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Recent collapse of crop belts and declining diversity of US agriculture since 1840

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Abstract

Over the last century, US agriculture greatly intensified and became industrialized, increasing in inputs and yields while decreasing in total cropland area. In the industrial sector, spatial agglomeration effects are typical, but such changes in the patterns of crop types and diversity would have major implications for the resilience of food systems to global change. Here, we investigate the extent to which agricultural industrialization in the United States was accompanied by agglomeration of crop types, not just overall cropland area, as well as declines in crop diversity. Based on county-level analyses of individual crop land cover area in the conterminous United States from 1840 to 2017, we found a strong and abrupt spatial concentration of most crop types in very recent years. For 13 of the 18 major crops, the widespread belts that characterized early 20th century US agriculture have collapsed, with spatial concentration increasing 15-fold after 2002. The number of counties producing each crop declined from 1940 to 2017 by up to 97%, and their total area declined by up to 98%, despite increasing total production. Concomitantly, the diversity of crop types within counties plummeted: in 1940, 88% of counties grew >10 crops, but only 2% did so in 2017, and combinations of crop types that once characterized entire agricultural regions are lost. Importantly, declining crop diversity with increasing cropland area is a recent phenomenon, suggesting that corresponding environmental effects in agriculturally dominated counties have fundamentally changed. For example, the spatial concentration of agriculture has important consequences for the spread of crop pests, agrochemical use, and climate change. Ultimately, the recent collapse of most agricultural belts and the loss of crop diversity suggest greater vulnerability of US food systems to environmental and economic change, but the spatial concentration of agriculture may also offer environmental benefits in areas that are no longer farmed.

KEYWORDS
agglomeration, agricultural intensification, agroecosystem, crop diversity, food security, land sparing

1 | INTRODUCTION

Agriculture is a major cause of environmental change, and has far-reaching effects on ecosystems, biodiversity, and human well-being (Defries et al., 2004; Foley et al., 2005; Tilman et al., 2001; Turner et al., 2007). Theoretically, reducing these effects can be achieved either by limiting the area that is farmed, effectively sparing remaining natural areas from conversion ("land sparing"), or by reducing the intensity of agriculture where it occurs ("land sharing"; Green et al., 2005; Kremen & Merenlender, 2018; Phalan et al., 2011). The need to produce sufficient food for growing populations results in strong trade-offs under both strategies (Ausubel et al., 2013; Kremen, 2015). Land sparing requires higher yields, which typically involves the use of more fertilizers, herbicides, and pesticides, which harm the environment (Tscharntke et al., 2012; Vandermeer, 2005). Land sharing involves an increase in area farmed, to the detriment of natural habitats (Phalan et al., 2011). Which strategy is better depends on regional context and conservation goals (Ekroos et al., 2016; Grau et al., 2013). The strong theoretical differences between land sparing and land sharing raise the question of how agricultural land use patterns have changed over time. Understanding these changes is important to manage landscapes and economies, maintain ecosystem services, and predict future land use, especially given climate change (Chameides et al., 1994; Dale, 1997), but doing so requires understanding how the patterns of different crops have changed, not just cropland area in the aggregate (Turner et al., 2007).

In the United States, as elsewhere, the total area in agricultural land use has changed rapidly over the last two centuries. North American landscapes have been used for agriculture by indigenous peoples for centuries, but the wholesale conversion of prairies and forests to agriculture began with European colonization in the 1600s, and intensified in the 1800s as federal legislation, notably the Homestead Acts of 1862 and 1909, plus the use of military force, quickened westward expansion (Clawson, 1979; Helfman, 1962; Hurt, 2002; Ramankutty et al., 2010; Schlebecker, 1973; Waisanen & Bliss, 2002). However, as agriculture replaced much of the prairies during the 1900s, the eastern United States witnessed agricultural abandonment and gradual reforestation, and the total area under cultivation has declined since the 1920s (Brown et al., 2005; Clawson, 1979; Ramankutty & Foley, 1999; Ramankutty et al., 2010; Sleeter et al., 2013). Thus, changes in cropland area in the United States since the 1800s increasingly resemble a pattern of land sparing.

Changes in total area under cultivation alone, however, fail to fully capture how much agriculture has changed (Aguilar et al., 2015; Hijmans et al., 2016). After WWII, US agriculture became highly industrialized (Alston et al., 2010; Schlebecker, 1975). Key aspects of agricultural industrialization were the mechanization of farming, the widespread use of fertilizers and pesticides, rapidly rising yields, increases in farm size, and specialization of farms (Brown & Schulte, 2011; Hurt, 2002; Meehan et al., 2011; Schlebecker, 1975). Concomitantly, transportation networks improved, agricultural products were shipped farther, and supply chains became longer. In other words, agricultural production increasingly resembled industrial production. In the industrial sector, production is characterized by spatial agglomeration, that is, factories that produce similar goods are concentrated in one area (e.g., car manufacturing in Detroit) because of increasing returns to scale stemming from efficient knowledge transfer, trade networks, larger skilled labor markets, and other factors (Krugman, 1979, 1991). This raises the question to what extent agriculture also became spatially concentrated as it industrialized. Agglomeration effects in agricultural production typically operate for individual crop types (Garrett et al., 2013), partly because transportation nodes or processing facilities are often specialized for individual crops. A great example of this is ethanol refineries. Typically designed to process a single crop (corn), ethanol refineries are most likely to be placed where corn is already common, but once they are built, they make it advantageous to grow more corn in their vicinity, causing a positive feedback and agglomeration. We would thus expect that crop types that were historically grown in wide belts (Baker, 1922) became spatially concentrated as agriculture industrialized.

The spatial concentration of agricultural land use, especially when accompanied by increasing yields as is envisioned under land sparing strategies, can have strong environmental ramifications, both positive and negative (Emmerson et al., 2016; Kremen, 2015; Ramankutty et al., 2018). On the one hand, a positive effect of concentration is that growing a given crop type only where it grows best is more efficient, and reducing the total area that needs to be farmed may reduce pressure to convert natural areas or offer opportunities for restoration (Barral et al., 2015; Phalan et al., 2011). Furthermore, the spread of agricultural pests may be curtailed if individual crop types are not grown in wide belts (Margosian et al., 2009). On the other hand, spatial concentration results in large field sizes, which causes the loss of habitat structures such as hedgerows that many species depend on (Baudry et al., 2000; Fahrig et al., 2015), and increasing yields typically rely on the heavy use of fertilizers, herbicides, and pesticides, all of which have strong, negative environmental effects and can vary substantially among crop types (Donald et al., 2001; Tscharntke et al., 2012; Tsiafouli et al., 2015).

The negative environmental effects of spatial concentration of crop types are exacerbated when concentration is accompanied by a loss in diversity, that is, the richness, evenness, and compositional dissimilarity of crop types grown in an area. Areas with lower crop diversity, that is, simplified croplands, can be more vulnerable to the rapid spread of crop pests and pathogens (Margosian et al., 2009) or to catastrophic losses from climate change (Ramankutty et al., 2002). Lower diversity of croplands can also reduce natural pest suppression, causing a greater reliance on pesticides and higher likelihood for pesticide resistance to evolve (Larsen & Noack, 2017). In the United States, crop diversity at the state level peaked between 1940 and 1960 (Hijmans et al., 2016), with ensuing cropland simplification resulting in increased clustering of counties with low crop diversity (Aguilar et al., 2015). However, at a finer spatial resolution, and prior to the post-WWII intensification of agriculture, patterns of crop diversity are unclear. We asked how the richness, evenness, and compositional dissimilarity of crop types changed at the county-level over time, and if more cropland area has always been associated with lower crop diversity. On the one hand, higher diversity in counties with more cropland would be expected given typical species–area relationships. On the other hand, counties that were largely agricultural may also be where agriculture was most rapidly industrialized, and hence where crop diversity was lowest.

Here, our main goal is to investigate the extent to which agricultural industrialization in the United States was accompanied by agglomeration of crop types and declines in crop diversity. We curate new county-level agricultural census data from 1840 to 2017, dramatically improving the spatial resolution of quantitative analyses. For 18 major crop types, we test if and when spatial concentration of individual crop types increased, and examine how crop diversity (richness, evenness, and compositional dissimilarity) has changed as a result. We predicted that: (a) individual crop types that used to occur in broad belts are now spatially concentrated, (b) richness and evenness of crop types declined since the mid-20th century and were lower in counties with a higher proportion of cropland, and (c) the compositional dissimilarity of crop types among counties increased with declines in richness and evenness, resulting in the loss of historic combinations of crops and potentially the appearance of new ones.

2 | MATERIALS AND METHODS

2.1 | Crop land cover data

We obtained county-level agricultural land use data from United States agricultural census records for every decade from 1840 to 1950, and for 1959, 1974, 1982, 1992, 2002, 2012, and 2017. Agricultural census records were collated by the United States Department of Agriculture's National Agricultural Statistics Service (USDA-NASS), and tabulated from 1840 to 2012 by Haines et al. (2016). We downloaded records from the agricultural census of 2017 from USDA-NASS (USDA-NASS, 2017) and curated them using custom R scripts (R Core Team, 2017). We focused our analyses on 18 crops that occupied at least 5% of county land area in multiple states during any census year, that is, barley, buckwheat, corn, cotton, flax, hay, oat, peanut, potato, pulses, rice, rye, sorghum, soybean, sweet potato, sugar cane, tobacco, and wheat, which together accounted for 80% of cropland in 2017. We did not include tree nuts, fruits, and vegetables (together accounting for 1.5% of cropland in 2017) because most of these crops were not reported in the census until the mid-1900s, were extremely concentrated in a few specialty crop production centers (e.g., California and Florida), and together only accounted in 41 counties (of 3,109) for >5% of cropland area (Table S1; Figure S1).

Many crop types represent an aggregation of varieties of a given species as reported in census records. Furthermore, individual crops are often grown for a range of purposes, for example, sorghum is grown for either grain, silage, or molasses. However, the agricultural censuses did not consistently differentiate crop varieties or usage, especially in the early decades, and that is why we had to aggregate varieties to obtain consistent estimates. For example, "wheat" represents a combination of spring, winter, and durum wheat varieties. Similarly, "hay" represents a combination of leguminous and graminaceous plant species cultivated for animal forage. The category "pulses" includes beans (excluding soybean), lentils, and peas, and includes varieties destined for dry and fresh consumption (stricter definitions limit pulses to dry beans/peas). For these crop types, we summed the values reported in the agricultural census per county and year. A detailed list of the specific crop varieties that were aggregated in the census is available at openICPSR (https://www.openicpsr.org/openicpsr/project/115795/version/V2/view).

2.2 | Data interpolation

Agricultural censuses from 1840 to 1880 typically reported crop production (output in bushels, pounds, or tons) rather than crop acreage. To estimate county-level crop acreage, we divided reported crop production by estimated yield (amount produced per acre). We computed yield estimates for each county using census data from 1880 to 1920, by dividing reported crop amount by reported crop acreage. For any crop–county combinations that lacked the necessary production and acreage data between 1880 and 1920, we used the nationwide average crop yield (USDA-NASS, 2018) prior to 1880 to estimate county-level yield. For crops that lacked nationwide estimates of yield prior to 1880 (flax, peanut, pulses, rice, sorghum, soybean, and sugar cane), we used the nationwide average crop yield prior to 1940. This was justified because yields were relatively stable until 1940, after which they increased for nearly all crops due to major advances in farming practices and technology (Hurt, 2002). To examine the sensitivity of crop acreage interpolations to how yields were estimated, we compared county and nationwide average yield estimates and their effect on crop acreage interpolations for each county between 1840 and 1880. We found that some crops exhibited considerable variability in county-level yield (potato and tobacco; Table S2), and that acreage interpolations based on nationwide average yields resulted in underestimates (pulses and rice) or overestimates (sugar cane) in some counties (Figure S2). For this reason, we suggest a cautious interpretation of crop acreage estimates for pulses, rice, and sugar cane prior to 1890. We emphasize, though, that our acreage interpolations were quite robust overall.

We analyzed crop land cover area as a proportion of total county area to avoid artifacts introduced by differing county sizes. The boundaries of many counties changed from 1840 to 2017. Minor changes were due to mapping errors and resurveys, but major changes reflect the redistribution of large political units into modern counties. For example, in 1850, La Pointe County, Wisconsin, encompassed modern Bayfield County, Douglas County, and portions of four other counties. By the mid-1900s, the modern distribution of counties was largely in place. We calculated county areas separately for each time period and interpolated the values of agricultural variables to match 2017 county boundaries using two approaches: areal weighting and dasymetric mapping (Syphard et al., 2009). Areal weighting entailed mapping agricultural variables to modern county boundaries by calculating the proportions of the overlap between modern and historic county boundaries, and using those proportions to weight the allocation of historic values to modern counties. Dasymetric mapping minimizes estimates of change, by identifying many-to-one and many-to-many cases of county boundary change between census periods, and redistributing agricultural variables in year t using proportional weighting based on the distribution of agricultural values in the year $t + 1$. This approach thus results in conservative estimates of change, by assuming that the distribution of agricultural variables in year t reflects the same distribution as in year $t + 1$. Ultimately, we conducted our analyses with the areal-weighted dataset, because differences between areal weighting and dasymetric mapping were minor (only 13.6% of the 1.287 million county–crop–year comparisons differed at all, and differences in percent area in a given crop were on average 0.42% ± 0.003%; Figure S3), and dasymetric mapping produced artificial zeroes for certain crop–county combinations in which crops were sparse in the 2017 census.

For several crop–county–year combinations, the tabulated census data were incomplete (Table S3). We imputed missing values for these by averaging the $t - 1$ and $t + 1$ census values, under the assumption that change was gradual between census periods. This approach could downwardly bias estimates of intercensus period variability, but avoids the omission of entire states from diversity and dissimilarity calculations. We quantified the potential bias of imputation by cross-validation. Specifically, for each crop–year combination that contained missing data, we imputed values for counties with complete data and compared imputed values with census values. Cross-validation confirmed that imputation bias was minimal (differences in crop proportions between imputed and census values were on average 0.0029 ± 0.0004; Figure S4).

County sizes were calculated using United States county boundary files available from the National Historical Geographic Information System ("National Historical Geographic Information System: Version 11.0 [Database]," 2016). We associated county areas with crop land cover variables, and applied areal weighting and dasymetric mapping to reallocate crop land cover area values using custom R scripts. Data on the proportion of county area for each crop, for each county, and for each census year are available at openICPSR (https://www.openicpsr.org/openicpsr/project/115795/version/V2/view).

2.3 | County-level concentration of crop types

To quantify the spatial concentration of crops, we applied the graph-based approach implemented in Conefor Sensinode v2.2 (Saura & Torné, 2009). We derived graphs for our maps of crop land cover area for each crop and census period, removing counties that lacked land cover of the focal crop. The number of components (groups of connected counties) was calculated using a distance threshold between county centroids of 146 km (the largest minimum distance between centroids of adjacent counties). The total number of links (connections among counties) was then computed and summed across components in each graph. We defined concentration as the ratio of components to links, such that crops occupying a large spatial extent have small values of concentration, and crops spread across numerous small components have large values. Estimates of concentration can be sensitive to how connections among counties are defined, which is why we set our distance threshold conservatively to reduce sensitivity to changes in larger counties, typical for the western United States.

2.4 | Diversity of crop types

To examine changes in the diversity of cropland composition from 1840 to 2017, we quantified the richness (number of crop types present in a county at a given time; maximum possible was 18) and evenness (similarity of proportions) of crop land cover types in each county for each census period. Evenness was calculated using Pielou's evenness index:

$$\text{Evenness} = \frac{H}{H_{max}},$$

where H is the Shannon–Weaver index:

$$H = -\sum_{i=1}^{S} p_i \ln(p_i),$$

where S is the number of crop types, p_i is the frequency of crop i, and H_{max} is the maximum possible value of H, given by:

$$H_{max} = \ln(S).$$

We summarized changes in the amount and diversity of croplands by ecoregion (Figure S3; USDA-FS, 2014), which provides an ecology-based county grouping that is agnostic to agricultural land use (unlike USDA-based county groupings). We examined relationships between crop type richness or evenness versus the proportion of all cropland area across all counties and census periods using linear regression, excluding counties in which cropland area occupied less than 10% of a county's area.

2.5 | Dissimilarity of crop type composition

To examine changes in crop type composition from 1840 to 2017, and to identify which crops contributing primarily to changes in composition, we calculated dissimilarity of crop land cover proportions relative to a pre-WWII baseline (1840–1930), that is, we measured how similar the composition of crops in 2017 was to that of any county in the United States prior to WWII. High values indicate a crop composition in 2017 that did not occur anywhere in the United States between 1840 and 1930. Vice versa, measuring how similar the crop composition of each county in 1840 was to that of any county in 2017 captured crop compositions that no longer exist. Specifically, based on land cover proportions for all 18 crop types, we calculated Euclidean distances,

d_{jk}, among counties within and between census periods using the equation:

$$d_{jk} = \sqrt{\sum_i (x_{ij} - x_{ik})^2},$$

where x_{ij} and x_{ik} are the proportions of crop i in counties j and k, respectively.

Within-year calculations (among counties in the same year) captured the overall compositional dissimilarity of crop types in a given time period. For visualization of within-year dissimilarity over time, we took the average of pairwise Euclidean distances among all counties per census period. Between-year calculations (between counties in year t vs. year $t + 1$) highlighted those time periods when dissimilarity changed the most. For between-year comparisons, we accounted for intercensus variability in crop land cover abundance by standardizing Euclidean distances. Specifically, we divided the Euclidean distance of each crop type by its spatiotemporal standard deviation from 1840 to 1930. This effectively downweighted the significance of changes in crop types that were inherently variable in space and time during the pre-WWII baseline (Radeloff et al., 2015). Lastly, we identified which crop types were the main causes for between-year dissimilarity when looking forward and backward in time, identifying crop land cover that substantially increased or decreased in 2017 relative to a pre-WWII baseline.

3 | RESULTS

3.1 | Changes in area and location of crop land cover

The area of each of the 18 major crops increased rapidly from 1840 to 1920, when the total area of cropland peaked at 28% of the conterminous United States (Figure 1). Corn, cotton, hay, and wheat were the most widespread crops, accounting in 1920 for 82% of the total area of the 18 crops that we investigated. After 1920, major changes occurred. Total cropland area started to decline, with the percent of land area in the 18 major crops dropping to 17% by 2017, and cotton and oats especially plummeted to relatively miniscule areas. However, the areal extent of rice, soybean, and sugar cane continued to increase, and soybean area, which was essentially zero prior to 1920, increased to >27 million ha by 2017 (Table 1).

The spatial location of crop types also changed rapidly (Figure 2; Figure S5). For example, pulses (legume crops, including beans and peas) were widespread in the Southeast until 1940, but became concentrated largely in the northern Great Plains by 2017. Rice and sugar cane became the main crops in some coastal regions (Figure S6). Barley was concentrated in the Northeast and the Great Lakes states in 1840, covered a large part of the Great Plains by 1940, and then became limited to the northern Great Plains by 2017 (Figure S5).

The declines in the area of most crops were not due to declines in total production. To the contrary, despite decreasing cropland area, total production increased for 12 of 15 crops from 1940 to 2017, due to substantial yield increases (Table 1). For example, while potato declined in area by 81%, total production almost doubled.

3.2 | Collapse of the agricultural belts and spatial concentration of crop types

All 18 major crops, regardless of their total area, formed contiguous belts from 1860 to 1940 (Figure 2; Figure S5). By 2017, however, 13 of the 18 crops were spatially concentrated into a few small, isolated clusters of counties. Their former belts had collapsed. Notably, the transition from belts to isolated clusters was not gradual, but abrupt and recent, with a 15-fold increase in spatial concentration occurring from 2002 to 2012 (Figure 3). The spatial concentration of buckwheat and flax was most striking, with belts of acreage as contiguous as corn in the 1800s shrinking to a few northern counties by 2017 (Figure 4; Figure S5). The fate of other small grains—barley, oat, and rye—was similar, but they maintained wider spatial distributions in 2017 (Figure 4; Figure S5). Sorghum occurred throughout the Great Plains from Texas to North Dakota in the mid-1900s, but the sorghum belt of 2017 centered on Kansas (Figure 2). Peanut, sweet potato, and tobacco were widely distributed in 1940 (produced in 44%, 83%, and 48% of counties, respectively; Figure S5), but became concentrated in a few southeastern production centers by 2017 (in 8%, 14%, and 8% of counties, respectively; Figure S5).

The level of spatial concentration in 2017 was independent of how widespread or dominant a given crop type was historically. For

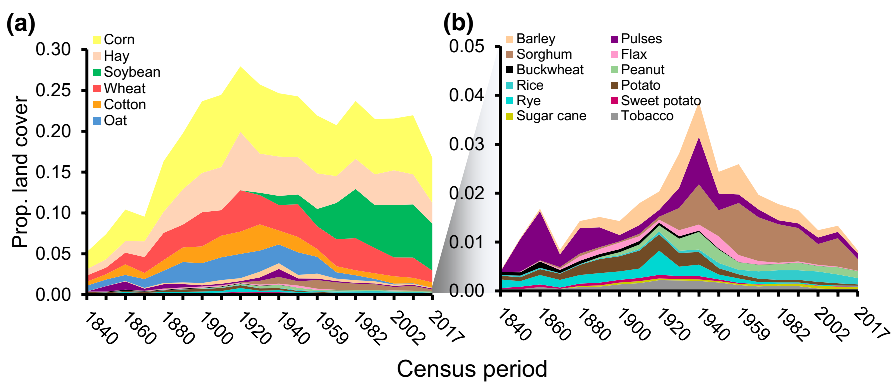

FIGURE 1 Overall crop land cover proportions over time, with (a) all crops included, and (b) excluding corn, hay, oat, soybean, and wheat [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 1 Changes in total land cover (hectares), production, and yield of the 18 major crops. Decreasing values are indicated with bold, red font. Rows are sorted first in decreasing order of change in hectares, then in decreasing order of change in production 1940–2017. Not reported in this table is variability in total land cover, production, and yield among counties and during intervening censuses, sometimes giving the appearance of disproportionate increases in production relative to yield, given decreasing land cover. Units of production values are in metric tonnes (barley, corn, flax, hay, oat, peanut, potato, rice, rye, sugar cane, sorghum, soybean, sweet potato, tobacco, wheat) or kilograms (buckwheat, pulses, and cotton). Units of yield are units of production per hectare

	Hectares (millions)			Production (millions)			Yield		
	Δ1870–1940	Δ1940–2017	2017	Δ1870–1940	Δ1940–2017	2017	Δ1870–1940	Δ1940–2017	2017
Soybean	4.64	22.67	27.3	2.12	117.38	119.5	0.44	0.90	1.3
Rice	0.28	0.44	0.78	1.11	6.97	8.1	103.92	236.59	340.5
Sugar cane	0.14	0.17	0.32	0.45	1.45	1.9	29.94	3.27	33.2
Hay	17.57	**−11.05**	15.7	67.77	32.11	119.3	0.18	1.00	2.2
Wheat	12.33	**−8.85**	11.6	15.25	25.20	47.4	0.09	0.85	1.3
Corn	23.65	**−7.95**	27.5	27.48	314.90	371.0	**−0.01**	3.75	4.5
Cotton	5.77	**−5.43**	3.8	3.72	3.81	9.5	20.41	295.74	410.5
Sorghum	5.62	**−4.03**	1.71	2.18	7.06	9.2	0.34	1.48	1.8
Pulses	3.74	**−3.51**	1.25	7.17	9.12	16.2	403.70	404.15	807.8
Potato	0.8	**−1.1**	0.25	7.32	9.79	20.0	1.59	15.97	19.6
Peanut	1.45	**−0.85**	0.6	0.80	2.48	3.3	0.39	1.43	1.8
Sweet potato	0.18	**−0.24**	0.05	0.52	0.33	1.6	**−0.19**	8.17	10.2
Oat	7.62	**−11.89**	0.23	15.09	**−18.46**	0.8	0.14	0.41	1.0
Barley	4.35	**−4.25**	0.61	6.14	**−3.69**	3.1	0.03	1.09	1.6
Rye	0.83	**−1.36**	0.08	0.61	**−0.76**	0.2	0.06	0.55	0.9
Flax	0.74	**−0.77**	0.07	0.72	**−0.69**	0.1	0.25	0.11	0.4
Tobacco	0.6	**−0.64**	0.11	0.51	**−0.34**	0.3	0.10	0.53	1.0
Buckwheat	**−0.19**	**−0.14**	0.01	**−93.62**	**−119.75**	0.4	—[a]	—[a]	—[a]

[a]There are no yield data for buckwheat.

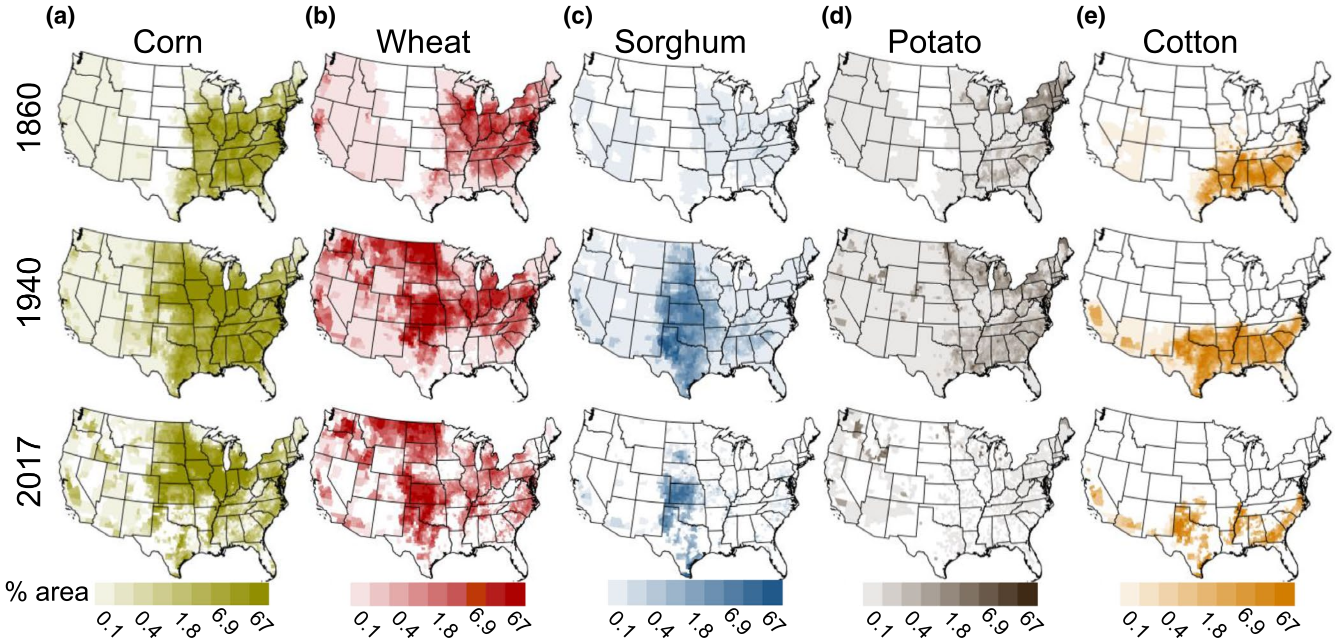

FIGURE 2 Maps of land cover area (represented as the percent of county area occupied by a given crop) for selected crops in the 1860, 1940, and 2017 censuses: (a) corn, (b) wheat, (c) sorghum, (d) potato, (e) cotton. Color scale breaks represent percentiles for each crop across all counties and years, taken after excluding values <0.1%. Maps of all crops and all census years are available in Figure S5 [Colour figure can be viewed at wileyonlinelibrary.com]

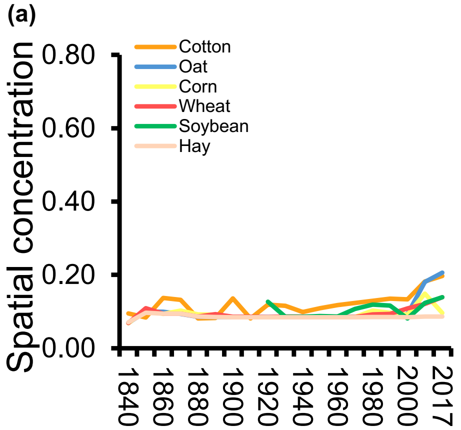

FIGURE 3 Spatial concentration of crop land cover over time: (a) most abundant crops, (b) crops accounting for a smaller proportion of US croplands. Concentration is defined as the ratio of components to links in graphs of crop land cover, where a link is a connection between two counties whose centroids are separated by less than 146 km, and a component is a cluster of connected counties. As crop land cover becomes more spatially concentrated, the number of components increases and the number of links decreases, increasing this index of concentration. The *y*-axis has been transformed ($y^{1/4}$) to enhance visibility [Colour figure can be viewed at wileyonlinelibrary.com]

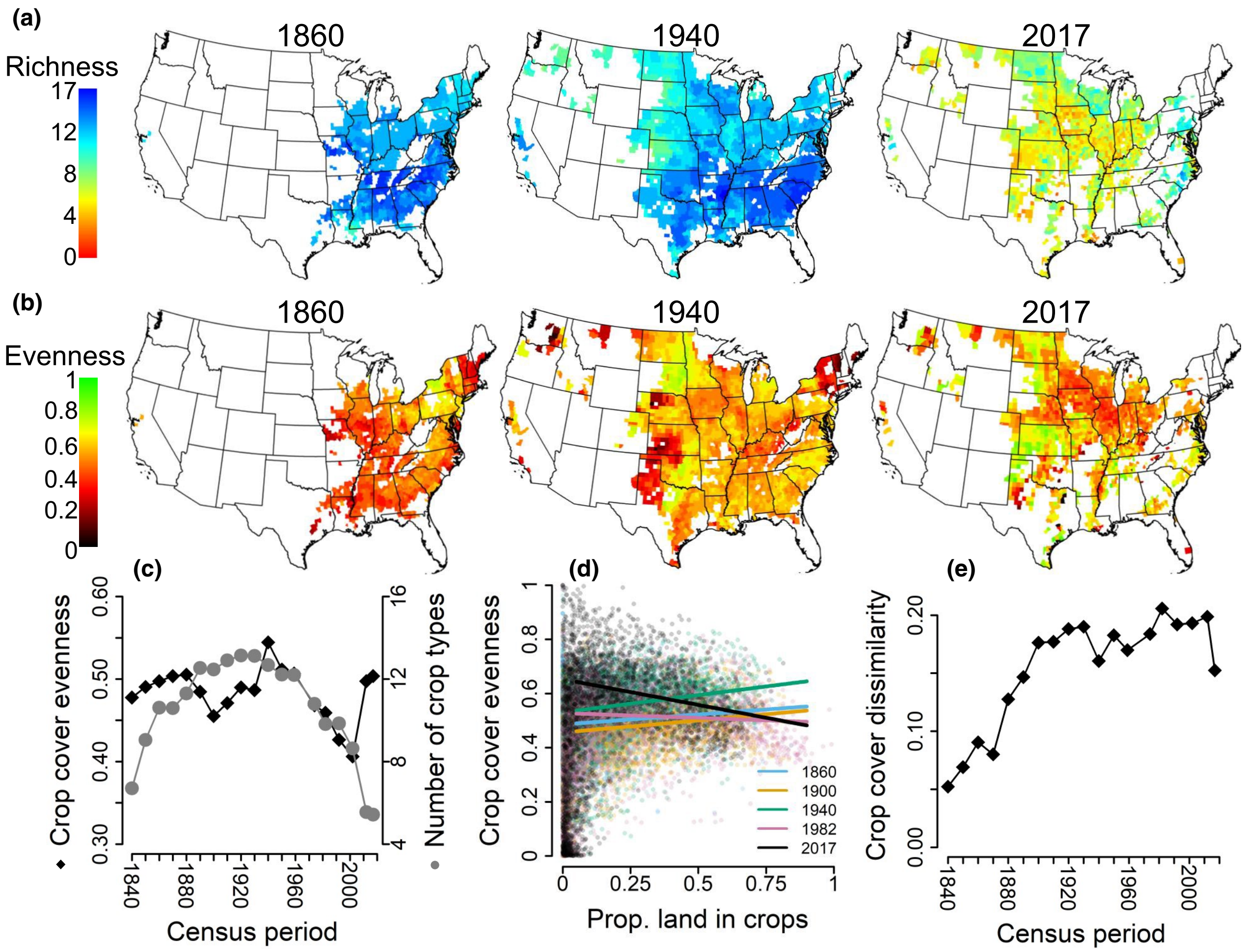

FIGURE 4 Changes in diversity and dissimilarity of cropland composition in the United States between 1840 and 2017. (a) Maps of crop land cover richness (number of crop types per county) and (b) evenness (Pielou's index) in the 1860, 1940, and 2017 censuses. Counties with less than 10% cropland area are not colored. (c) Crop land cover richness (gray circles) and evenness (black diamonds) averaged among counties. Standard errors are included but are too small to see. (d) Relationship between the proportion of land devoted to crop production in a county and the evenness of crop land cover in the 1860, 1900, 1940, 1982, and 2017 censuses. Lines indicate fitted values from linear regression, excluding counties with less than 10% cropland area. We selected colors from a colorblind-friendly color palette (Wong, 2011). (e) Dissimilarity (Euclidean distance) of crop land cover composition averaged among counties within census periods. Standard errors are included but are too small to see [Colour figure can be viewed at wileyonlinelibrary.com]

example, cotton, which was dominant and widespread in the South prior to 1940, became spatially concentrated and largely limited to the Coastal Plain of the Southeast by 2017 (Figure 2). In contrast, pulses, which were historically grown on much less area than cotton, maintained connectivity, and the spatial concentration of pulses in 2017 is similarly low as that of major crops such as corn, hay, and wheat. Interestingly, the spatial concentration of individual crop types was also independent of changes in total production or area. For example, hay maintained the greatest spatial connectivity of any crop type even though it declined by over 11 million ha from 1940 to 2017. In contrast, oat production, which also declined by over 11 million ha in the same period (Table 1; Figure 2), is now highly spatially concentrated, at a level that is similar to that of cotton. Even more surprisingly, rice and sugar cane increased in total area and production, but their former belts collapsed, and these crops now exhibit very high spatial concentration (Figure 3). In other words, changes in the area and in the total production of a given crop type since 1940 did not explain its level of spatial concentration in 2017.

3.3 | Changes in crop diversity

County-level crop diversity followed an arc of change similar to the total area in cropland, peaking in 1930 or 1940, for richness and evenness, respectively (Figure 4a–c; Figures S7 and S8). By 2017, the richness of crops was far lower than that in 1940, especially in the regions that have the most agriculture. In 1860 and 1940, 55% and 60% of counties, respectively, had at least a dozen of the 18 major crops, but by 2017, only 17 counties (0.5%) retained that level of diversity. Evenness was lowest in 2000, but has increased since then. Between 1860 and 1940, evenness of crop types was generally highest in the northern United States, but by the 2000s, evenness was highest in the central Great Plains, where counties typically included even proportions of corn, hay, sorghum, soybean, and wheat; but crop richness was much lower there than elsewhere (Figure 4; Figures S6–S8). The last remaining strongholds of both richness and evenness of crops are in North Dakota, which was dominated by wheat in the 1800s but now has a more even mix of corn, hay, pulses, soybean, and wheat (in addition to other small grains like barley, flax, oat, and rye), and in the Coastal Plain of the Southeast, where a hegemony of corn and cotton of the 1800s gave way to a more even distribution of corn, cotton, hay, peanut, soybean, and wheat by 2012 (Figure S5). We acknowledge that our focus on the 18 major crops misses the proliferation of fruit, nut, and vegetable specialty crops grown in production centers like the Central Valley of California (Figure S1), but notably these crops are highly spatially concentrated as well.

Surprisingly, the relationship between the proportion of a given county's area devoted to crops and the evenness of its crops switched direction over time. From 1860 to 1940, that relationship was positive, that is, counties with more of their land in crops were less specialized and had similar proportions of each crop, for counties with >10% agriculture. However, by 2017, the relationship was negative, and counties with the most agriculture became dominated by a few crops (Figure 4d). Overall, this resulted in a slight negative relationship between crop richness and the proportion of county land devoted to crop production (Figure S9). Counties with <10% cropland area varied greatly in their evenness of crop types (Figure 4d), comprising both agriculturally unproductive counties (e.g., in mountainous regions) and highly productive counties in arid areas where agriculture is limited to irrigated fields.

3.4 | Changes in the dissimilarity of crop composition

The dissimilarity of crop composition among counties at a given point in time increased greatly from 1860 to 1940, and remained high until 2017 (Figure 4e). This means that while all 19th century agricultural counties were fairly similar in terms of their composition of crops, by the 20th century, counties differed greatly. Comparison of dissimilarity of crop type composition among counties between 1860, 1940, and 2017 highlighted those crop compositions that are novel, and those that have disappeared. The most novel counties, that is, the counties with a 2017 crop composition that are most different from any county in 1940, occurred in parts of the Great Plains where sorghum increased, and in the Mississippi River Valley where soybean and rice increased (Figure S10a). Strong increases in rice, sorghum, and sugar cane in parts of the southern United States also resulted in novel crop compositions in 1940 relative to 1860 (Figure S10b). In contrast, two formerly widespread crop compositions disappeared entirely by 2017 from all counties. One included mixtures of corn, cotton, potato, pulses, sugar cane, sweet potato, and tobacco (Figure S10c,d), once common in the Coastal Plain of the Southeast. The other included a mixture of barley, corn, hay, oat, sorghum, and wheat, which was common in Iowa and nearby areas in the 1940s (Figure S10c).

4 | DISCUSSION

The geographic patterns of agricultural crops across the United States have changed profoundly since the 1840s. After 2000, the spatial distributions of the majority of crops became highly concentrated (though not as dramatically so for corn, beans, hay, and wheat), and for the majority of crops that concentration process was rapid and strong. However, total production of most crops increased even as their areal extent declined because of yield increases. Counties have become specialized and the diversity of crop types in each county plummeted as agriculture intensified and industrialized after WWII. Counties with the most cropland are now among the lowest in diversity, in a pattern opposite to that seen before WWII.

Overall, the changes in the patterns of agricultural land use in the United States since WWII are consistent with a land sparing strategy rather than land sharing. Due to substantial increases in yield, the United States had a higher production of most crops by 2017, while growing them on less area than in 1940 (Table 1). In some areas, especially the Northeast, the decline in cropland area resulted in an increase in forests, which regrew on abandoned fields (Clawson, 1979), while in other areas, farmland was lost due to urban sprawl (Freedgood et al., 2020), and there was a strong increase in the use of fertilizers, herbicides, and pesticides (Fernandez-Cornejo et al., 1960), so the observed changes had both positive and negative environmental effects. Furthermore, while the observed changes were consistent with a land sparing strategy, land sparing was, for the most part, not the explicit goal of farmers and land management agencies.

4.1 | Potential causes of the collapse of crop belts

4.1.1 | Urbanization, industrialization, and agglomeration economies

The patterns of agricultural production depend on settlement patterns, transportation and trade networks, economic structure, and technology. This means that there are many potential causes for the collapse of crop belts, and it is likely that several causes acted in unison. For example, when settlements are dispersed, and transportation costs are high, it is necessary to grow all crop types everywhere, even in regions not optimally suited for all of these crops, in order to provide a local supply. In contrast, when transportation costs are low, and trade flows freely, it is advantageous to specialize and grow crops in their ideal environment (Garrett et al., 2013). The pressure to increase production partially stemmed from growing demand, both nationally and internationally, due to a growing and more affluent population (Ausubel et al., 2013; Coelli & Rao, 2005; Ramankutty et al., 2018). Furthermore, when productivity in the non-farm sectors rises, then labor costs rise, and that entails pressure on agriculture to increase its productivity as well or to face labor shortages. The drop of employment in agriculture from 70% in 1800 to 3% in 2010, concomitant with large increases in total production, highlights how much the productivity of farmers and farm workers has increased, an increase that was at least partially a response to changes in the economy at large (Lebergott, 1966). Similarly, increases in productivity via mechanization, and in chemical inputs, were probably both causes and consequences of the industrialization of agriculture (Hurt, 2002). From gradual improvements in farming technology, such as sturdier plows and more efficient harvesters, to increasing use of agricultural chemicals and high-yielding crop varieties during the 1950s, rising demand due to a growing and more affluent population was met by an increasingly intensified and industrialized agriculture (Schlebecker, 1973, 1975). Once agriculture industrialized, the spatial patterns of production began to mirror industrial production of goods (Garrett et al., 2013), and as we have shown here, agriculture became increasingly specialized and crop land cover agglomerated, resulting in the collapse of the agricultural belts and the decline in the local diversity of crop types, both of which had been typical for pre-WWII agriculture in the United States.

4.1.2 | Federal policy

Federal agricultural polices greatly affected the overall area in agriculture, the prevalence of certain crops, and the industrialization of agriculture. In regard to overall area in agriculture, early federal policies, such as the Homestead Act of 1862 and its successors, encouraged westward expansion of agriculture by offering free land to farmers (Schlebecker, 1975). Federal irrigation programs of the early 1900s, as well as the Enlarged Homestead Act of 1909, spurred agricultural intensification in the arid West, and greatly enlarged the extent of crop belts (Ramankutty & Foley, 1999; Schlebecker, 1975). However, in response to widespread soil erosion, the Soil Conservation Service incentivized the cessation of cultivation of erosion-prone lands since the 1930s. Subsequent federal efforts, such as the Conservation Reserve Program initiated in the 1980s, removed additional marginal crop land from agricultural production (Secchi et al., 2009), partly to bolster prices for crops by lowering supply, and partly to reduce the environmental effects of agriculture. A great example of federal policies affecting specific crops are the import tariffs and subsidies supporting the ethanol industry since the 1980s, which have stimulated an increase in the total area of corn (Wallander et al., 2011). Similarly, the gradual liberalization of world trade and rapid increase in recent years has resulted in rising production of crops for which there is strong international demand, such as cotton, sorghum, soybean, and rice, in contrast to crops with less demand, such as sweet potato (USDA-ESMIS, 2011; USDA-FAS, 2018). Agricultural policies that influence the economy of agricultural production are an important driver of large-scale spatial and temporal patterns, but we stress that the changes in the patterns of agricultural land use that we observed were most likely caused by many factors.

4.2 | Ramifications of changes in the distribution of crop types

4.2.1 | Change in the spread of agricultural pests due to spatial concentration

The spatial concentration of crop types that caused collapse of the former crop belts (Figures 2 and 3) has important, but potentially opposing, consequences for the vulnerability of crops to pest insects, microbial pathogens, and weeds. Concentration of individual crop types in a few highly productive clusters of counties means that once pests are introduced into such an intensively cultivated region, they can spread rapidly and grow to large population size (Venette & Ragsdale, 2004), and might not be effectively managed by crop rotation due to reduced intercrop rotation distances in space and time (Crossley et al., 2019; Sexson & Wyman, 2005). In addition, the development and spread of pesticide resistance are more likely when pest populations become large and highly interconnected. However, the pre-WWII agricultural landscape of the entire United States may have been more conducive to continental-scale spread of pests (e.g., 70), and the subsequent collapse of the agricultural belts may limit the spread from one area of production to another, potentially making current agricultural production more resilient if multiple production centers exist. A great example is provided by the Colorado potato beetle (*Leptinotarsa decemlineata*), which spread rapidly from the Great Plains eastward during the 1860s and 1870s, aided by the contiguous extent of potato land cover in this vast region (30, 31; Figure 2; Figure S11). In contrast, the sustained spread of pests in contemporary agricultural landscapes will be limited to pests that (a) are highly polyphagous; (b) specialize on those few crop types that are still contiguously distributed, such as western bean cutworm which affects corn and recently spread eastward (29); (c) are capable of long-distance wind-aided dispersal (Crossley & Hogg, 2015); or (d) readily spread via human transportation networks (Dalton, 2006).

4.2.2 | Diversity in croplands

We observed a surprising switch where counties with a higher proportion of their area in cropland were more diverse historically but are less diverse now. Studies of historic and contemporary effects of agricultural land use change on biodiversity and ecosystem functioning often examine agriculture in the aggregate (Larsen, 2013; Rusch et al., 2016; Seibold et al., 2019). Increases in the amount of the landscape devoted to agriculture are typically assumed to result in a reduction in the diversity of crops, an increase in inputs, and a decrease in biodiversity, exerting numerous negative cascading effects on ecosystems and the environment (Landis et al., 2018; Larsen & Noack, 2017; Meehan et al., 2011; Tscharntke et al., 2005; Werling et al., 2014). However, we found that until 1940, a higher proportion of cropland area was associated with *higher* crop diversity, and that that relationship only became negative after WWII, due to the specialization and agglomeration of crops (Figure 4). This suggests that the environmental effects of higher crop area may also have been fundamentally different prior to and after WWII.

The environmental effects of changes in crop diversity depend on focal taxa, environmental interactions, and crop management practices. For example, crop types are a critical determinant of the composition of phytophagous insect and microbial communities (Guillemaud et al., 2011; Lichtenberg et al., 2017), but crop diversity may have a lesser effect on bird abundance and diversity compared to availability of non-crop habitats and in-crop management practices (Donald et al., 2001; Hiron et al., 2015; Kirk et al., 2011; Redlich et al., 2018; Sirami et al., 2019). Thus, predicting the consequences of cropland area change requires the examination of changes in specific crops and their effect on specific taxa. Second, the effects of changes in crops depend on soil and climate. Many counties throughout the Great Plains peaked in both the proportion of crops grown (Figure S5), and crop diversity, in the 1930s (Figure 4). However, when overcultivation combined with persistent drought resulted in the Dust Bowl, the effects were most severe in the southern Great Plains (Cook et al., 2009; Lee & Gill, 2015). Third, the quantity and specificity of pesticides changed considerably during the mid-1900s, which means, for example, that one hectare of potato in 1910 had very different environmental effects than one hectare in 2017 (Casagrande, 1987). Even within a crop, certain crop varieties can require fewer chemical inputs (e.g., *Bt*-corn), and some cropping systems demand fewer mechanical inputs (e.g., no-till management), with numerous benefits and challenges for agroecosystems (Derpsch et al., 2010; Grandy et al., 2006; Halde et al., 2015; Manley et al., 2005; VanBeek et al., 2014). There can also be spillover effects from one crop to another, as is the case for insecticide use in snap beans and peppers, which can be lower when grown near *Bt*-corn (Dively et al., 2018). Our quantification of crop-specific changes in US agricultural land cover since 1840 thus represents an important step toward a full assessment of the consequences of historical agricultural land use change for species and the environment.

The changes in crops and agricultural area also have strong biodiversity conservation implications. Many areas that were brought into agricultural production in the 19th century were no longer in production as of 2017, especially in the Laurentian Mixed Forest, Southeast Mixed Forest, and Eastern Broadleaf Forest (Oceanic) ecoregions (Figure S5). While some of these croplands have been lost to urban sprawl and low-density residential development (Freedgood et al., 2020), other areas may offer an opportunity to restore natural habitat and wildlife (Queiroz et al., 2014), akin to a land sparing strategy. However, ecoregions such as the Lower Mississippi River Forest have experienced continuous agricultural development since the late 19th century, with 32% of the ecoregion in corn, cotton, rice, or soybean by 2012 (Figures S5 and S6). Other ecoregions that once contained abundant tallgrass prairies, that is, Prairie Parkland (Temperate) and Eastern Broadleaf Forest (Continental) continue to sustain amounts of cropland comparable to the late-1800s (Figure S5). Abandonment of agriculture in these regions is unlikely, at least in the near-term, and environmental gains may be achieved by focused regional efforts to reduce chemical inputs and mitigate consequences to downstream terrestrial and aquatic ecosystems, for example, by planting prairie strips in field margins (Schulte et al., 2017), that is, to embrace a land sparing strategy. Croplands cover a miniscule proportion of much of the mountainous and desert West, but increases in crop land cover, particularly in barley, hay, pulses, and wheat, were substantial there in the first half of the 20th century (Figures S5 and S6), concomitant with advances in dryland irrigation, the two world wars with strong demands by the US military, increasing international demand, and federal policies encouraging westward expansion (Hurt, 2002). Although total cropland area has decreased there since 1950 (Figure 1; Figure S5), increasing demand for food, feed, and fuel could trigger greater cultivation again, unless increasing temperatures or decreasing precipitation make this untenable (Ramankutty et al., 2002).

4.2.3 | Vulnerability to environmental and economic disturbance

The collapse of most agricultural belts and the intensification and industrialization of agriculture in the United States after WWII resulted in spatial concentration of crops, declines in crop diversity, and disappearance of once-common crop combinations. Environmentally, this likely had both positive and negative effects, but from a food security perspective, the fact that food is increasingly being produced in highly specialized and efficient production centers raises concerns about the sustainability of supply chains given rising pressures from human populations, agricultural pests, and a changing climate (Lehmann et al., 2020; Ramankutty et al., 2002). Previously, declines in one region might be offset by improved conditions in another region, but agglomeration of crop production in very few production centers can lead to catastrophic losses from environmental and economic perturbations. Recent examples include widespread flooding in the Midwest (Van Dam, Karklis, & Meko, 2019), which greatly affected corn and soybean production, and the disruption in labor in meat production centers following coronavirus outbreaks (Bell, 2020).

It is striking how rapidly spatial patterns of crops have changed, suggesting that future changes are also likely, yet hard to predict. A return to historical agricultural land use patterns is unlikely, and it is not clear that it would be beneficial given the mixed potential effects of spatial concentration. However, long-term, county-level analyses of changes in land cover of individual crops represent an important step toward understanding and predicting these changes. When paired with the wealth of data available from other biological and social disciplines, these data have great potential to further elucidate both causes and consequences of agricultural land use change.

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AUTHOR CONTRIBUTION

M.S.C. was involved in conceptualization, data curation, formal analysis, visualization, and writing of the manuscript. K.D.B. was involved in formal analysis, visualization, and writing of the manuscript. S.D.S. was involved in conceptualization and writing of the manuscript. V.C.R. was involved in conceptualization, methodology, and writing of the manuscript.

DATA AVAILABILITY STATEMENT

All curated data used for analyses in this study are available at openICPSR (https://www.openicpsr.org/openicpsr/project/115795/version/V2/view).

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

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