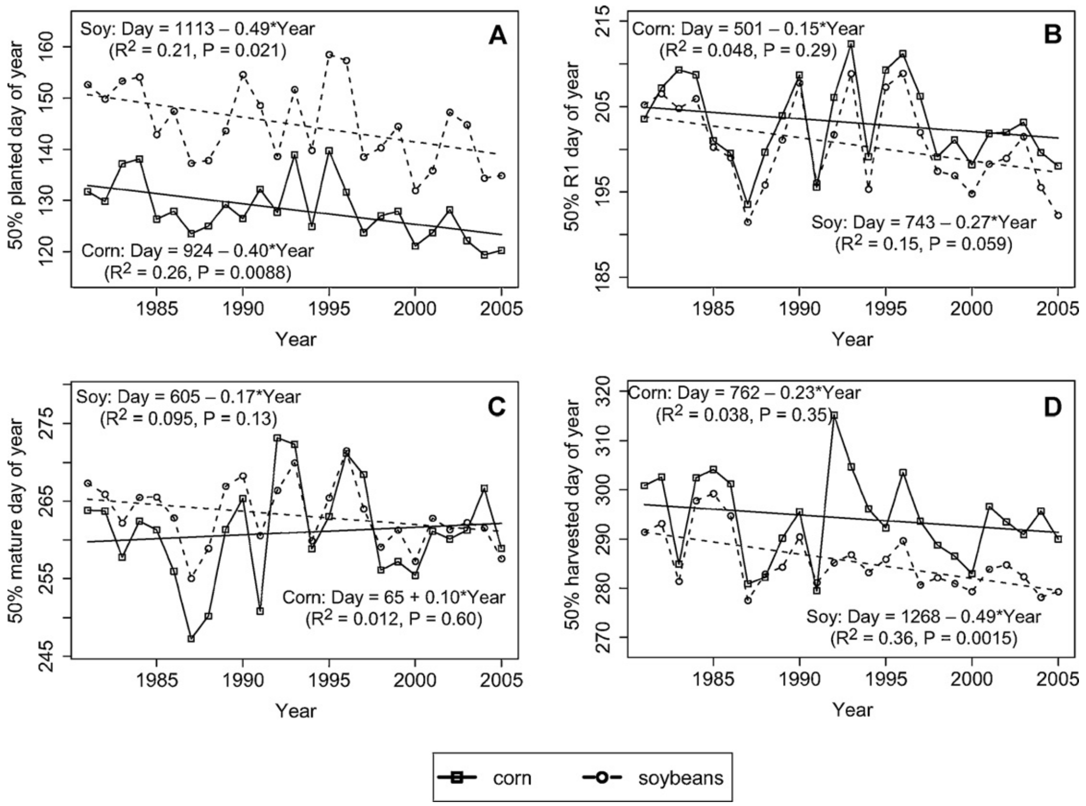

Fig. 1. Day of year when corn and soybean planting (A), start of the reproductive period (R1) (B), maturity (C) and harvest (D) progress were 50% complete, over the period 1981–2005. Dates of 50% completion were determined by interpolating weekly state-level observations. Spatial averages were then computed by weighting each state's data by the crop's harvested area in that state. Included states are, for corn: IL, IN, IA, KS, KY, MI, MN, MO, NE, OH, SD, and WI; and for soybeans: AR, IL, IN, IA, KS, KY, LA, MI, MN, MO, NE, OH, and TN.

experienced a shortening of the vegetative period. This may be due to the choice of different cultivars, for example, with the adoption of the Early Soybean Production System.

For corn, maturity dates have, if anything, been getting slightly later across the U.S. (Fig. 1C; Table 2). Although the trend in average maturity date is not significant itself, this positive trend has resulted in a significant lengthening of the reproductive period in corn across the U.S., by 0.25 days per year (Table 3). Soybean maturity (dropping leaves) has been trending slightly earlier, but this trend is not significant. The length of the soybean reproductive period has stayed roughly constant.

Thus, the total corn growth period – the period from planting to maturity – has been growing longer by 0.50 days per year (Table 3). This means that the growth period was about 12 days longer around 2005 than it was around 1981. Soybean's growth period has been lengthening by 0.31 days per year.

Both corn and soybeans have experienced a trend to earlier harvest dates, although this trend does not differ significantly from

Table 2

Linear trends in the 50% planted, R1, maturity and harvest dates, for corn and soybeans. Trends are given in days per year over the period 1981–2005. "AVERAGE" gives the trends for the weighted average across the given states, where each state's progress is weighted by the crop's harvested area in that state.

State	Corn trends (days per year)				Soybean trends (days per year)			
	Planted	R1	Maturity	Harvested	Planted	R1	Maturity	Harvested
AR					−0.98***	−1.25***	−0.86***	−1.07***
IL	−0.39	−0.07	0.11	−0.34	−0.25	0.06	0.06	−0.02
IN	−0.39	−0.20	0.11	−0.29	−0.58	−0.19	−0.24	−0.32
IA	−0.36*	−0.07	0.07	−0.06	−0.55*	−0.29	−0.09	−0.37
KS	−0.54**	−0.56**	−0.36*	−0.52*	−1.01***	−0.81***	−0.41*	−0.66**
KY	−0.74*	−0.59**	−0.68***	−1.00***	−0.56	−0.40	−0.64***	−0.83***
LA					−0.98***	−1.40***	−1.34***	−1.79***
MI	−0.12	−0.03	0.20	−0.20	−0.33	−0.29	0.07	−0.59**
MN	−0.51**	−0.24	0.06	−0.24	−0.32	−0.15	−0.05	−0.50*
MO	−0.67	−0.55*	−0.41	−0.76**	−0.62*	−0.28	−0.25	−0.47*
NE	−0.50**	−0.33*	−0.20	−0.34	−0.54**	−0.25	−0.33*	−0.53**
OH	−0.40	−0.03	0.34	−0.11	−0.55	−0.32	−0.22	−0.38
SD	−0.46*	−0.14	0.25	−0.04				
TN					−0.52*	−0.55**	−0.59***	−0.55*
WI	−0.27*	−0.03	0.44	−0.30				
Average	−0.40**	−0.15	0.10	−0.23	−0.49*	−0.27	−0.17	−0.49**

* $P < 0.05$ (significance value for slope).

** $P < 0.01$ (significance value for slope).

*** $P < 0.001$ (significance value for slope).

Table 3
As in Table 2 but for trends in number of days between stages (given in days per year over the period 1981–2005).

State	Corn trends (days per year)				Soybean trends (days per year)			
	Planted to R1	R1 to maturity	Planted to maturity	Maturity to harvest	Planted to R1	R1 to maturity	Planted to maturity	Maturity to harvest
AR					-0.27^{*}	0.39^{**}	0.11	−0.21
IL	0.32	0.18	0.50	-0.46^{***}	0.31	0.00	0.31	−0.08
IN	0.19	0.31^{*}	0.49	-0.40^{*}	0.38^{*}	−0.05	0.33	−0.08
IA	0.29^{*}	0.13	0.43^{*}	−0.12	0.26	0.20^{*}	0.46^{**}	−0.28
KS	−0.01	0.19	0.18	−0.15	0.20	0.40^{**}	0.60^{***}	−0.25
KY	0.15	−0.08	0.07	−0.32	0.16	−0.24	−0.08	−0.19
LA					-0.42^{**}	0.06	-0.36^{*}	-0.45^{*}
MI	0.09	0.23	0.32	-0.40^{*}	0.04	0.37^{***}	0.40^{*}	-0.67^{***}
MN	0.27	0.30	0.57^{*}	−0.30	0.17	0.10	0.27	-0.45^{**}
MO	0.12	0.14	0.27	−0.35	0.35^{*}	0.03	0.37	−0.22
NE	0.17	0.12	0.30	−0.14	0.29^{*}	−0.08	0.21	−0.19
OH	0.37	0.37^{*}	0.74^{*}	-0.45^{*}	0.23	0.09	0.32	−0.16
SD	0.32	0.39^{**}	0.71^{**}	−0.30				
TN					−0.03	−0.04	−0.07	0.05
WI	0.24	0.47^{**}	0.71^{*}	-0.73^{***}				
Average	0.25^{*}	0.25^{*}	0.50^{*}	-0.33^{*}	0.21	0.10	0.31^{*}	-0.32^{*}

* $P < 0.05$ (significance value for slope).
** $P < 0.01$ (significance value for slope).
*** $P < 0.001$ (significance value for slope).

zero for corn (Fig. 1D; Table 2). Consequently, both crops have experienced a decrease in the amount of time between maturity and harvest, by about 0.33 days per year (Fig. 2; Table 3). This period is used for drying of the grain. The decrease in the length of this period largely offsets the increase in time between planting and maturity, so that the total time between planting and harvest has not changed much between 1981 and 2005. This trend to longer reproductive periods coupled with faster dry-down – and thus relatively constant time between planting and harvest – has also been documented for corn hybrids released between the 1930s and early 1980s (Duvick, 2005). For this earlier period, Duvick (2005) attributed the faster dry-down at least in part to changes in cultivars—i.e., the newer cultivars required less time to achieve the same amount of grain drying.

3.3. Trends in GDD between corn development stages

The number of GDD from planting to maturity tends to be a more fixed characteristic of a given cultivar than is the number of days from planting to maturity. Thus, in addition to changes in the number of days between stages, it is also useful to look at changes in the number of GDD between stages, since this can tell us about changes in which cultivars were planted from year to year. We used these changes in GDD to drive the cultivar changes in our model simulations. In the remainder of the paper, we assume that increases (decreases) in GDD_{mat} imply a shift towards the use of longer season (shorter season) cultivars, even though in reality GDD_{mat} is not entirely constant for a given cultivar (Nielsen et al., 2002). Note that for all of the following analyses in the paper, we focus on corn.

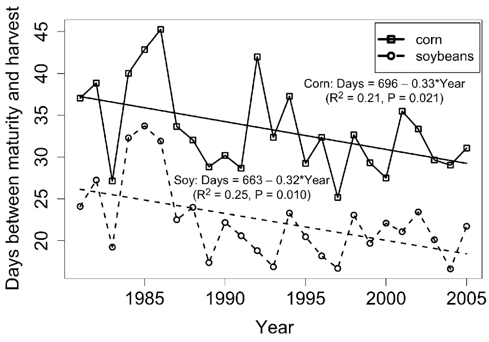

Fig. 2. Number of days between maturity and harvest for corn and soybeans, over the period 1981–2005. See Fig. 1 for details on the computation of these values.

Despite the trend to a longer vegetative period in corn, there has been essentially no change in GDD_{veg} (Fig. 3). Thus, this cultivar aspect remained fairly constant in the simulations, even with transient cultivars. The only states that experienced a significant trend in this variable were KS, KY and MO, the southernmost states in our study. These states all experienced a trend between −3 and −4°-days per year.

There was, however, a significant trend to greater GDD_{reprod} (Fig. 3). The average trend, 3.7°-days per year, is equivalent to a 14% increase in GDD_{reprod} over the 25-year period, 1981–2005. Ten of the 12 states experienced a significant increase in GDD_{reprod}; the exceptions were KY and MI, for which the trends did not differ significantly from zero. This suggests that there has been a trend towards the use of cultivars with a longer reproductive period.

We can also break down these GDD trends in terms of GDD_{mat} and the grainfill initiation fraction (Table 4). This separation corresponds with the variables needed by Agro-IBIS. With this separation, we see two separate trends in corn cultivars from 1981 to 2005. First, there was an increase in GDD_{mat}—that is, a trend to longer season cultivars. This trend, 3.2°-days per year, is equivalent to a 5.4% increase in GDD_{mat} over the 25-year period. Second, there was a decrease in the fraction of the season (in a GDD sense)

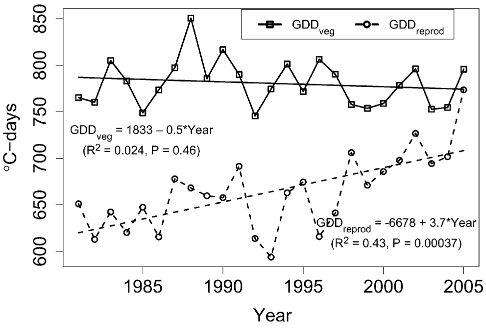

Fig. 3. Number of growing degree days (GDD) between planting and R1 (GDD_{veg}), and between R1 and maturity (GDD_{reprod}), for corn over the period 1981–2005. GDD were calculated according to Equation (1). We first computed the GDD requirement for each state (see Section 2.2), then computed the weighted regional average of these state-level GDD requirements based on the harvested area of corn in each state.

Table 4

Mean values and trends (per-year) of the management variables used to drive Agro-IBIS simulations of corn. To drive the model, we allowed interannual variability in planting dates, but linearized the three cultivar-related variables. "AVERAGE" gives the means and trends for the weighted average across the 12 states, where each state's value is weighted by the crop's harvested area in that state.

State	Planting date		GDD_{mat} (°C-days)		Grainfill initiation fraction[a]		Days from maturity to harvest	
	Mean	Trend[b]	Mean	Trend[c]	Mean	Trend[c]	Mean	Trend[b,c]
IL	May 5	−0.39	1540	3.7^{***}	0.552	−0.0008	29.3	-0.46^{***}
IN	May 11	−0.39	1483	3.3^{*}	0.570	-0.0021^{***}	35.8	-0.40^{*}
IA	May 7	-0.36^{*}	1410	2.4	0.600	−0.0009	35.3	−0.12
KS	May 4	-0.54^{**}	1575	1.1	0.571	-0.0023^{***}	23.6	−0.15
KY	May 5	-0.74^{*}	1612	−2.5	0.552	−0.0010	26.7	−0.32
MI	May 14	−0.12	1312	1.8	0.593	−0.0009	36.2	-0.40^{*}
MN	May 9	-0.51^{**}	1324	3.7	0.595	-0.0025^{**}	30.2	−0.30
MO	May 4	−0.67	1574	−0.6	0.564	-0.0021^{***}	28.2	−0.35
NE	May 10	-0.50^{**}	1481	3.5^{*}	0.568	-0.0014^{**}	31.6	−0.14
OH	May 11	−0.40	1442	4.7^{*}	0.573	-0.0011^{*}	33.7	-0.45^{*}
SD	May 16	-0.46^{*}	1319	5.9^{***}	0.628	-0.0020^{***}	35.4	−0.30
WI	May 14	-0.27^{*}	1264	5.1^{**}	0.612	-0.0015^{**}	35.4	-0.73^{***}
Average	May 9	-0.42^{**}	1443	3.2^{*}	0.581	-0.0014^{***}	32.4	-0.31^{*}

[a] The grainfill initiation fractions given here are the corrected values described in Section 2.4.1 (not simply GDD_{veg}/GDD_{mat}).

[b] For planting date and days from maturity to harvest, the state-level trends are the same as those presented in Tables 2 and 3 and Fig. 2, but the regional averages differ slightly. The averages presented in this table use the same averaging scheme as is used for the model results, so should be used when interpreting these results; however, for pure data analyses, the averages presented in Tables 2 and 3 are more rigorous.

[c] The significance levels for the trends in the cultivar-related variables were calculated using the values of these variables before they were linearized.

* $P < 0.05$ (significance value for slope).

** $P < 0.01$ (significance value for slope).

*** $P < 0.001$ (significance value for slope).

devoted to the vegetative period. Grainfill initiation occurred 59.8% of the way through the season around 1981, and 56.3% of the way through the season around 2005.

3.4. Modeled trends in number of days between corn development stages

We can better understand the observed trends in the number of days between corn development stages by using the model results (Fig. 4). In this way, we can determine which of the observed trends can likely be attributed directly to the trend to earlier planting, and which can more likely be attributed to changes in cultivars. Note that, in this section, we are essentially just using the model as a GDD calculator.

The trend to earlier planting (Table 4), with fixed cultivars, led to an extension of the planting to emergence and emergence to grainfill stages (Fig. 4). Earlier planting pushes these stages into cooler times of year, requiring more days to accumulate a given number of GDD. However, earlier planting led to a shortening of the grainfill period. Earlier planting leads to earlier grainfill initiation, which pushes the grainfill period into a warmer part of the summer, so fewer days are required to accumulate a given number of GDD.

Changes in cultivars (Table 4), with planting dates the same as in the CONTROL run, led to a slight extension of the planting to emergence stage (since the length of this stage depends on GDD_{mat}), but a slight shortening of the emergence to grainfill stage (Fig. 4). Thus, the total length of the vegetative period remained roughly constant, in agreement with the lack of change in GDD_{veg} (Fig. 3). The length of the grainfill period, on the other hand, increased substantially due to the changes in cultivars. The cultivar trend also led to a substantial shortening of the maturity to harvest period, following directly from the observations (Fig. 2; Table 4).

Thus, the observed increase in time between planting and R1 (Table 3) was mostly driven by earlier planting, whereas the increase in time between R1 and maturity was driven by a shift to longer season cultivars.

It is also interesting to note that, according to the model, most of the observed extension of the vegetative period occurred during the planting to emergence period (see the PLANT + CULT bars in Fig. 4). This means that the extension of the vegetative period probably has not substantially increased biomass production. However, this conclusion depends on how emergence is simulated in the model. In Agro-IBIS, the GDD requirement of the emergence period is proportional to GDD_{mat}. If we instead assumed, for example, that the GDD requirement of the emergence period remained constant from 1981 to 2005, then we would have seen a slightly greater extension of the period from emergence to grainfill initiation.

Finally, note that there are small discrepancies between the PLANT + CULT results (Fig. 4) and the observed trends (Table 3). These discrepancies can mostly be explained by small changes in the length of each stage in the CONTROL run. These changes in the CONTROL run were driven by changes in climate; however, none of these climate-driven changes differed significantly from zero.

3.5. Modeled corn yield trends

3.5.1. Effect of planting date

The trend to earlier planting alone did not have a significant effect on simulated yields, averaged across the 12 states (Fig. 5). Only four states saw significant yield trends due to the planting date trends: KY, MO and NE saw increases in yields, and IN saw a decrease in yields. In general, the states that experienced yield gains were those that had a greater trend to earlier planting.

Earlier planting has two competing effects on simulated yields. On the one hand, it leads to a lengthened vegetative growth period, resulting in a higher peak LAI and increased yields. On the other hand, it leads to a shortened grainfill period and thus decreased yields: phenology is driven by accumulated temperature, whereas biomass growth is driven more by total intercepted radiation (see also Fig. 4 and Section 3.4). The balance between these two effects, and the resulting net effect of planting date on yield, is sensitive to a few model parameters, such as the grainfill initiation fraction, the threshold for cold-induced premature maturity, and the base for GDD accumulation. (The latter affects the results by governing the delay in emergence for a given delay in planting.) Note that, in our simulations, much of the increased length of the vegetative period was taken up by an increased time from planting to emergence, which has no benefit for crop growth (Fig. 4). If, instead, there were a greater increase in time from emergence to R1, earlier planting would have a greater benefit for yields. Finally, the lack of

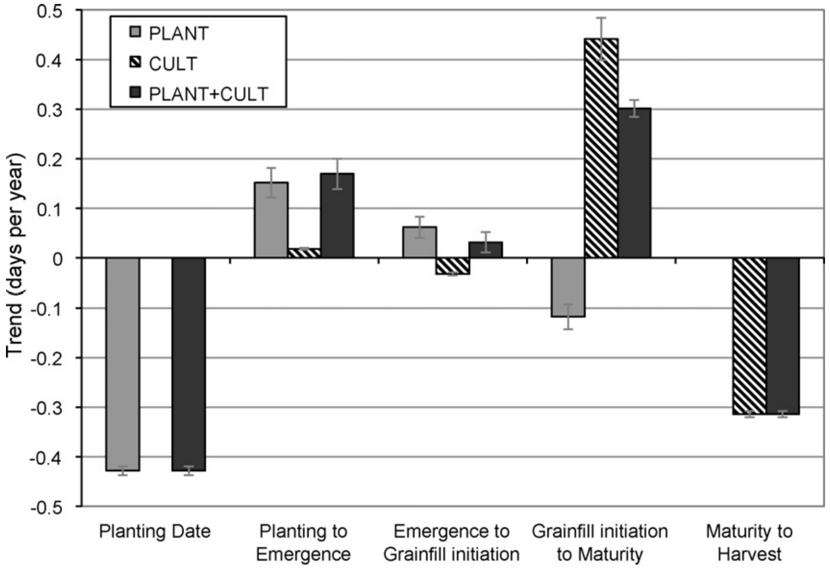

Fig. 4. Effects of changes in corn planting dates and cultivars on modeled planting date and number of days between development stages. Bars show linear trends (1981–2005) of the regionally averaged differences between each of the experimental runs and the CONTROL run. PLANT shows the difference when planting dates vary but cultivars remain fixed, CULT the difference when cultivars vary but planting dates remain as in the CONTROL run, and PLANT + CULT the difference when both planting dates and cultivars vary (see Table 4 for the trends driving these changes). Error bars show 95% confidence intervals.

a yield response to planting date could have arisen partly because Agro-IBIS does not simulate the remobilization of existing dry matter to the grain. If this process were included, then a lengthening vegetative period could more likely have led to increased yields.

Based on field studies (Lauer et al., 1999; Lauer, 2009; Nafziger, 2008), we expected to see a yield gain due to earlier planting. However, these field studies have generally shown that there is a few week-long planting window for which yields are near their optimum – e.g., mid April to early May in most of IL (Nafziger, 1994, 2008), late April to early May in IA (Abendroth and Elmore, 2010; Farnham, 2001), and early May in southern WI (Lauer et al., 1999; Lauer, 2009) – with slight yield losses for earlier planting and larger yield losses for delayed planting. The planting dates in our simulations (Table 4) are close to the observed optimum dates, so tend to be in a part of the curve where the observed response to planting date is relatively low. Because of this, small errors in the model could easily change the sign of the model's planting date response relative to the observed response. Thus, the lack of a response to planting date in the model should not be taken as a negation of studies that have shown yield responses to planting date. Rather, it should be taken as an indication that this planting date response is complex and dependent on a number of other factors.

The lack of a yield response to planting date is consistent with the findings of Irwin et al. (2008). Using a regression model, these authors found that the effect of statewide average planting date on corn yields in IL, IN and IA was not statistically significant, once you account for a linear technology trend and interannual variability in temperature and precipitation. However, the statistical analysis performed by Kucharik (2008) suggested a greater effect of planting date on yields, especially in the northern and western Corn

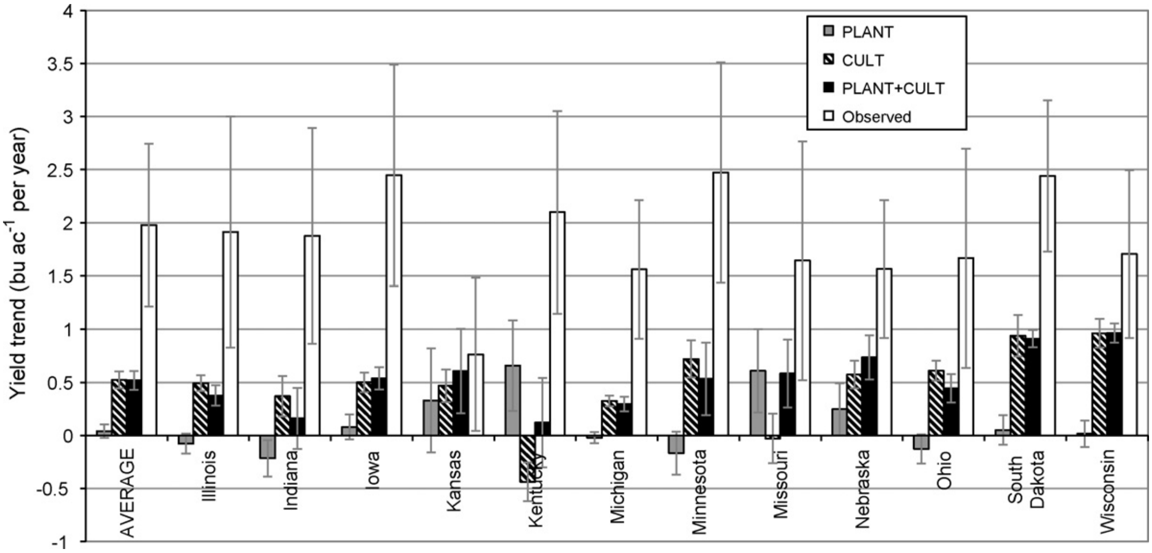

Fig. 5. Effects of changes in corn planting dates and cultivars on modeled crop yield. Bars show linear trends (1981–2005) of the regionally averaged and state-by-state differences between each of the experimental runs and the CONTROL run (see Table 1 for descriptions of these runs). Error bars show 95% confidence intervals. Also shown are the observed yield trends over this period for each state and the regional average, from USDA-NASS (2010). The regional-average observed yields were derived in the same way as the regional-average model results: using each state's average harvested area over the period 1981–2005.

Belt. Discrepancies between that analysis and the present study may be due in part to model uncertainties such as those described above. Another explanation, though, is that the yield effects that Kucharik (2008) attributed to planting date were actually due in part to changes in cultivars. To the extent that earlier planting in a given year is associated with the use of longer season cultivars in that year, Kucharik's statistical analysis would not have been able to separate these two effects.

3.5.2. *Effect of cultivar GDD requirement*

Changes in $\mathrm{GDD_{mat}}$ and the grainfill initiation fraction resulted in a significant trend to increasing yields: 0.52 bu $\mathrm{ac^{-1}}$ per year averaged over the 12 states, or 12.6 bu $\mathrm{ac^{-1}}$ over the 25-year period (Fig. 5). The yield increase results from the increasing length of the growth period, and in particular the grainfill period, which allows for more grain production. This yield trend is equal to a 0.17 bu $\mathrm{ac^{-1}}$ yield gain for every °C-day increase in $\mathrm{GDD_{mat}}$, or a 1.2 bu $\mathrm{ac^{-1}}$ yield gain for every day increase in the growth period. Differences between states can be explained almost entirely by variability in the states' $\mathrm{GDD_{mat}}$ trends (Yield trend [bu $\mathrm{ac^{-1}}$ per year] = 0.15 × $\mathrm{GDD_{mat}}$ trend [°C-days per year] + 0.05, $R^2 = 0.89$); differences in trends in the grainfill initiation fraction explained very little of this variability ($R^2 = 0.06$). The ten states in which there was a trend to longer season cultivars (i.e., greater $\mathrm{GDD_{mat}}$) all experienced significant trends to increasing yields as a result of cultivar changes. The only state that experienced a significant trend to lower yields was KY, for which there was a trend to shorter season cultivars.

We performed an additional set of simulations to separate the effects of trends in $\mathrm{GDD_{mat}}$ and trends in the grainfill initiation fraction. In one simulation, we held the grainfill initiation fraction fixed in time but allowed $\mathrm{GDD_{mat}}$ to vary, and in another simulation we did the reverse. From these simulations, we found that most of regional-average trend to increasing yields is due to the increase in $\mathrm{GDD_{mat}}$. This result is consistent with the results of the state-level regression presented above. The shift in grainfill initiation fraction – to a relatively longer grainfill period and relatively shorter vegetative period – produced a yield trend that did not differ significantly from the CONTROL run. Although an earlier grainfill initiation means more time for grain accumulation, it also means potentially lower LAI, and thus a reduced rate of carbon accumulation by photosynthesis during the grainfill period.

In interpreting the results in this section, note that Agro-IBIS simulates yields, but not economic profitability. In reality, a shift to longer season cultivars with no change in planting date might result in higher grain moisture content at a typical harvest date, which results in higher drying costs and lower profitability (Lauer et al., 1999). Fall frost damage can exacerbate this problem by slowing grain drydown (Carter and Hesterman, 1990; Ritchie et al., 1993). Consequently, in reality, it could be that the yield gains come from longer season cultivars, but earlier planting is necessary to allow the use of longer season cultivars without risking a decrease in profitability: note that the simultaneous changes in cultivars and planting dates have resulted in nearly constant maturation dates (Fig. 4; Table 2).

3.5.3. *Combined effect and comparison with observed yield trends*

The combined effect of trends in planting dates and cultivars is generally similar to the sum of the two individual effects (Fig. 5). On average, the combined effect led to a yield trend of 0.52 bu $\mathrm{ac^{-1}}$ per year, or 12.5 bu $\mathrm{ac^{-1}}$ over the 25-year period. This is about the same as the effect of changes in cultivars alone, since changes in planting date had a near-zero effect. However, as noted above, planting date probably becomes more important when considering profitability rather than just yields. The combined effect on yields is positive in all 12 states, although it is not statistically significant in IN or KY.

Averaged across the 12 states, the simulated effect of trends to earlier planting and longer season cultivars accounts for 26% of the observed yield trend from 1981 to 2005 (Fig. 5). This percentage varies from 5.8% for KY, where shorter season cultivars led to a near-zero simulated yield trend, to 80% for KS, where the observed yield increase has been relatively small. With respect to the division of yield increases into management factors and breeding factors (Duvick, 2005; Lee and Tollenaar, 2007), these trends probably encompass some of each, even though we refer to them as management changes in the paper for simplicity.

Our experimental design attempted to isolate the effects of planting date and cultivar choice. However, it is possible that part of the simulated yield increase is actually attributable to interactive effects between these management changes and other yield-influencing factors. For example, part of the trend to earlier planting and longer season cultivars may have been driven by climatic changes, in which case the yield increase is partly attributable to interactive effects of climate and management change (Twine and Kucharik, 2009). In addition, we allowed irrigation application to respond to demand. Longer season cultivars resulted in slightly greater irrigation application, so in irrigated areas (11% of corn area in our domain), the yield increase was partly attributable to the interactive effects of longer season cultivars and greater irrigation application. (However, the yield trend was nearly identical in irrigated and non-irrigated grid cells in KS and NE, the states with the most irrigation.) We also assumed no N limitation. This carries the implicit assumption that fertilizer application was adjusted as necessary to meet the possibly increased demand from longer season cultivars. Again, this interactive effect is folded into our result.

Because of these interactive effects, the large yield contributions that we find here do not necessarily contradict previous findings on the contributions of other management factors (e.g., increasing applications of fertilizer, irrigation and herbicides, and higher plant densities: Egli, 2008) and breeding factors (e.g., increased stress tolerance and more upright leaves: Duvick, 2005; Duvick and Cassman, 1999; Egli, 2008) to yield increases. Nevertheless, our result implies that, if planting dates and crop GDD requirements had remained fixed at their circa-1981 values – thus removing both the direct and interactive contributions of these changes – then yields around 2005 would have been 12.5 bu $\mathrm{ac^{-1}}$ lower.

3.6. *Modeled trends in water and energy fluxes*

In this section, we describe changes in R_{net} and its partitioning into LE and H. In general:

$$R_{\mathrm{net}} = LE + H + G, \tag{2}$$

where G is the soil heat flux. However, we ignore G because it is relatively small on the time scales considered here.

The combination of earlier planting and changes in cultivars has two major consequences for water and energy fluxes. First, the crop growth period (from planting to maturity) starts earlier but ends around the same time (Table 2; Fig. 4). This results in an earlier onset of green leaf area, which generally means greater green leaf area throughout the month of June (Fig. 6). The greater green leaf area, in turn, has led to an increase in LE (due to an increase in transpiration) and a corresponding decrease in H in June and on the annual average (Fig. 7). This has probably meant a slight cooling of the near-surface air temperature in June.

Second, the period from maturity to harvest is shortened (Table 3; Figs. 2 and 4). Because the crop is mostly brown during this period, the shortening of this period has led to a decrease in brown leaf area in October (Fig. 6). Brown crops have higher albedo than bare ground, and thus lower R_{net}. Therefore, the decrease in

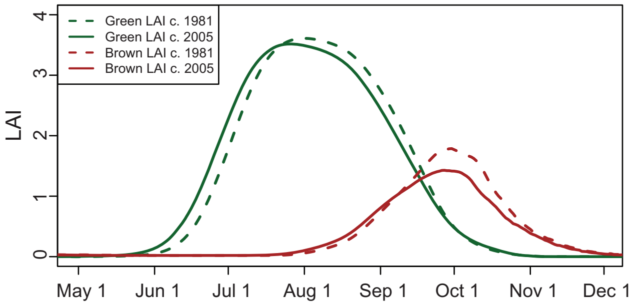

Fig. 6. Effects of changes in corn planting dates and cultivars on growing season green and brown leaf area index (LAI), averaged across the region. 1981 (2005) values were calculated as the average from the CONTROL run minus (plus) the linear trend of the difference between the PLANT + CULT run and the CONTROL run, multiplied by 12 years.

brown leaf area has led to an increase in R_{net} in October and on the annual average (Fig. 7). In October, this increase in R_{net} is balanced by an increase in *H*, and thus probably a slight warming of the near-surface air temperature.

Although there were some moderate monthly changes in water and energy fluxes, annual average changes were small. The June LE increase was 7.1 W m^{-2} over the 25-year period, equal to a 7.3 mm increase in monthly ET. (Note that these and other values are weighted averages over the region's corn-growing croplands, and would need to be normalized appropriately to give averages over the region's entire land area.) This is a 7.3% increase over June's LE in the CONTROL run. This was matched by a 5.7 W m^{-2} decrease in *H*. The annual-average LE increase was 0.50 W m^{-2}, or 6.3 mm year^{-1}, over the 25 years. This is an increase of 1.1%. The increase in R_{net} in October was 2.7 W m^{-2} over the 25-year period, an increase of 8.2%. The annual-average increase in R_{net} was 0.32 W m^{-2} over the 25 years, an increase of 0.5%.

Changes in water and energy fluxes that we simulated were generally smaller than have been simulated for land cover conversions from natural vegetation to croplands (Twine et al., 2004). They are also smaller than changes caused by another management factor that can affect the water and energy balance: irrigation (Sacks et al., 2009). Nevertheless, the changes in the present study were not entirely negligible, especially at the start and end of the growing season. These changes could be indications of what to expect with the adoption of bioenergy crops such as miscanthus that have a longer growth season than most crops currently grown in the U.S. (VanLoocke et al., 2010). For example, in areas that switch to growing these longer season crops, we should expect to see an increase in annual ET.

Finally, note that Agro-IBIS does not simulate post-harvest crop residues. In reality, harvest sometimes leads to the replacement of standing, brown vegetation with brown residue, rather than the bare ground that was simulated here. In places where this is the case – e.g., in no-till systems – our simulated increase in October R_{net} due to the shorter time between maturity and harvest was probably an overestimate. In effect, our simulations assumed that all farmers practiced conventional tillage, with tillage occurring immediately after harvest. Residue management is an aspect of Agro-IBIS that has been targeted for future improvement (Kucharik and Twine, 2007).

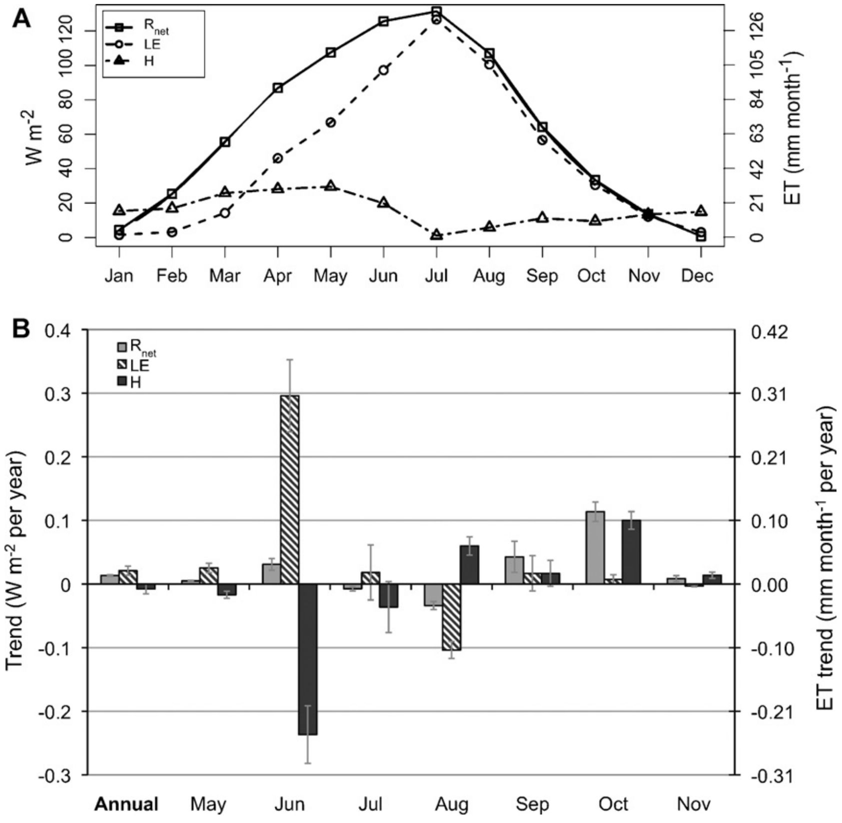

Fig. 7. (A) Regionally averaged monthly fluxes of net radiation (R_{net}), latent (LE) and sensible (*H*) heat fluxes in the CONTROL run, averaged over 1981–2005. For R_{net}, a positive flux is downwards; for LE and *H*, a positive flux is upwards. (B) Effects of changes in corn planting dates and cultivars on modeled R_{net}, LE and *H*. Bars show linear trends (1981–2005) of the regionally averaged differences between the PLANT + CULT run and the CONTROL run, for the annual average and selected monthly averages. (For months not shown, differences were small.) Error bars show 95% confidence intervals. The right-hand axes translate the LE values into evapotranspiration (ET) units. Averages are given over corn-growing croplands—*not* the region's total area.

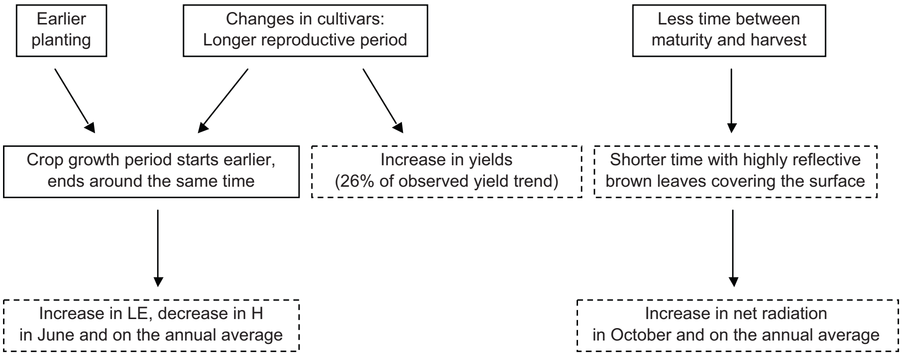

Fig. 8. Summary of the major findings of this study, for corn. Solid boxes are results based on observations; dashed boxes are results from Agro-IBIS simulations, driven by the observations.

4. Conclusions

Over the last three decades, farmers across the U.S. have been shifting corn and soybean planting to earlier dates. For both crops, but especially for corn, this has been accompanied by a lengthening of the growth period. The period from corn planting to maturity was about 12 days longer around 2005 than it was around 1981. This lengthening was due to two factors. First, earlier planting leads to a lengthening of the vegetative growth period, because this period occurs at a cooler time of year when it takes longer to accumulate a given number of GDD. Second, there has been a 14% increase in the number of GDD needed for corn to progress through the reproductive period and reach physiological maturity. This probably reflects an adoption of longer season cultivars. However, the lengthening growth period has been accompanied by a shortening of the period from maturity to harvest in both crops. (See Fig. 8 for a summary of these and the other major findings of this study.)

The trend to using longer season corn cultivars was responsible for a 12.6 bu ac^{-1} yield increase across the U.S. Corn Belt from 1981 to 2005, according to our simulations. Thus, these changes in cultivars account for 26% of the observed yield trend over this period. However, part of this effect may be attributable to the interactive effects of these management changes with other management and climatic changes, such as increases in irrigation and fertilizer application. Our model indicated that the trend to earlier planting did not directly contribute to this yield increase. However, earlier planting has still played an important role, allowing the use of longer season cultivars while maintaining roughly constant maturity dates. This is important to avoid excessive grain moisture contents at harvest, which can occur with delayed maturity.

These management changes have also modified the seasonal water and energy balance of the surface, although the annual average effects are small. Together, the trends to earlier planting and longer season cultivars have meant an increase in LE and decrease in H in June and on the annual average. In addition, the decreased time from maturity to harvest has meant an increase in R_{net} in October and on the annual average, due to a shortened time when the surface is covered with highly reflective brown vegetation.

These results have implications for the development of other regional and global crop models. First, the length of the growing season is an important parameter for modeling crop yields and the surface water and energy balance. On the global scale, this can be specified with the aid of two recent datasets (Portmann et al., 2010; Sacks et al., 2010). However, depending on the question being addressed, other parameters emerge as important. For example, the amount of time between maturity and harvest, along with changing leaf physical properties during senescence, are important processes for the surface energy balance. These processes were missing from Agro-IBIS prior to this study, and they are also missing from many other crop models, which often assume that harvest occurs as soon as the crop reaches maturity.

Some of the management trends documented here may have been driven by changes in climate (Twine and Kucharik, 2009). But some trends, like the trend to earlier planting, seem to have been driven more by changes in agronomic technologies (Kucharik, 2006). It seems likely that both climatic and technological changes will continue to drive future management changes. This points to the value of large-scale, long-term records of agricultural management practices, such as those used in this study. By drawing on such records, crop models can better capture the true drivers of agricultural management decisions, rather than simply attributing many of these decisions to climate.

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