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Where is the USA Corn Belt, and how is it changing?

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HIGHLIGHTS

- A new geospatial framework for mapping the USA Corn Belt is presented.
- Mapped patterns are defined for different user-specified levels of corn intensity.
- Temporal changes in the Corn Belt were explored and may be updated.
- The Corn Belt and related irrigated areas link food, biofuel, and water security.

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ABSTRACT

The "Corn Belt" is a commonly used term, but often referenced as a vaguely defined region in the Midwest USA. A few key studies have delineated synoptic maps of the Corn Belt boundaries going back to the early 20th century, but a modern flexible and accessible framework for mapping the Corn Belt in space and time is needed. New tools provide reference maps for the Corn Belt in the 21st century and the ability to quantify space-time changes in corn cropping patterns. The Landuse and Agricultural Management Practices web-Service (LAMPS) was used to estimate the average corn (maize, *Zea mays* L.) area in each county of the contiguous 48 USA states for the years 2010–2016. LAMPS provides a modified areal Fraction of corn (F_c) used to map the Corn Belt at three intensity levels, for example. The resulting patterns illustrate a mostly contiguous Midwest Corn Belt surrounded by more scattered regions, including southern and eastern regions. We also mapped irrigated areas and temporal changes in F_c. Mapped patterns have the potential to help researchers study issues related to food, feed, biofuel, and water security.

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1. Introduction

Corn is the most important grain crop globally, used for human food, livestock feed and biofuel (ethanol production). Over 36% of global corn production is in the USA, largely within the Midwest Corn Belt (Ort and Long, 2014). The Corn Belt is generally considered the region of the USA extending across 12 Midwest states (Panagopoulos et al., 2015), largely planted in a corn-soybean rotation (Suyker and Verma, 2012). Even though maps of the Corn Belt and corn production areas date back to the year 1919 (Baker, 1927), the term "Corn Belt" is often subjectively defined and therefore geospatially variable. It has been coarsely identified by whole states with the greatest areas of corn (Daloğlu et al., 2014; Grassini et al., 2014; Kellner et al., 2016; Tan and Liu, 2015). Others have identified a Western Corn Belt (Grassini et al., 2011; Morell et al., 2016; Sahajpal et al., 2014; Wimberly et al., 2017; Wright and Wimberly, 2013) and an Eastern Corn Belt (Auch and Laingen, 2015; Kellner et al., 2016) in the Midwest. Many studies within the region make no attempt to define the Corn Belt (Angel et al., 2017; Golecha and Gan, 2016; Liu et al., 2016; McLaughlin and Reckhow, 2017; Turhollow et al., 2014). Thus, one may be left asking, "What is the Corn Belt, where is it currently, and how is it changing?"

A few key studies have given geographical delineations of the Corn Belt. The USDA published a 1949 map of the Corn Belt as a contiguous region of the Midwest classified as predominantly "feed grains and livestock" (Bureau of Agricultural Economics, 1950). Later, Hart (1986) published a geospatial map of the Midwest Corn Belt in 1982 using county level statistics for corn acreage. He also mapped a soybean belt and changes in corn acreage from 1949 to 1982. Hart noted, "The transformation of the Corn Belt began in 1933 when hybrid seed corn was introduced, but it did not really take off until after World War II." Laingen (2012) published an overlay of the contiguous Corn Belt geometries in 1919 (Baker, 1927) and 1949 (Bureau of Agricultural Economics, 1950) while providing an historical perspective of the term "Corn Belt" being first printed in 1882. Laingen (2012) then delineated the 2007 Corn Belt and analyzed changes from 1949 to 2007 in the

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geospatial area of corn. Finally, Metson et al. (2016) based a map of the Corn Belt on the criterion of corn grain and silage production exceeding 200 kg per km^2 of land area. They used corn production data from the year circa-2000 (Monfreda et al., 2008), then applied a spatial filter to smooth the resulting shape. Their Corn Belt region was delineated to estimate transportation distances for phosphorus fertilizers.

There remains a need for an efficient, standardized yet flexible geospatial framework to quantify the Corn Belt in space and time for application to science, management, economics and policy issues. Others have developed advanced methods for classifying landcover from remotely sensed (Landsat) hyperspectral multi-temporal imagery (Yan and Roy, 2015) and delineating geometries of field boundaries (Yan and Roy, 2014; Yan and Roy, 2016). Here, we use available data (see Methods below) and publically available web services to quantify the intensity of corn areas at the county level, for example. The present objectives are to:

1. Map a recent (2010–2016) geospatial example of the Corn Belt (areas planted in corn above selected thresholds) and demonstrate its space-time dynamics,
2. provide publically accessible technical methods in a computationally efficient web-based tool to repeat the analyses for different time periods of interest and user-specified thresholds, and
3. illustrate potential interactions between the mapped Corn Belt and irrigated areas.

2. Methods for mapping the Corn Belt

We offer a geospatial definition of the Corn Belt based on a 30-m pixel resolution satellite detection of corn as determined by the USDA National Agricultural Statistical Service (NASS) web-service CropScape (Han et al., 2012). CropScape provides a Crop Data Layer (CDL) for each year since approximately 2001 or earlier in some areas. We queried the CDL using the Landuse and Agricultural Management Practices web-Service (LAMPS) (Kipka et al., 2016; LAMPS Wikipage, 2016) with county-level polygons over the contiguous 48 states.

Kipka et al. (2016) derived a Confidence Index that accounts for uncertainty in the satellite detection algorithm using the User Accuracy values reported for each crop by state and year in CropScape (Han et al., 2012). Limited independent testing of accuracy has been conducted, but a detailed study in South Dakota (Reitsma et al., 2016) identified cropland User Accuracy values of 0.897 for 2006 and 0.884 for 2012. User Accuracy values for corn typically range from approximately 0.90 to 0.99 over the Midwest states. LAMPS generates the Confidence Index, denoted here as the modified areal Fraction of corn, F_c, as follows:

$$F_c = \text{User Accuracy} \times \frac{a}{A} \tag{1}$$

where A (m^2) is the polygon area estimated by the total number of crop raster pixels representing the polygon (county in this application), and a (m^2) is the pixel area of an individual crop class (corn) within the polygon area. Here, we report the average F_c for each county (polygon) over the period of years queried. CropScape coverage varies across the contiguous 48 states, both in terms of time period and spatial resolution of the data. We chose the period of 2010–2016 for which 30-m resolution data were available for all 48 states, even though parts of the Midwest have coarser data (56-m pixels) going back to 1997. Lark et al. (2017) identified several limitations of the CDL, including changes in resolution with time, and recommended practices for estimating general land-use change using the CDL. Here, the CDL is considered to be adequate for estimating annual sequences of corn at the county level.

Because corn is often planted in rotation with other crops, primarily soybean in the Midwest, rather than as continuous corn from year-to-year, the metric for corn must consider some average intensity over time and space. Thus, the time period queried with LAMPS generally spans multiple rotation periods (e.g., four years spans two corn-soybean rotations). If rotations of different fields within each county are asynchronous or randomized, even single-year queries would be unbiased, but some synchronization might be expected (see Supporting Information for an example of one county in Iowa using field-scale polygons to derive crop rotations). One factor favoring synchronization is a quasi-biennial pattern in corn yield in Iowa related to climate variability (Malone et al., 2009). Temporal and spatial variability among fields or management areas within each county means that one would not expect to approach 100% spatial coverage of corn for each year. For example, even if actual cultivated areas covered 80% of a county polygon, 100% corn-soybean rotation would comprise only $0.5 \times 0.8 = 0.4$ or 40% corn in a given year. Thus, different threshold values of F_c were explored to produce quantifiable patterns of corn intensity for the Corn Belt.

We used the 2013 US Census county map (U.S. Census Bureau, 2013 (accessed on 5/16/2017)) as input data containing polygons and attributes for 3109 counties averaging 2511 km^2 in size. LAMPS web-service execution time is controlled primarily by the physical domain area, due to the underlying 30-m raster maps, rather than the number of polygons queried. It takes 51 s on average for LAMPS to create the results for an area of about 3000 km^2. Processing the entire continental US would require an estimated 44 h of sequential processing time, which was considered unacceptable. Fortunately, polygons have no interdependencies, so can be processed in parallel. LAMPS uses a map/reduce method (Wickham, 2011) that is implemented within the Cloud Services Innovation Platform (CSIP). CSIP is the underlying Model-as-a Service framework used to implement LAMPS (Lloyd et al., 2012). Upon service invocation, the large polygon dataset is partitioned into smaller sets, then processed in parallel in a cluster of many LAMPS services (map operation). Finally, the service aggregates partial results into the final result set (reduce operation). The leveraged Kubernetes infrastructure deployed 5 LAMPS Docker containers in CSIP, with each container running multiple instances of the LAMPS service. Docker (2017) is a lightweight software deployment platform, and Kubernetes (2017) is a container orchestration framework; both are well suited for scientific applications.

An average partition size of 12,000 km^2 provided near-optimal overall performance for this application. As a result, LAMPS processed the 3007 counties in 10.6 h on our CSIP cluster. Each container had 16 cores and 4 GB of memory available for this task.

The LAMPS output file, containing >1 million rows, was imported into a local relational database and queried with a single SQL (Structured Query Language) command to obtain all "Corn" vegetation records with an average F_c >0.05. In a final step, the query result was joined with the county attribute table in a GIS and the county map was reclassified to visualize the results.

3. Results

3.1. Corn patterns

Maps of the Corn Belt were generated using different ranges of F_c averaged for the years 2010–2016 (Fig. 1). Counties with average F_c between 0.20 and 0.58 (denoted as red) indicate the core, mostly contiguous region of the Corn Belt, which is hereby quantified with a known confidence using F_c. In Iowa, where 87 out of 99 counties are mapped as $F_c \geq 0.2$, the average User Accuracy for this period is 0.984. Thus one may estimate an uncertainty of ± 0.016 F_c. Over all 99 counties, the average F_c is 0.36 (36%) with an uncertainty of only 0.006. If most of this corn area is in a typical corn-soybean rotation, the average fraction of total area is approximately 72%, which is roughly consistent with a previous threshold of 80% corn-soybean (Hart, 1986).

By reducing the minimum F_c from 0.2 to 0.1, the total area of the Corn Belt nearly doubles in size from approximately 650,000 to 1,100,000 km^2 (see Fig. 2), but it becomes more discontinuous in space (Fig. 1). Notably, this second threshold level encompasses counties mostly on the edges of the core Corn Belt, and merges islands

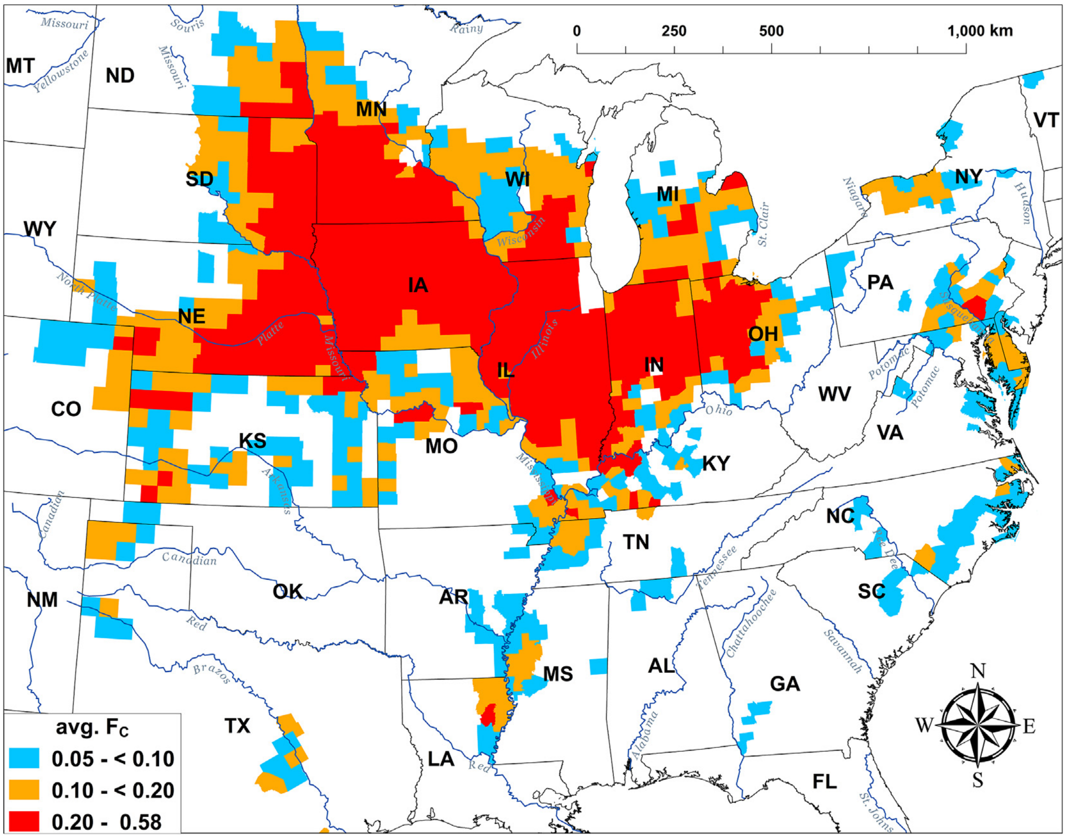

Fig. 1. Corn Belt region based on the temporal average of the modified areal Fraction of corn (F_c) values calculated for the years 2010 through 2016. Polygons are county boundaries within each state. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

of $F_c \geq 0.2$ into more contiguous areas in some states (NE, ND, MI, MO). The third level of $F_c \geq 0.05$ adds approximately 500,000 km^2 to the total area (Fig. 2), and continues the pattern of adding areas on the edges of the first two F_c ranges. Adding the two lowest F_c ranges resulted in a more contiguous region that is connected to the core Midwest Corn Belt, as well as some key discontinuous regions such as the southern corridor of the Mississippi River and eastern states.

3.2. Irrigation patterns

Once the geospatial distribution of the Corn Belt is identified using various F_c thresholds, many other questions may arise. For instance,

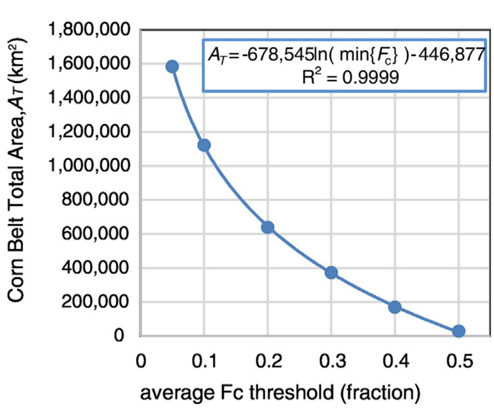

Fig. 2. Total Area (A_T) of the Corn Belt versus the average modified areal Fraction of corn threshold (min{F_c}); values of 0.05, 0.1 and 0.2 were used in Fig. 1.

"How much of the Corn Belt is irrigated, and to what degree within each county?" To answer these questions, we used LAMPS to query the USGS irrigation maps (U.S. Geological Survey, 2015) based on Moderate Resolution Imaging Spectroradiometer (MODIS) satellite data taken every five years (to date: 2002, 2007, 2012). We chose the year 2012 because it is most relevant to our 2010–2016 Corn Belt map. Fig. 3 shows the percent area irrigated (blue color ramp) for each county within the greater Corn Belt ($F_c > 0.05$). Note that irrigated area (%) reflects irrigation of all crops within the county, not only corn, and some counties have both irrigated and non-irrigated corn. Green areas are non-irrigated or rainfed (<1% irrigated area). The decision to irrigate is based on many factors including the cost and availability of irrigation water, precipitation (timing and amount), and potential evapotranspiration (PET, strongly influenced by temperature). Major rivers, a common source of irrigation water, are also shown on this map. In the more western states of Nebraska (NE) and Kansas (KS), for example, irrigated corn is associated with the Platte River and Arkansas River, respectively. The Ogallala or High Plains Aquifer is a major water source for parts of NE, KS and TX. Eastern Colorado also pumps groundwater from the Ogallala Aquifer, but most of the corn area in CO is rainfed based on the 2012 irrigation map. Areas irrigated by surface water in CO and other parts of the west may comprise relatively small corridors within each county, and such patterns are not resolved at the county level. Irrigation is mapped along the Mississippi River, where groundwater pumping from the Mississippi Embayment Aquifer (Clark and Hart, 2009) is a key to corn production in parts of Mississippi (MS), Louisiana (LA), Arkansas (AR), Tennessee (TN), and even corners of Missouri (MO) and Kentucky (KY). Pockets of irrigated corn also show up in Texas (TX), for example.

Another interesting feature in Fig. 3 is the non-irrigated area of the Corn Belt. Iowa is fully encompassed by the Corn Belt, but most of this corn (or corn-soybean) production is supported by natural precipitation

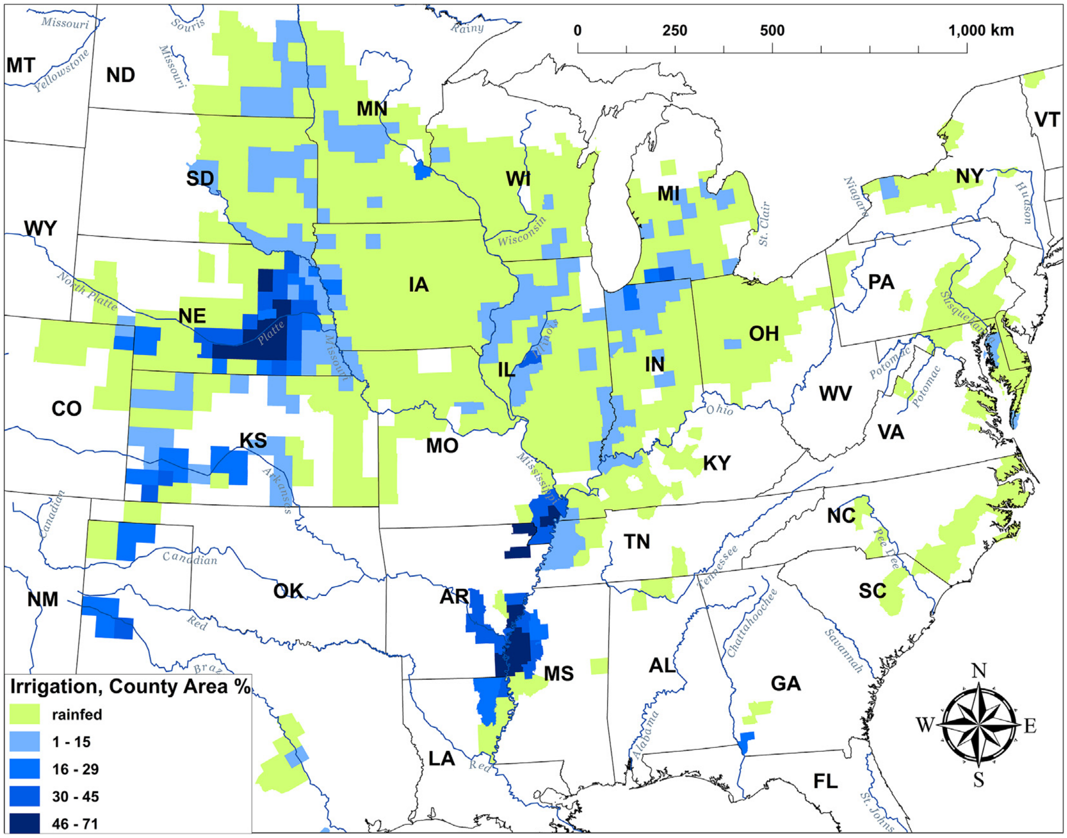

Fig. 3. Irrigation of the Corn Belt region ($F_c > 0.05$ in Fig. 1) based on the 2012 Irrigated Agriculture Dataset for the United States (MIrAD-US) upscaled for each county (Brown and Pervez, 2014; U.S. Geological Survey). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

(e.g., ranging from about 700 to 1000 mm/yr in Iowa). Both, climate and soils play roles in this pattern. Deep soils with high water-holding capacity make agricultural systems more resilient to periods with low precipitation (designated as drought or otherwise) than in areas such as the western/southwestern edges of the Corn Belt that have shallower soils, much lower precipitation (e.g., 400 mm/yr in southeastern Colorado) and high PET (e.g., 1800 mm/yr) (Ascough et al., 2010). In these areas, corn is often replaced with sorghum if irrigation water is limited, and other factors may also affect the spatiotemporal distribution of sorghum (Laingen, 2015). In general, crop irrigated area tends to be lower in the northern states, where seasonal temperature and evaporative demand is lower, and in eastern states where precipitation is higher.

3.3. Corn Belt dynamics

We also asked, "How has the spatial pattern of the Corn Belt changed in time?" Many factors likely influence such changes, including climate change (Bhattarai et al., 2017), global demand for corn, biofuel production for ethanol, subsidies (Clay et al., 2014; Wright and Wimberly, 2013), and crop prices. Coincidentally, corn grain price peaked in 2012 (Macrotrends, 2017). LAMPS can query CropScape for any set of years to look for such changes, and we chose to look at the most recent years in defining our Corn Belt. We used two available periods of 2010–2012 and 2014–2016, where the gap year of 2013 was excluded. We also analyzed change with two periods of four years each overlapping on 2013 to include two cycles of a corn-soybean rotation. However, test results (see Supplementary Information) indicated that county-level analyses are not strongly affected by synchronization of crop phases. As expected, analysis including 2013 as overlap year (not shown) reduced the computed change slightly.

Fig. 4 shows the change in average F_c (ΔF_c) for each county. By plotting the change in F_c value instead of a percentage change, absolute changes in corn area are illustrated. Percent change may over-emphasize changes in locations where the base level (F_c for 2010–2012) was small. In this illustration of change (increase or decrease indicated by $|\Delta F_c| > 0.01$), the minimum magnitude of change may be relatively small. In the case of decreased F_c, the greatest magnitude is under 10% ($\Delta F_c = -0.099$) at the county level, and the maximum increase is only $\Delta F_c = 0.058$. The net change or average ΔF_c over all counties in the delineated Corn Belt is -0.00278 or a decrease of approximately 4400 km^2 or 440,000 ha. Additional ΔF_c classes could be mapped if desired for detailed assessments.

Many counties are mapped as having no major change in the area of corn (tan). The state of Minnesota (MN), for example, had very little change overall and only a few counties with increases (red) or decreases (blue). There are four main contiguous areas of decreased F_c. The largest and most central area of decreased F_c in the Corn Belt covers most of Illinois (IL) and parts of Iowa (IA). Corn acreage has also decreased in western Kansas (KS) and eastern Colorado (CO) near the western edge of the Corn Belt. Another pocket of decreased corn lies in the south, where growing corn is highly dependent on irrigation water. Finally, we see a region of decreased corn in the northeastern states; whereas there are no decreases in the southeastern states. The main area of contiguous corn intensification (positive changes in F_c) lies in the Dakotas (ND, SD), which concurs with more regional detailed results for the period 2004–2014 showing associated conversions from grasslands to croplands (Wimberly et al., 2017). These counties with increased corn overlap the northwestern extent of the core Corn Belt (Fig. 1) and indicate a pattern of growth to the northwest in both irrigated and non-irrigated areas. Other areas of increases are mottled with a

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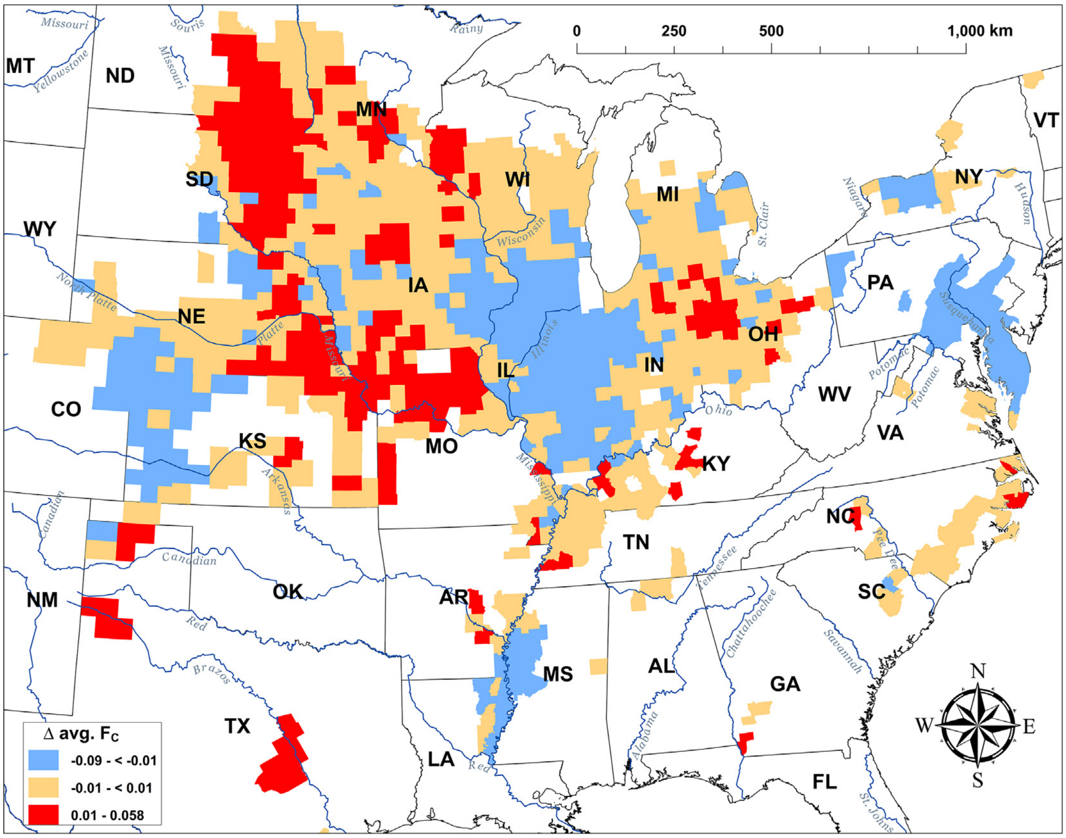

Fig. 4. Change in average modified areal Fraction of corn (F_c) based on Crop Data Layer (CDL) data for 2013–2016 minus CDL data for 2010–2013, where 2013 is an overlapping year for these periods. Positive (red) values indicate increased areas planted in corn. Absolute changes of $F_c < 0.01$ (tan counties) are considered insignificant or areas of no change for mapping purposes. The mean change in F_c over all counties is 0.0035, which is an equivalent net areal increase of 5600 km^2. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

cluster of counties in southeast Nebraska (NE), northeast Kansas (KS) and northern Missouri (MO).

4. Discussion

There are many short- and long-term factors influencing whether producers grow corn (e.g., projected crop prices and weather, changing climate, cost of inputs, availability and cost of irrigation water, and ethanol subsidies or lack thereof), and these factors likely interact. A careful study of these interactions and causative factors is beyond our current scope, but others are endeavoring to use CDL information to address factors causing cropland dynamics (e.g., Lark et al., 2015; Stoebner and Lant, 2014; Wright et al., 2017; Wright and Wimberly, 2013). For such studies, maps such as Fig. 4 can be readily generated using LAMPS in the framework present here, and used together with other knowledge to better predict or understand the causes of space-time changes.

The spatial correlation of change in F_c could also be analyzed for other purposes, particularly for quantifying the impact of the change. Changes in the distribution of corn will affect transportation and storage of grain, with implications for interstate commerce and regional fertilizer and agrochemical use. One could also project spatial patterns of change forward in time based on historical trends and expected driving factors, such as the drought in 2012. The resulting morphology of the Corn Belt (projected from Fig. 1) could affect wildlife migration and other ecosystems services. Here, the pattern is presented simply to illustrate the potential for exploring various systems that interact with the dynamics of the Corn Belt in space and time.

This analysis demonstrated that the Corn Belt can be geospatially quantified, thus answering the question, "Where is the USA Corn Belt?" Yet the answer is not static, and the geographic extent of Corn Belt will vary based on the specific questions of interest. As defined here, the core area of the Corn Belt (2010–2016) encompasses large areas of 8 Midwestern states including SD, NE, MN, IA, WI, IL, IN and OH. Dynamics of the Corn Belt can also be queried for user-defined periods, which may inform various stakeholders, including those interested in agricultural economics and food security, biofuel production and greenhouse gas emissions, and others who need a quantifiable reference area for the Corn Belt and its changes over time. The spatial distribution and intensity of irrigation is clearly tied to available water resources, linking food and water security. Such maps may be useful to planners and policy makers.

In addition to the outputs illustrated here, users can obtain representative crop rotations through linkage of LAMPS with the Land Management Operations Database (David et al., 2014). Finally, LAMPS is free and readily available (LAMPS Wikipage, 2016) as a web service for any user to query their region at any level of spatial detail >30 m. Users can customize the F_c thresholds to be used, and other crops or land uses could be investigated.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2017.09.325.

References

Angel, J.R., Widhalm, M., Todey, D., Massey, R., Biehl, L., 2017. The U2U corn growing degree day tool: tracking corn growth across the US Corn Belt. Climate Risk Manag. 15, 73–81.

Ascough, J.C., Andales, A.A., Sherrod, L.A., McMaster, G.S., Hansen, N.C., DeJonge, K.C., et al., 2010. Simulating landscape catena effects in no-till dryland agroecosystems using GPFARM. Agric. Syst. 103, 569–584.

Auch, R.F., Laingen, C., 2015. Having it both ways? Land use change in a U.S. midwestern agricultural ecoregion. Prof. Geogr. 67, 84–97.

Baker, O.E., 1927. Agricultural regions of North America, Part IV – the Corn Belt. Econ. Geogr. 3, 447–465.

Bhattarai, M.D., Secchi, S., Schoof, J., 2017. Projecting corn and soybeans yields under climate change in a Corn Belt watershed. Agric. Syst. 152, 90–99.

Brown, J.F., Pervez, M.S., 2014. Merging remote sensing data and national agricultural statistics to model change in irrigated agriculture. Agric. Syst. 127, 28–40.

Bureau of Agricultural Economics, 1950. Generalized Types of farming in the United States: including a list of counties in type-of-farming regions and subregions. In: Elliot, F.F. (Ed.), Agriculture Information Bulletin No. 3. USDA.

Clark, B.R., Hart, R.M., 2009. The Mississippi embayment regional aquifer study (MERAS): documentation of a groundwater-flow model constructed to assess water availability in the Mississippi embayment. Scientific Investigations Report, p. 62.

Clay, D.E., Clay, S.A., Reitsma, K.D., Dunn, B.H., Smart, A.J., Carlson, G.G., et al., 2014. Does the conversion of grasslands to row crop production in semi-arid areas threaten global food supplies? Glob. Food Sec. 3, 22–30.

Daloğlu, I., Nassauer, J.I., Riolo, R.L., Scavia, D., 2014. Development of a farmer typology of agricultural conservation behavior in the American corn belt. Agric. Syst. 129, 93–102.

David, O., Yaege, L., Rojas, K., Green, T.R., Kipka, H., Lloyd, W., et al., 2014. The land management and operations database (LMOD). In: Ames, D.P., Quinn, N.W.T., Rizzoli, A.E. (Eds.), Proc. 7th International Congress on Environmental Modelling and Software. Vol. 4, pp. 1825–1832 (San Diego, CA, USA).

Docker, 2017. https://www.docker.com/what-docker, Accessed date: 16 May 2017.

Golecha, R., Gan, J., 2016. Cellulosic biorefinery portfolio and diversification: strategies to mitigate cellulosic biorefinery risks in US Corn Belt. Energ. Strat. Rev. 13, 147–153.

Grassini, P., Yang, H., Irmak, S., Thorburn, J., Burr, C., Cassman, K.G., 2011. High-yield irrigated maize in the Western U.S. Corn Belt: II. Irrigation management and crop water productivity. Field Crop Res. 120, 133–141.

Grassini, P., Specht, J.E., Tollenaar, M., Ciampitti, I., Cassman, K.G., 2014. High-Yield Maize-Soybean Cropping Systems in the US Corn Belt. pp. 17–41.

Han, W., Yang, Z., Di, L., Mueller, R., 2012. CropScape: a web service based application for exploring and disseminating US conterminous geospatial cropland data products for decision support. Comput. Electron. Agric. 84, 111–123.

Hart, J.F., 1986. Change in the Corn Belt. Geogr. Rev. 76, 51–72.

Kellner, O., Niyogi, D., Marks, F.D., 2016. Contribution of landfalling tropical system rainfall to the hydroclimate of the eastern U.S. Corn Belt 1981–2012. Weather Climate Extremes 13, 54–67.

Kipka, H., Green, T.R., David, O., Garcia, L.A., Ascough, J.C., Arabi, M., 2016. Development of the land-use and agricultural management practice web-service (LAMPS) for generating crop rotations in space and time. Soil Tillage Res. 155, 233–249.

Kubernetes, 2017. https://kubernetes.io (accessed on 5/16/2017).

Laingen, C., 2012. Delineating the 2007 Corn Belt region. Appl. Geogr. Conf. 35, 173–181.

Laingen, C.A., 2015. Spatiotemporal analysis of sorghum in the United States. Pap. Appl. Geogr. 1, 307–311.

LAMPS Wikipage, 2016. https://alm.engr.colostate.edu/cb/item/13580, Accessed date: 17 May 2017.

Lark, T.J., Salmon, J.M., Gibbs, H.K., 2015. Cropland expansion outpaces agricultural and biofuel policies in the United States. Environ. Res. Lett. 10, 044003.

Lark, T.J., Mueller, R.M., Johnson, D.M., Gibbs, H.K., 2017. Measuring land-use and land-cover change using the U.S. department of agriculture's cropland data layer: cautions and recommendations. Int. J. Appl. Earth Obs. Geoinf. 62, 224–235.

Liu, X., Jacobs, E., Kumar, A., Biehl, L., Andresen, J., Niyogi, D., 2016. The Purdue Agro-climatic (PAC) dataset for the U.S. Corn Belt: development and initial results. Climate Risk Manag. 15, 61–72.

Lloyd, W., David, O., Lyon, J., Rojas, K.W., Ascough, J.C., Green, T.R., et al., 2012. The cloud services innovation platform - enabling service-based environmental modelling using infrastructure-as-a-service cloud computing. In: Seppelt, R., Voinov, A.A., Lange, S., Bankamp, D. (Eds.), Proc. 6th Intl. Congress on Environmental Modelling and Software, pp. 1208–1215 (Leipzig, Germany).

Macrotrends, 2017. http://www.macrotrends.net/2532/corn-prices-historical-chart-data, Accessed date: 12 June 2017.

Malone, R.W., Meek, D.W., Hatfield, J.L., Mann, M.E., Jaquis, R.J., Ma, L., 2009. Quasi-biennial corn yield cycles in Iowa. Agric. For. Meteorol. 149, 1087–1094.

McLaughlin, D.B., Reckhow, K.H.A., 2017. Bayesian network assessment of macroinvertebrate responses to nutrients and other factors in streams of the Eastern Corn Belt Plains, Ohio, USA. Ecol. Model. 345, 21–29.

Metson, G.S., MacDonald, G.K., Haberman, D., Nesme, T., Bennett, E.M., 2016. Feeding the Corn Belt: opportunities for phosphorus recycling in U.S. agriculture. Sci. Total Environ. 542, 1117–1126.

Monfreda, C., Ramankutty, N., Foley, J.A., 2008. Farming the planet: 2. Geographic distribution of crop areas, yields, physiological types, and net primary production in the year 2000. Glob. Biogeochem. Cycles 22, 1–19.

Morell, F.J., Yang, H.S., Cassman, K.G., Wart, J.V., Elmore, R.W., Licht, M., et al., 2016. Can crop simulation models be used to predict local to regional maize yields and total production in the U.S. Corn Belt? Field Crop Res. 192, 1–12.

Ort, D.R., Long, S.P., 2014. Limits on yields in the Corn Belt. Science 344, 484–485.

Panagopoulos, Y., Gassman, P.W., Jha, M.K., Kling, C.L., Campbell, T., Srinivasan, R., et al., 2015. A refined regional modeling approach for the Corn Belt - experiences and recommendations for large-scale integrated modeling. J. Hydrol. 524, 348–366.

Reitsma, K.D., Clay, D.E., Clay, S.A., Dunn, B.H., Reese, C., 2016. Does the U.S. cropland data layer provide an accurate benchmark for land-use change estimates? Agron. J. 108, 266–272.

Sahajpal, R., Zhang, X., Izaurralde, R.C., Gelfand, I., Hurtt, G.C., 2014. Identifying representative crop rotation patterns and grassland loss in the US Western Corn Belt. Comput. Electron. Agric. 108, 173–182.

Stoebner, T.J., Lant, C.L., 2014. Geographic determinants of rural land covers and the agricultural margin in the Central United States. Appl. Geogr. 55, 138–154.

Suyker, A.E., Verma, S.B., 2012. Gross primary production and ecosystem respiration of irrigated and rainfed maize-soybean cropping systems over 8 years. Agric. For. Meteorol. 165, 12–24.

Tan, Z., Liu, S., 2015. Corn Belt soil carbon and macronutrient budgets with projected sustainable stover harvest. Agric. Ecosyst. Environ. 212, 119–126.

Turhollow, A., Perlack, R., Eaton, L., Langholtz, M., Brandt, C., Downing, M., et al., 2014. The updated billion-ton resource assessment. Biomass Bioenergy 70, 149–164.

U.S. Census Bureau, 2013. Cartographic boundary file, state-county for United States, 1: 5,000,000. https://www.census.gov/geo/maps-data/data/cbf/cbf_counties.html, Accessed date: 16 May 2017.

U.S. Geological Survey, 2015. https://earlywarning.usgs.gov/USirrigation (accessed on 4/25/2017).

Wickham, H., 2011. The split-apply-combine strategy for data analysis. J. Stat. Softw. 40, 1–29.

Wimberly, M.C., Janssen, L.L., Hennessy, D.A., Luri, M., Chowdhury, N.M., Feng, H., 2017. Cropland expansion and grassland loss in the eastern Dakotas: new insights from a farm-level survey. Land Use Policy 63, 160–173.

Wright, C.K., Wimberly, M.C., 2013. Recent land use change in the Western Corn Belt threatens grasslands and wetlands. Proc National Academy of Sciences of the United States of America (PNAS). 110 (4134–9).

Wright, C.K., Larson, B., Lark, T.J., Gibbs, H.K., 2017. Recent grassland losses are concentrated around U.S. ethanol refineries. Environ. Res. Lett. 12, 044001.

Yan, L., Roy, D.P., 2014. Automated crop field extraction from multi-temporal Web Enabled Landsat Data. Remote Sens. Environ. 144, 42–64.

Yan, L., Roy, D.P., 2015. Improved time series land cover classification by missing-observation-adaptive nonlinear dimensionality reduction. Remote Sens. Environ. 158, 478–491.

Yan, L., Roy, D.P., 2016. Conterminous United States crop field size quantification from multi-temporal Landsat data. Remote Sens. Environ. 172, 67–86.

Supplementary Information

Materials and Methods. Spatial variability of corn grain yield within and among fields has been estimated from satellite imagery (Lobell and Azzari, 2017). Fully exploring the question of randomness versus synchrony of the corn phase in crop rotations within each and every county is beyond the scope of the present study. However, field boundary geometry data were available for counties in Iowa (Tomer, 2016), which allowed us to illustrate the variability within one county. Field-level data provide series of annual dominant crops within each field. LAMPS has a second option to fit temporal series to representative crop rotations for each region using a genetic similarity algorithm (Kipka et al., 2016). Crop rotations are also temporally referenced, so a two-year corn-soybean rotation can be identified as having corn in either even or odd years for each field. Corn may also be identified in more or less intensive rotations or as continuous corn, similar to pixel-based crop rotations (Sahajpal et al., 2014), and "other" field crops or rotations without corn may be identified using the field boundary polygons.

The algorithm in LAMPS for matching crop sequences to representative rotations uses an adjustment factor (Δ) to optimize similarity between detected and representative rotations. The matching process in LAMPS uses the Adjusted Average Confidence Index ($AACI$):

$$AACI = \frac{\frac{1}{n}\sum_{i=1}^{n} CI_i}{\max\left(CI\right)}\left[1+\left(n-1\right)\Delta\right] \tag{S1}$$

where CI is equivalent to F_c, but for all detected crop types, n is the number of years of data used from CropScape, max(CI) is the maximum value of CI in n years, and Δ is the weighting factor that causes the average CI to be "adjusted" to favor longer rotations. The optimal value for a test case in Colorado was $\Delta = 0.15$ (Kipka et al., 2016), whereas for this case in Iowa the optimal value is $\Delta = 0.30$.

Example Results. Fig. S1 is a map of the results within Wright County, IA for the years 2010-2016. Orange and green classes show corn-soybean and soybean-corn rotations with corn in even or odd years, respectively. The map also shows fields classified as "majority corn" with corn detected in 5 or 6 of the 7 years, or "continuous corn" with all 7 years planted in corn. The spatial pattern of these classes is neither completely random nor highly spatially correlated.

Visually there is some degree of auto-correlation between adjacent fields and fields within short distances of each other, but no major spatial continuity. Geospatial analyses, such as those applied to crop rotations outside of the Corn Belt (Mueller-Warrant et al., 2017), were not pursued for this illustration.

The number of fields with corn-soybean (4 years of corn in 2010-2016) and soybean-corn (3 years of corn) are not exactly equal in Wright County (Fig. S2). The difference is causes by other rotations with 4 years of corn and a small degree of synchronous management, whereas the similar magnitude indicates the farmers are not synchronizing rotations overall within this county. Among only corn-soybean rotations (both odd and even year phases) the average fraction of corn was 0.51, while the average fraction of soybean was 0.49. This finding (illustrative only) combined with a limited number of fields with only 1 or 2 years of corn support the assumption that the current results are not strongly affected by synchronization of management patterns within each county, even when averaging over only two years (each frame of Movie S1). Interested readers are referred to a broader nine-state study (Plourde et al., 2013) which used CDL data to identify corn area versus the fraction of years of corn for 2003-2010.

Finally the county level results are based upon the fraction of area in corn, not the number of fields, but those two quantities are closely related (Fig. S2) for rotations with 3 or more years of corn. Fig. S2 shows that fields with less intensive corn (1 or 2 years) or no corn (0 years) have smaller polygon areas in general. Thus, these polygons have less influence on the county level results.

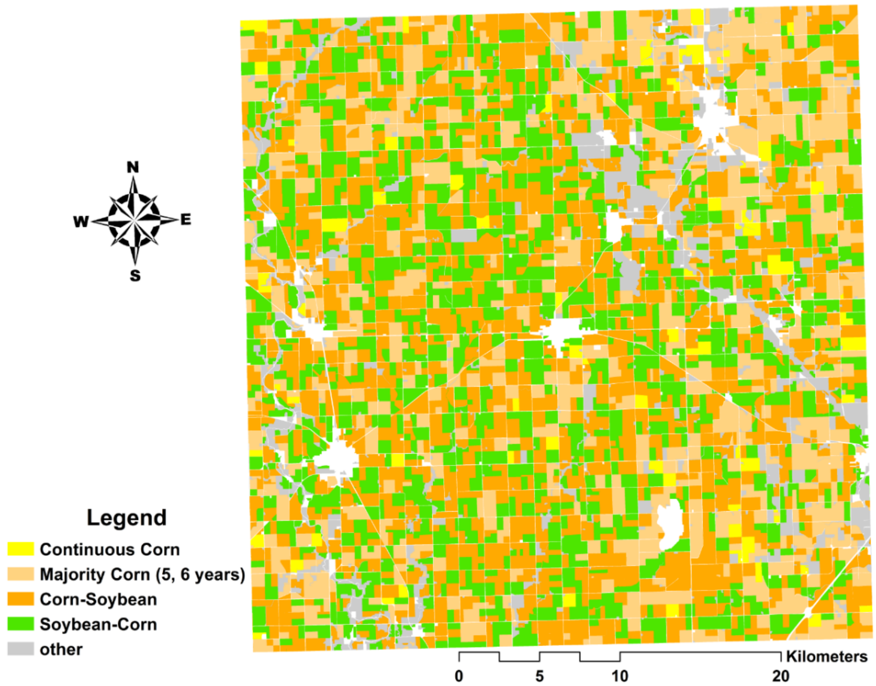

Fig. S1. A map of fields in Wright County, IA shows alternating corn-soybean rotations, more intensive corn, and "other" crop rotations without corn. Corn-soybean and soybean-corn rotations have corn in even or odd years, respectively, for the years 2010-2016. Areas with no color (white) were excluded as urban areas, road corridors, or water bodies. The total number of fields/polygons is 5882.

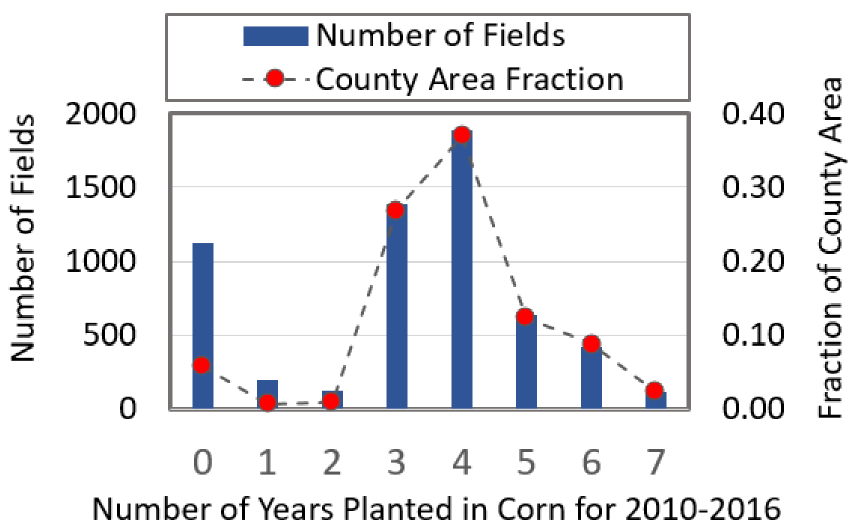

Fig. S2. Histogram of the number of fields with 0-7 years of corn in the period of analysis (2010-2016) and the associated fractions of the total county area. Corn-soybean and soybean-corn rotations starting in 2010 have 3 and 4 years of corn, respectively.

Movie S1. Animation of the interannual Corn Belt dynamics from 2010-2016 can be viewed at: https://alm.engr.colostate.edu/cb/item/13580 (scroll down to "Example Applications" and click on the "CornBelt.avi" link. The file "CornBelt.mp4" was also uploaded as Supporting Information.

We queried two-year periods and computed the running average for each year (frame) of the video. Viewers may watch the video play (3 seconds per frame), but more detailed inspection is possible by pausing the video and stepping manually through the frames.

References

Lobell, D.B., Azzari, G., 2017. Satellite detection of rising maize yield heterogeneity in the U.S. Midwest. Environ. Res. Lett. 12, 014014.

Mueller-Warrant, G.W., Trippe, K.M., Whittaker, G.W., Anderson, N.P., Sullivan, C.S., 2017. Spatial methods for deriving crop rotation history. Int. J. Appl. Earth Obs. Geoinf. 60, 22–37.

Plourde, J.D., Pijanowski, B.C., Pekin, B.K., 2013. Evidence for increased monoculture cropping in the Central United States. Agric. Ecosyst. Environ. 165, 50–59.

Tomer, M.D., 2016. Polygon Data of Field Boudaries for Iowa, (personal comm.).