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Innovations through crop switching happen on the diverse margins of US agriculture

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Crop switching, in which farmers grow a crop that is novel to a given field, can help agricultural systems adapt to changing environmental, cultural, and market forces. Yet while regional crop production trends receive significant attention, relatively little is known about the local-scale crop switching that underlies these macrotrends. We characterized local crop-switching patterns across the United States using the US Department of Agriculture (USDA) Cropland Data Layer, an annual time series of high resolution (30 m pixel size) remote-sensed cropland data from 2008 to 2022. We found that at multiple spatial scales, crop switching was most common in sparsely cultivated landscapes and in landscapes with high crop diversity, whereas it was low in homogeneous, highly agricultural areas such as the Midwestern corn belt, suggesting a number of potential social and economic mechanisms influencing farmers' crop choices. Crop-switching rates were high overall, occurring on more than 6% of all US cropland in the average year. Applying a framework that classified crop switches based on their temporal novelty (crop introduction versus discontinuation), spatial novelty (locally divergent versus convergent switching), and categorical novelty (transformative versus incremental switching), we found distinct spatial patterns for these three novelty dimensions, indicating a dynamic and multifaceted set of cropping changes across US farms. Collectively, these results suggest that innovation through crop switching is playing out very differently in various parts of the country, with potentially significant implications for the resilience of agricultural systems to changes in climate and other systemic trends.

crop switching | crop diversity | land use change | agriculture

Significance

Despite its central importance as a mechanism of adaptive change in agricultural systems, relatively little is known about where and how crop switching occurs. This study provides a continental-scale, field-level portrait of recent crop-switching trends across US farms, identifying strong geographic patterns in farmers' choices to introduce crops new to a given field. A framework linking crop switching to three facets of crop diversity shows that switches drove diversification in some landscapes and homogenization in others, potentially influencing ecological and economic resilience. Crop switching was most common in areas with less agriculture and higher existing crop diversity, highlighting interesting opportunities for both policy and future research to explore drivers and effects of crop switching for agricultural diversity and adaptability.

Agricultural systems are dynamic, frequently changing in response to markets, trade, and climate, among other factors (1–3). One key component of this dynamism is crop switching—a farmer's decision to plant a new crop not previously grown at a given site. Crop switching can enable farmers to respond to economic, climate, and environmental impacts, and can be important for management and efficiency (4–9). While crop switching has been variously defined, we consider the cultivation of a crop type in a given year to be crop switching if there is an immediately preceding or following period of seven years during which that crop type was not grown in that location. Importantly, this definition of crop switching excludes the continuation of established crop rotations [the practice of repeatedly alternating among crop types or fallow cropland over multiple years, e.g. corn-soy rotations in the US Midwest (10)], but it includes the modification of crop rotations by adding or removing crops.

Crop switching is one of only a few mechanisms that drive overall change in the acreage and diversity of crops planted across a region (along with crop rotations, cropland fallowing, and land use conversion). As such, crop switching may be crucial in bolstering landscape-scale crop diversity, which is important for crop yields and other aspects of food system resilience (11, 12). Crop switching may also be critical in responding to the declining reliability of major food staples as a result of ongoing climate change (11, 13). Crop switching has the potential to halve agricultural losses from climate change in the United States (6) while reducing greenhouse gas emissions, water use, and fertilizer and pesticide inputs across a variety of crops and regions (13–17), and also potentially improving farmer incomes (4, 14, 15). While many of these benefits may be achievable via incremental changes to similar crop varieties, others will require transformative changes to fundamentally new cropping systems (18, 19), which may be increasingly necessary given a number of converging ecological threats (20, 21).

Despite the many potential benefits to farmers and society from crop switching, crop choices for individual farmers entail a complex set of decisions weighing the risks, benefits,

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and uncertainties of the status quo against those of the novel crop (22). Greater degrees of novelty may thus be associated with greater risk and greater potential reward. The decision to switch is likely influenced by many factors including a farmer's social circle, availability of and trust in scientific information, the influence of private and public advisors, the presence of the crop in the region, and the degree of support for adaptive innovation in the local community.

In spite of the importance of crop switching, it remains poorly understood. Even in data-rich regions like the United States, there is a lack of understanding of the frequency, geographic distribution, and basic attributes of crop switching, much less a science of the factors influencing crop-switching choices. These knowledge gaps limit the ability to predict and manage evolving agricultural systems. Without an understanding of the extent to which crop switching has historically occurred, modeling efforts about future crop switching (particularly in response to climate change) could set potentially unreasonable expectations about the extent to which farmers can and will wholly switch crops to respond to future challenges. And without accounting for variation in social factors and agricultural neighborhood effects associated with crop switching, spatial optimization models that aim to inform crop redistribution goals (14, 23, 24) may miss important constraints or opportunities. To address these gaps, we characterized the extent and variation of crop switching across US farms at 30 m spatial resolution, using data from the US Department of Agriculture (USDA's) Cropland Data Layer (25) from 2008 to 2022. We also classified each instance of crop switching along three dimensions of novelty, and assessed how the relative rates of these novelty characteristics vary as a function of landscape-scale variables.

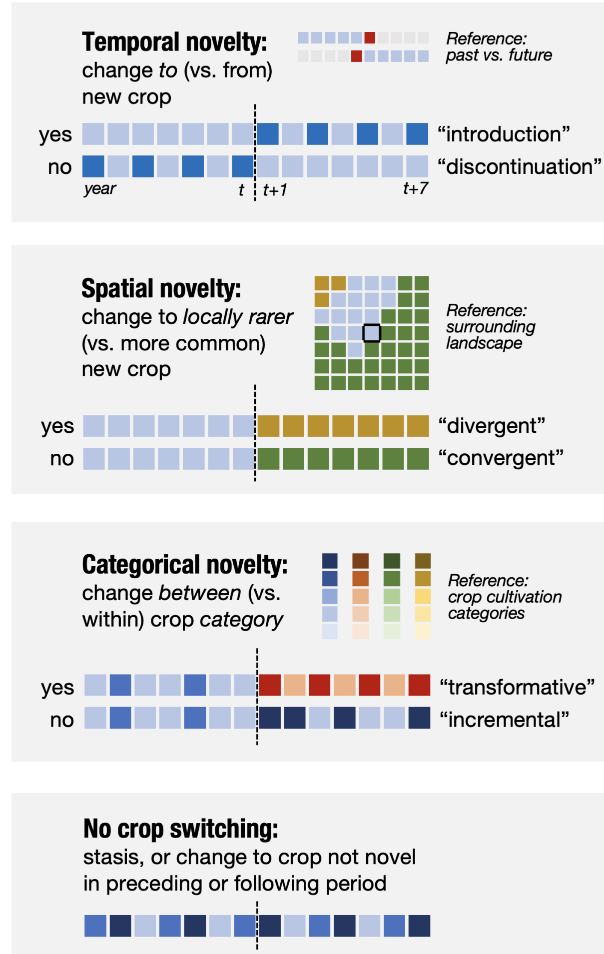

Fig. 1. Conceptual illustrations of three dimensions of crop switching: temporal-, spatial-, and categorical novelty. Each uses a different frame of reference to classify a given crop switch from year *t* to *t+1* as novel or not. Two hypothetical crop time series are shown for each measure, both of which exhibit crop switching but only one of which exhibits the novelty attribute in question. An example of crop change that does not qualify as switching (an ongoing crop rotation) is shown in the *Bottom* panel. Each color represents a crop type.

Dimensions of crop novelty. A crop switch can be novel in various respects, and we propose a framework for classifying crop-switching events on three binary dimensions of novelty: categorical, spatial, and temporal (Fig. 1). Each uses a different frame of reference to differentiate a new crop from what was previously grown in the same location. *Categorical Novelty* occurs when the crop switch is to a different crop category. We considered four crop categories (field crops, tree crops, perennial berries, and annual fruits and vegetables) with widely divergent cultivation practices. We define incremental crop switching as a change within one category (e.g., within the field crop category from corn to soy), and transformative crop switching as a change between categories (e.g., from a field crop to an annual fruit or vegetable) (18). Cultivation and labor practices differ widely among crop categories, and an incremental switch between crops of the same category (requiring similar equipment and expertise) is a smaller departure than is a transformative switch (19). By using these categories to differentiate incremental from transformative switches, we can characterize how fundamentally large a change is.

A crop switch exhibits *Spatial Novelty* if the new crop is less commonly grown in the surrounding agricultural landscape compared to the prior crop. Here, we considered crop changes in the context of the surrounding 30 km landscape. Farms are part of social and economic networks that connect them to other nearby farms through shared culture, information, labor, and supply chains (26). Agricultural management decisions (e.g., crop choices) are widely recognized to be influenced by farmer social networks (27–30). Crop choices are part of a rich array of dynamics operating at this landscape scale, so one key insight is whether a given crop switch represents a choice to converge toward a common set of locally established crops (convergent switching), or to diverge from conventions with a switch to a more locally novel crop (divergent switching). Convergent and divergent crop switches give insight into the levels of farmer risk aversion or tolerance within a given region, as well as a variety of other considerations including whether farmers see their neighbors' as economically successful models, social learning, and networks, and whether a landscape is transitioning toward a less versus more spatially diverse agricultural landscape (26).

Finally, a crop switch exhibits *Temporal Novelty* if it represents the introduction of a crop not previously grown in that field, as opposed to the discontinuation of a previously grown crop. While the prototypical crop switch may involve both discontinuing one crop and introducing a new alternative in its place, these two practices do not always co-occur. Multiyear crop rotations are common, and when a farmer begins, ends, or modifies a rotation, a crop may be introduced or discontinued without the counterpart occurring. The switch from a corn monoculture to a corn-soy rotation, for example, represents an introduction without a corresponding discontinuation. Differentiating these scenarios is important because of their implications for multiyear crop diversity: An imbalance between introduction and discontinuation implies a trend in the temporal diversity of crops in a given field, which is connected to farms' environmental and economic sustainability (31, 32).

Predictors of crop switching. Crop choices are part of a complex set of social and economic relationships. We considered two indicators that could be related to crop switching: cultivated landcover, the proportion of a given landscape that is cultivated cropland, and crop diversity, the variety of different crop types grown in a given agricultural landscape (measured as Shannon diversity over space and time). Greater cultivated landcover could suggest greater productivity or a higher concentration of farms, and thus a potential concentration of social, knowledge, and financial and technical resources that could enhance crop switching, or it could suggest greater cultural or economic incentives to grow locally common crops instead of exploring novel alternatives. Crop diversity is potentially important as both a driver and an outcome of crop switching. High levels of landscape crop diversity could support crop switching through imparting social norms and by increasing access to a richer set of examples, information networks, markets, and community resources (26). Crop diversification can also be an outcome of crop switching if switches are spatially or temporally novel, so changes in spatial and temporal measures of crop diversity (33) can serve as indicators of these dynamics.

We quantified patterns at four different spatial scales. Each 30 m "pixel" belongs to a coarser 30 km "landscape," a larger tile defined by superimposing a coarser grid on the 30 m data (*SI Appendix*, Fig. S1). Each landscape in turn belongs to one of nine USDA-defined farm resource "regions" (34), which represent areas with similar agricultural characteristics. Together these comprise the "national" dataset covering the contiguous 48 US states. Crop-switching characteristics were classified at the pixel scale, summarized as crop-switching rates at the landscape scale, and then visualized, aggregated, or regressed against other variables to examine larger-scale patterns.

Results

Crop-Switching Prevalence. We found that rates of crop switching varied both temporally and spatially across the United States (Figs. 2 and 3). A high proportion of cropland exhibited crop introduction (37%) and/or discontinuation (39%) in at least one of the eight evaluation years. Because crop discontinuation and introduction were evaluated for different time periods (2008 to 2015 and 2015 to 2022, respectively), rates are reported separately for these practices, and it was not possible to quantify total combined crop-switching rates. In the average individual year, 6.8% of cropland exhibited crop introduction and 6.9% exhibited crop discontinuation, an area roughly equivalent to the US state of Georgia. While there was year-to-year variation, no metric exhibited a sustained or statistically significant trend over the 8-y study period (Fig. 2), though a longer observation period might reveal trends.

We found major spatial variation in overall rates of crop switching, ranging from an annual average of only 2.2% of cropland in the USDA's Heartland farming region to 12% on average annually in the Northern Great Plains (Figs. 3 and 4). Crop-switching hot spots—statistically significant spatial concentrations of high crop-switching rates—were found in the Northern Great Plains, Southern Seaboard, and Fruitful Rim regions, while cold spots included large parts of the Heartland and smaller pockets in other regions (*SI Appendix*, Fig. S3). Crop-switching prevalence was higher in landscapes with less cropland,

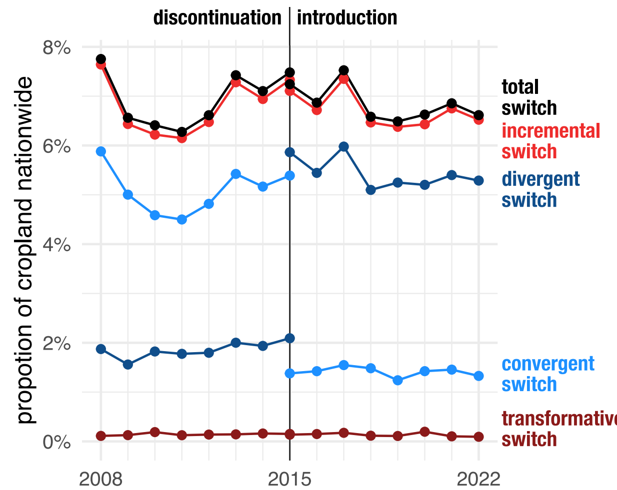

Fig. 2. Annual time series of nationwide crop-switching rates. Crop discontinuation is evaluated for 2008 to 2015 while crop introduction is evaluated for 2015 to 2021. In both cases, incremental and transformative crop switching sum to the overall total rate of crop switching, as do convergent and divergent switching.

both nationally and within each individual USDA region (except the Basin and Range region); it was also higher in landscapes with higher crop diversity, both within and among regions (Fig. 4). These relationships with cropland cover and crop diversity are independent, as the two predictors are nearly uncorrelated at the 30 km landscape scale (r = 0.06; *SI Appendix*, Fig. S2).

Temporal Novelty. Although our use of distinct time periods to evaluate rates of crop introduction (2015 to 2022) and discontinuation (2008 to 2015) precludes a perfect comparison, the fact that neither metric exhibited a temporal trend within its time period means that they can be roughly compared to identify major differences between these rates. Our results show that average rates of crop introduction and discontinuation were quite evenly balanced at the national scale (49.6% of all switches were introductions), but diverged substantially in many individual 30 km landscapes (23% of 30 km landscapes had a more than twofold difference, with the direction and magnitude of difference varying greatly among USDA regions) (Figs. 3*C* and 5). Farms in the Northern Great Plains, Northern Crescent, and Prairie Gateway had the highest relative rates of introduction (e.g., adding to crop rotations), while farms in the Mississippi Portal and Basin and Range regions had the highest relative rates of discontinuation (e.g., subtracting from crop rotations) (Fig. 4 and *SI Appendix*, Fig. S3). We found that the trend in temporal diversity in a given 30 km landscape was strongly positively correlated with the difference between introduction and discontinuation rates (Spearman's ρ = 0.85; Fig. 5*B*), confirming a larger-scale connection between crop introduction and increasing temporal diversity.

Categorical Novelty. We found that the vast majority of crop switching was incremental, with only 1.8% classified as transformative for crop introduction and 1.9% for crop discontinuation (Fig. 2). The ratio of transformative to incremental crop switching was highest in the Fruitful Rim and Northern Crescent, and lowest in the Northern Great Plains and Heartland, which represent significant hot spots and cold spots, respectively (Fig. 3 and *SI Appendix*, Fig. S3). Higher relative rates of transformative switching tended to occur in landscapes with

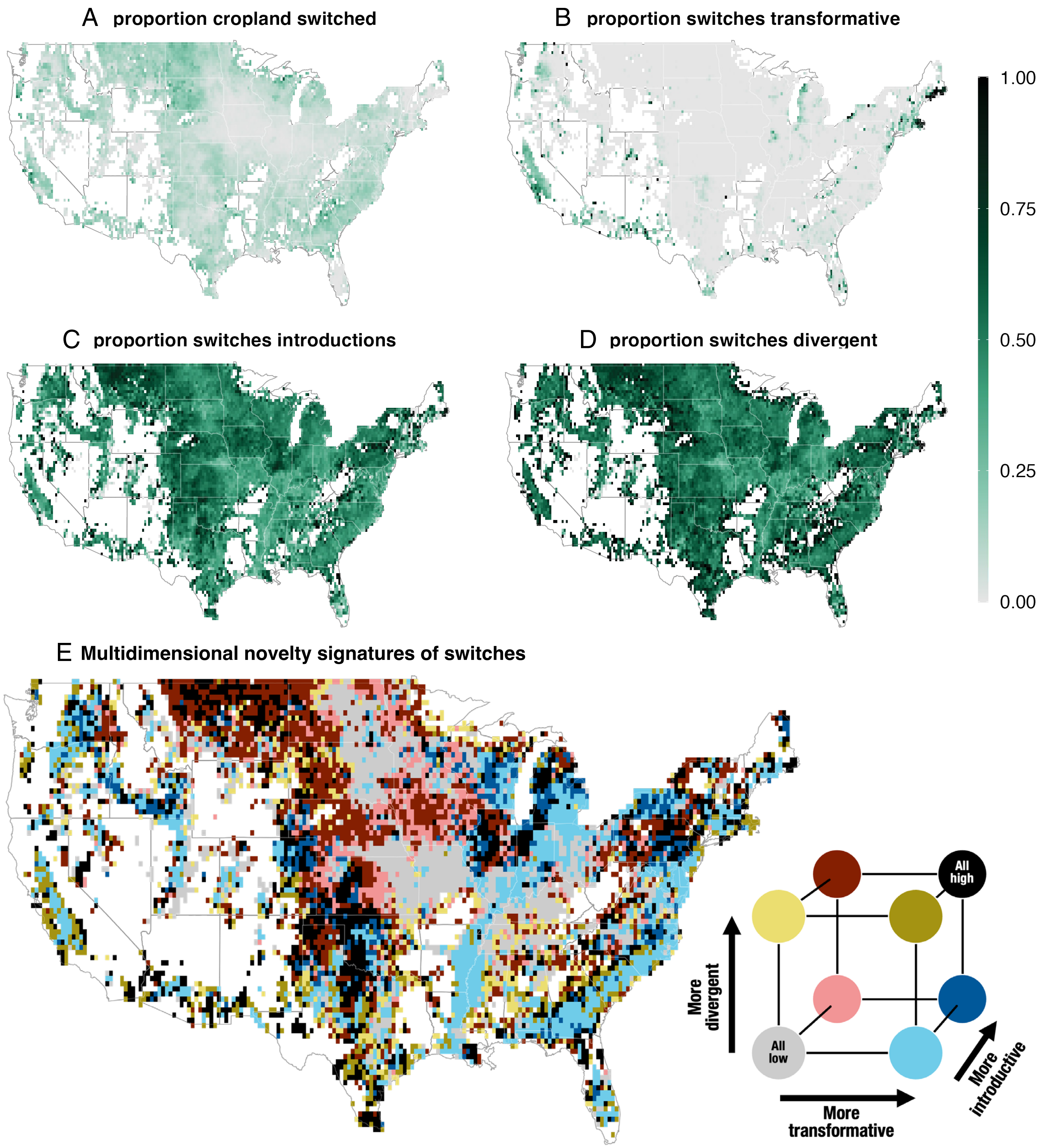

Fig. 3. Spatial patterns in rates and attributes of crop switching. (*A*) Proportion of cropland that switched in the average year. (*B–D*) Proportion of crop switches that were transformative (categorically novel), introductions (temporally novel), and divergent (spatially novel), respectively. (*E*) Multivariate combinations of the three novelty characteristics shown in (*B–D*), with color denoting whether switches in each novelty characteristic occurred at higher than median rate; crop switching is high in all three markers of innovation in the black areas, is low in all three attributes in the gray areas, and is high in different combinations of attributes in areas with other colors. White indicates areas without cropland in our dataset.

lower crop diversity and lower cropland coverage, though these relationships were reversed within the Fruitful Rim (*SI Appendix*, Fig. S6).

The crop types involved in transformative crop switching highlighted strong trends in the specific crop categories that were introduced and discontinued (Fig. 6). The crop categories that were most commonly discontinued in transformative crop switches were field crops and vegetables; field crops were mainly discontinued in favor of tree crops, and vegetables in favor of field crops (Fig. 6*A*). Transformative crop introduction primarily involved planting vegetables and tree crops in place of field crops (Fig. 6*B*).

The balance between introduction and discontinuation of individual crop categories was spatially variable, with each

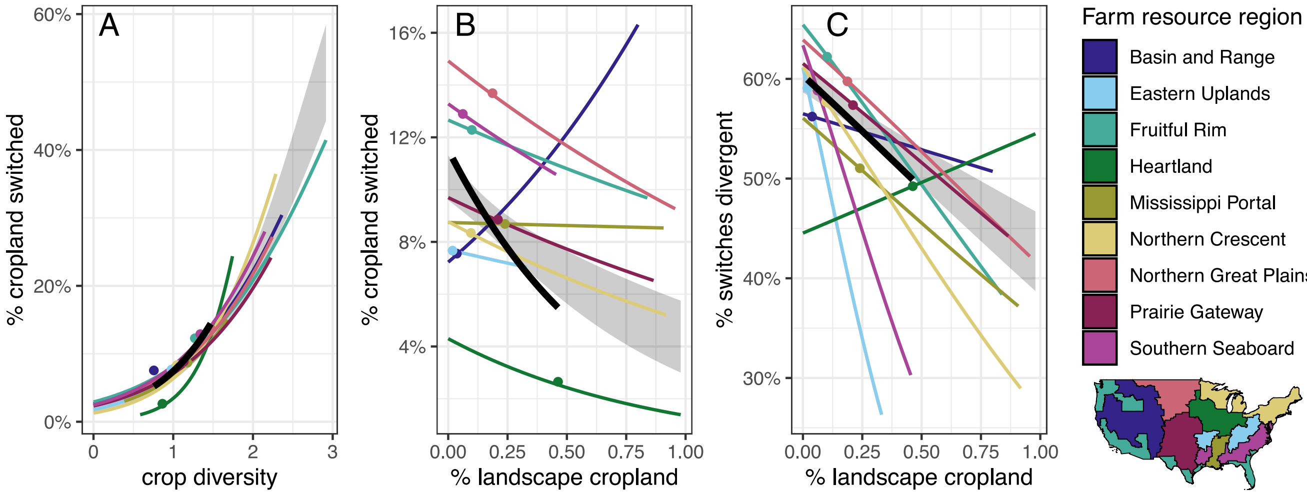

Fig. 4. Predictors of spatial variation in crop-switching rates. (*A*) Overall crop-switching rate versus crop diversity. (*B*) Overall crop-switching rate versus proportion of landscape that is cropland. (*C*) Proportion of switches that were divergent versus proportion of landscape that is cropland. The figures show logistic regressions on 30 km summary data, with gray ribbons representing the 95% CIs for the nationwide relationship, colored lines representing relationships within individual USDA farm resource regions, and heavy black lines representing the relationship among regional means (which are marked with points). All landscapes are weighted equally. "Percent landscape cropland" refers to the 30 km landscape, while "crop diversity" is the spatiotemporal Shannon diversity index of crop types within a 30 km landscape and all years from 2008 to 2022.

category experiencing increases in some locations and declines elsewhere as a result of transformative crop switching (Fig. 6*C*). Field crops declined in the Prairie Gateway and Fertile Rim but increased in the Mississippi Portal and Northern Great Plains, while tree crops increased in California and declined in Florida; other crop categories exhibited strong trends as well (Fig. 6*C*). Note that these results only cover fields with transformative crop switching, and may not reflect overall trends in crop prevalence across all cultivated land.

Spatial Novelty. We classified crop switching as divergent when a pixel switched to a crop that was rarer within its 30 km landscape than was the crop previously grown in the pixel, and as convergent when it switched to a more common crop. Divergent switches represented 53% of all crop switching nationwide, with convergent switches comprising the remaining 47%.

There was substantial geographic variation in relative rates of divergence as a proportion of all crop switching, ranging from a low of 45% in the Mississippi Portal to a high of 55% in the Northern Great Plains (Fig. 4). Within every region except the Heartland, divergent crop switching occurred at higher relative rates in landscapes with less total cropland and in landscapes with higher crop diversity, though the latter relationship was less consistent and varied by region (Fig. 4).

Divergent crop switching drives spatial crop diversification, as do other divergent crop changes not classified as switching. Nationwide, spatial crop diversity in the average landscape increased between the first and second halves of our study period (paired t test: $t = 9.0016$, $P < 2e^{-16}$), and the fact that the majority of switches were divergent indicates that crop switching contributed to this diversification. Geographic variation around these means also indicated a strong positive relationship between divergent switching rates and spatial crop diversification itself (Spearman's $\rho = 0.43$; Fig. 5*A*).

Relationships among Novelty Dimensions. Landscape-level rates of crop switching were weakly positively correlated nationwide with the proportions of those crop switches that were spatially, categorically, and temporally novel (ρ = 0.35, 0.05, and 0.09, respectively; *SI Appendix*, Fig. S5), meaning that trends in overall switching rates are not being driven by any single dimension of crop switching.

We express relationships among the three dimensions of crop novelty at the 30 m pixel scale as log odds ratios (LOR), which compares how switches that do versus don't show one kind of novelty differ in their rates of a second kind of novelty; positive and negative values represent positive and negative associations between the two novelty dimensions, respectively. Nationwide, we found a strong positive association between spatial and temporal novelty (LOR = 2.36), and virtually no association between categorical and either temporal novelty (LOR = −0.05) or spatial novelty (LOR = 0.04).

Relationships between crop-switching rates at the 30 km landscape scale (*SI Appendix*, Fig. S5) largely mirrored these overall patterns, with strong positive correlation between landscape average rates of categorical and temporal novelty ($\rho = 0.55$), and negligible correlation between rates of categorical novelty and either temporal novelty ($\rho = -0.07$) or spatial novelty ($\rho = -0.08$).

Uncertainty. We analyzed detailed Cropland Data Layer (CDL) classification error data to estimate the accuracy of crop-switching detection, which is propagated from classification error rates for all the individual crops in the time series for a given pixel (*SI Appendix*, Fig. S1). The results indicate that most crop-switching classifications in our analysis were correct, both for pixels that we classified as switches and for pixels that we did not. We found that 99.8% of all individual cropland pixels in our results were likelier than not to have been correctly classified for crop switching (i.e. had user's accuracy greater than 50%). Mean user's crop-switching classification accuracy was 94% (median: 96%), while mean hypothetical producer's accuracy was 92% (median: 94%) (*SI Appendix*, Fig. S8). All accuracy metrics differed by less than one percentage point between crop introduction and discontinuation.

Accuracy was higher for pixels where crop switching was not identified (mean user's accuracy of 94%) than pixels where switching was identified (86%). Since these two user's accuracy rates are relatively similar and since crop switching was detected

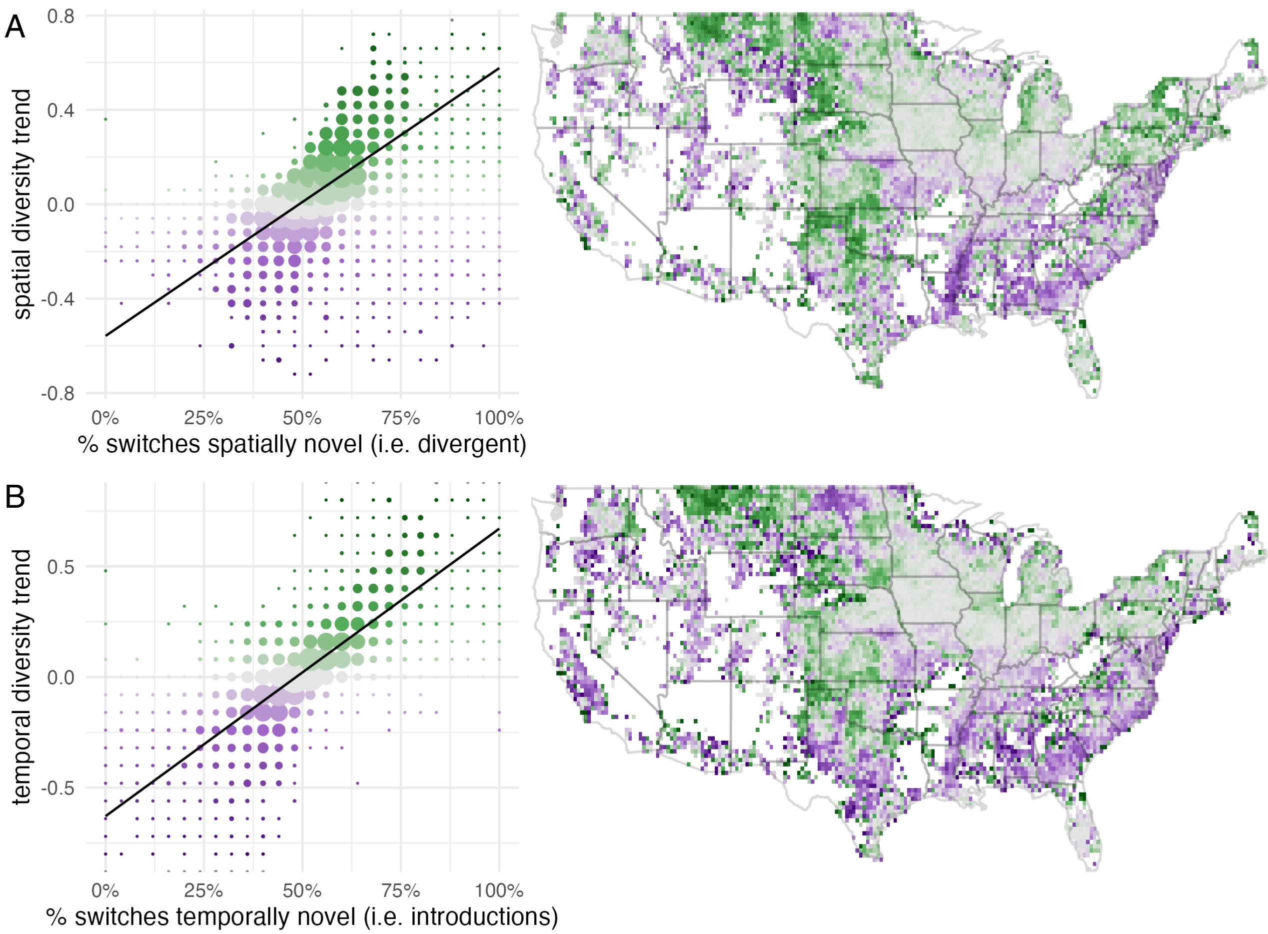

Fig. 5. Strong positive associations between crop-switching characteristics and crop diversity trends over time. (*A*) The proportion of crop switches that were spatially novel in a given landscape (x-axis) predicts its change in spatial crop diversity (Shannon) between 2008 to 2015 and 2015 to 2022 (y-axis and map). (*B*) The proportion of crop switches that were temporally novel in a given landscape (x-axis) predicts its change in temporal crop diversity between 2008 to 2015 and 2015 to 2022 (y-axis and map), with diversity measured as the number of unique crops grown over 8 y in the average cultivated pixel. In the scatter plots, the black lines are linear fits, and points are binned and sized in proportion to cultivated land area in order to avoid overplotting; some y-dimension outliers are cropped out of the figure for clarity but are included in the trend calculation and other summary statistics.

in a small minority of pixels in the average year, these results suggest that true crop-switching rates may be higher than what we detected in the data.

Uncertainty varied geographically, with the highest accuracy in the Heartland and Mississippi Portal regions, and the lowest in the Southern Seaboard and Eastern Uplands regions (*SI Appendix*, Fig. S9). But mean accuracy was greater than 80% even in relatively uncertain regions, indicating reasonable confidence in the general crop-switching patterns we identify.

Discussion

Our results demonstrate that crop choices on US farms are dynamic and have a variety of relationships to the surrounding landscape, and likely social, economic, and other infrastructure drivers as well. A large proportion of US cropland underwent crop switching during our study period, with more than 35% of cultivated land exhibiting crop introduction or discontinuation at least once over eight years, and more than 6% of both in any given year. Crop introductions and discontinuations occurred at similar rates nationally, indicating that crop switching had a neutral effect on temporal diversity. But divergent switches occurred more frequently than convergent switches, indicating they had a net effect of increasing spatial crop diversity. Transformative switches represented a small minority (2%) of all crop switching, confirming that incremental changes among similar crops are the predominant form of switching. While these transformative changes are relatively rare, they are of outsize importance due to the magnitude of change they represent, and warrant further attention to understand their drivers, economic impacts, and future ripple effects through the landscape.

Geographic variation in crop-switching rates and its three dimensions of novelty revealed strong spatial patterns that were largely independent, with no metric explaining more than 30% of the variation in another metric. This indicates that crop switching is a complex, multifaceted phenomenon, with the three measures of crop novelty representing genuinely distinct dimensions of change.

Two key characteristics of this spatial variation were that rates of crop switching were higher in landscapes with less total cropland and in landscapes with higher crop diversity. Both patterns were consistently observed within nearly all farming regions, and also at a larger scale comparing regional means. Importantly, because cropland cover and crop diversity are virtually uncorrelated across the United States, the associations between these predictors and crop switching are distinct. These two findings suggest a number of likely cultural and social processes at play.

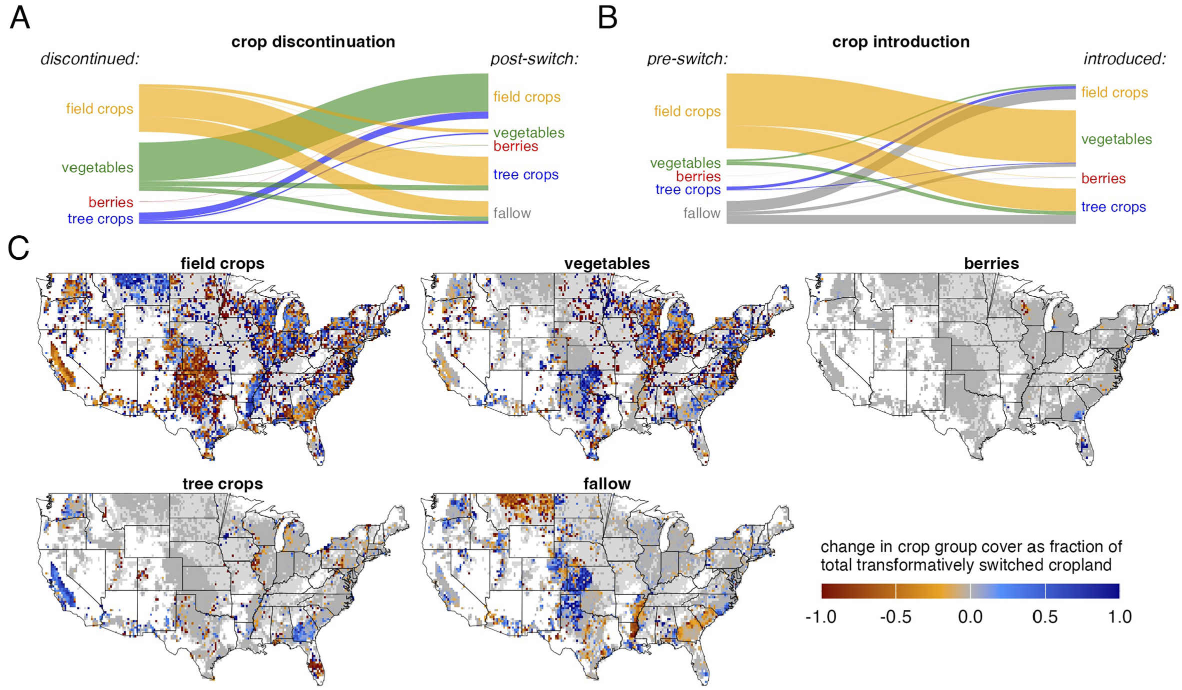

Fig. 6. Shifts among crop categories resulting from transformative crop switching. (*A* and *B*) Relative area of cropland undergoing transformative switches between each pair of crop categories, for crop discontinuation and introduction, respectively; for each case of transformative crop switching, tallies cover the discontinued crop and the set of crops grown in the 7-y reference period following discontinuation, and the opposite for crop introduction. (*C*) Geographic patterns in transformative crop switching; color represents the net amount of land switching into or out of a given crop category as a fraction of total transformative crop switching in a given landscape, which sums to zero across the five maps (e.g., a value of −0.5 for field crops would indicate that net 50% of the transformative switching in that landscape involved switching away from field crops). Areas in lighter gray had no transformative switching.

First, we found that the margins of agriculture—landscapes with less total cropland—had higher rates of crop switching, and higher relative rates of divergent crop switching (Fig. 4 *B* and *C*). As embodied in the maxim that "desperation is the mother of innovation," innovation is frequently documented to occur in marginal spaces. Low cropland cover is likely associated with farmer choices to avoid areas with conditions more adverse for crop cultivation, e.g. due to marginal climate, soils, or irrigation access. These same adverse conditions may underlie our finding that the farmers that do occupy these marginal landscapes switch crops more frequently (with unsatisfactory economic returns driving them to explore alternative crop choices more frequently than they would in highly productive landscapes) and tend to switch to crops that are less locally common (perhaps because the median neighbor offers a less successful model to emulate than does the median neighbor in a highly productive landscape).

It is also possible that this result is driven by social in addition to economic characteristics of marginal landscapes. The challenges of farming in marginal conditions may select for farmers that have higher risk tolerance, a characteristic that could in turn make them more likely to dynamically explore alternative farming practices, including by switching crops. Additionally, areas with fewer farms may have fewer cultural norms or institutional mechanisms steering farmers toward preconceived best practices, leaving more room for experimentation and thus higher rates of crop switching.

Second, we found that crop switching was more common in landscapes with high crop diversity (Fig. 4*A*). Farmers that are surrounded by greater diversity are participating in complex, highly developed social networks (26), which likely provide opportunities to understand different cropping systems, infrastructure, and equipment needs for a new system. Existing research supports these concepts, demonstrating that farmers who diversify their cropping or farm operations are more likely to participate in less traditional markets and practices including selling to local markets, using organic practices, and integrating livestock in their crop systems (2, 35).

Conversely, in more homogeneous regions such as the Heartland, which had both the lowest rates of overall crop switching and the lowest relative rates of divergent switching, we posit two potential mechanisms at play. First, these systems are likely stable because they are currently at an adaptive peak, with little incentive to switch away from the productive, profitable, intensively farmed field crops that dominate these regions. Second, however, this homogeneity may also limit potentially adaptive crop switching due to a scarcity of the examples, expertise, and networks present in more diverse systems (26)—limitations that could hamper the resilience of these economically important regions in the future under continued rapid climate change. Such results suggest that efforts to diversify more homogeneous landscapes like the Heartland would thus require particular technical assistance that enables farmers to see and learn what may not be present more naturally within the landscape, as well as shifting economic and policy incentives (36).

These results add to a body of literature on the importance of crop diversity for various desirable attributes of agroecosystems. Diversity has been credited with increasing and stabilizing crop yields (12, 37), decreasing pesticide use (38, 39), and increasing biodiversity of native species (40). If diversity also facilitates crop switching as our analysis suggests, it could help farming systems adapt to challenges like climate change. Diversity is necessary for cultural evolution, providing opportunities for individuals to learn or emulate behaviors from others (41). Thus, the association we find between crop diversity and crop switching could be a signal of cultural evolution, with farmers learning from each other which crops to plant (e.g. ref. 42). These results add to existing evidence of climate change adaptation in US agriculture, showing a shift toward crops more suitable under recent climate change (43). Future studies of agricultural adaptation should examine the causal nature of these dynamics, including the social transmission of farming behaviors.

Our findings demonstrate that crop switching is often density-, diversity-, and path-dependent. It is notable that these dimensions of the problem are currently not found in models designed as decision-making tools that perform spatial optimizations to suggest crop switching or crop redistribution (14). Recent models often simply ignore human factors and neighborhood effects entirely (23). Alternatively, models that specifically include stakeholders or farmers' preferences tend to assume homogeneous behaviors across all farmers; e.g., assuming a uniformly convergent bias (24). Without suggesting any causal mechanisms, our findings can inform more realistic correlations between crop switching and local crop density, diversity, and history. Across these three dimensions, simple correlations might be able to capture more complex farming practices and help decision-making tools make recommendations more likely to be accepted by farmers.

Beyond crop diversity predicting crop switching, our results also confirm crop switching as a driver of diversity change. While spatial and temporal diversity both confer the diversity benefits noted above, the distinction between the two types of diversity is important both conceptually and empirically (33). As expected, landscapes where divergent (spatially novel) crop switching predominated saw increased spatial crop diversity, while those where convergent switching predominated exhibited decreasing diversity. Similarly, landscapes where the majority of crop switches were introductions (temporally novel) increased in temporal diversity, and vice versa. These results confirm that crop-switching characteristics are predictive of overall diversity changes; despite the mechanistic relationship between crop switching and diversity, the observed positive correlations are not guaranteed because the diversity trends represent all cropland and are thus influenced by other changes in addition to crop switching.

Our results have uncertainties arising from omission and commission errors in CDL crop classifications based on satellite imagery (44). While this dataset is the best available to address our study questions, CDL reports fairly high misclassification rates for relatively rare crop types in certain parts of the country. The steps we took to reduce classification errors using spatial and temporal filters, in combination with uncertainty analyses estimating that user's accuracy in detecting crop switching is 94% in spite of CDL misclassifications, help to give confidence that our broad conclusions are not artifacts of classification errors. Nevertheless, a nontrivial level of uncertainty remains, and may be particularly high for rare crop types. This uncertainty likely affects some aspects of our results more than others—for example, while it could influence relative rates of transformative versus incremental switching, it is less likely to influence relative rates of crop introduction versus discontinuation. Further research using complementary instruments (e.g., surveying farmers on crop-switching behaviors) could be used to help corroborate and extend the imagery-derived trends reported here.

Conclusions

The results we present here offer an important set of insights into crop-switching dynamics across US farms, helping to address major gaps in our knowledge about this central component of agricultural adaptation. We show that both the prevalence and nature of crop switching vary substantially across the country, and that these patterns are linked to spatial and temporal trends in crop diversity and cultivated landcover. Our framework and findings also lay the groundwork for future studies on crop switching. In particular, additional research is needed to better understand the set of causal factors driving the strong spatial and temporal variation in the different dimensions of crop-switching rates we have identified, including the roles of climatic, economic, social, and policy factors that jointly shape farmers' crop choices.

Materials and Methods

We assessed crop switching in the contiguous United States using the USDA's annual CDL (30 m pixel resolution, 2008 to 2022) (25). CDL categorizes land use into 105 specific crop types (e.g., soybeans, peanuts, oranges; see *SI Appendix*), as well as fallow cropland, noncultivated agricultural cover types (e.g. pasture, hay), and various types of nonagricultural land. Our analysis focused on cultivated crop types, so we excluded all noncrop land use types as well as a small number of rare crop types that were not easily categorized for the transformative switching analysis (e.g. double crop of lettuce/durum wheat) or that verge into agroforestry (e.g. Christmas tree farms). This left 101 crop types, including fallow cropland, in our analysis. We excluded any pixel that was classified as anything other than these 101 types in any year, which are often either field edges that have higher rates of classification error (45), or locations with land use change separate from crop switching. The remaining cultivated land included in the analysis covers more than 1,125,000 km^2 (*SI Appendix*, Fig. S2*A*).

To remove noise in annual CDL layers, which manifests as stray misclassifications such as a single pixel of soybeans in a field of corn (8), we used a modal neighborhood filter that identified such outliers and replaced the value with the most frequent crop variety grown within a 75 m radius (circular 5 pixel window). Using this approach, stray pixels were reclassified while preserving the 30 m resolution of the images. This resulted in the reclassification of 3.3% of cropland pixels in the average year. The reclassification rate varied strongly by geography, with low correction rates in the corn-intensive Heartland and higher correction rates elsewhere (*SI Appendix*, Fig. S7).

We defined crop switching as the occurrence in a given 30 m CDL pixel of a crop type not grown in that location during any year in an adjacent seven-year reference period. The reference period is the preceding seven years when assessing crop introductions, and the following seven years when assessing discontinuations. The long reference period minimizes misidentification of routine crop rotations as crop switching, by increasing the likelihood that all crops in multiyear, multicrop rotations are included in the reference observations.

Crop introduction was evaluated for each year from 2015 through 2022. Crop discontinuation was evaluated for each year from 2008 through 2015. Since the fallowing of cropland is distinct from crop switching, changes were not classified as crop switching if they involved the introduction or discontinuation of fallow cropland, or if all seven reference years were fallow cropland.

To differentiate between incremental and transformative crop switching, we classified each of the 100 crop types (excluding fallow) into four categories of crops with similar cultivation practices: field crops, annual fruits and vegetables, perennial berries, and tree crops (see *SI Appendix* for details). We defined transformative crop switching as the introduction or discontinuation of a crop in a category that was not represented at all in that pixel during the reference period, and incremental crop switching as the introduction or discontinuation of a crop type in a category that did have other subtypes grown in that pixel during the reference period.

Convergent and divergent crop switching reflect whether a 30 m pixel switched to a crop that was more common or less common, respectively, within the surrounding local 30 km landscape than was the crop it switched away from. Convergent crop switching has a homogenizing effect on spatial crop diversity within a landscape, while divergent switching has a diversifying effect. For each year and landscape, we computed a crop frequency distribution, p, representing the proportion of agricultural pixels covered by each of the 101 crop types. For each instance of a pixel switching crops, we identified the crop types it switched from and to (for crop discontinuation, this represents the discontinued crop and the crop grown in the following year, while for crop introduction, it represents the introduced crop and the crop grown in the prior year), and compared the frequency of these two crop types in the frequency distribution for the earlier of the two years. (The earlier year's frequency was used because it represents the information that would inform a farmer's decision to switch crops, but we found that using the later year's frequency yielded similar results.) Switches from higher- to lower-frequency crops were classified as divergent, and the opposite for convergent.

After classifying these different forms of crop switching for each pixel and year, we aggregated the results to the landscape scale, calculating the proportion of each 30 km landscape that was cropland, the proportion of cropland exhibiting each type of crop switching, and the proportion of total crop switching with each combination of characteristics. We also calculated the acreages of cropland in each 30 km landscape that switched between each pair of crop categories. The 30 km cell size was chosen because it is large enough to encompass numerous farms for reliable calculation of landscape-level variables yet fine enough that farms within a landscape will share many attributes, and because it is coarse enough to make visualizing nationwide maps tractable yet fine enough to retain detailed geographic patterns.

To assess relationships between crop switching and crop diversity, we calculated spatial and temporal diversity metrics. For each 30 m pixel, temporal diversity was defined as the number of distinct crop types grown in that location over time, and was calculated over the entire 15-y time series (2008 to 2022), as well as for the eight years when discontinuation was evaluated (2008 to 2015) and when introduction was evaluated (2015 to 2022); each of these temporal diversity values were then averaged to the 30 km landscape scale. We calculated spatial diversity within each 30 km landscape for each year as the Shannon diversity index of crop types for each pixel in the landscape, $-\Sigma(p \cdot \log(p))$, where p is a vector of proportional crop frequencies as described above.

To identify statistically significant spatial concentrations of especially high and low values for each of the four crop-switching metrics, we used the landscape-scale results to calculate the Getis Ord Gi* hot spot statistic (46) using the R package *sfdep* (47). The Gi* statistic is a z-score representing how the average value for a location and its neighbors deviates from the distribution of these neighborhood averages across all neighborhoods in the dataset; *P*-values are based on random permutations of the data, which we performed 999 of. The definition of a "neighborhood" is somewhat subjective, so we used three alternative neighborhood sizes (a 30 km landscape grid cell and its 4, 8, or 36 nearest neighbors) to assess hot spots.

Like all imagery-based land cover data, the CDL contains classification errors that introduce uncertainty in downstream analyses. Several of the methodological steps described above help to minimize this uncertainty, and are recommended under best practices for working with these data (45). This includes using temporal filtering to exclude pixels not classified as cropland in all years, using spatial neighborhood filtering to average out high-frequency misclassifications (*SI Appendix*, Fig. S7), reporting longer-term average trends using data from all years, and employing crop change measures with reduced sensitivity to classification errors (since many forms of classification error still result in correct detection of a crop switch).

We also conducted a set of uncertainty analyses based on state-level "confusion matrices" provided by CDL, which report detailed crop-specific classification error rates. We used these data to assess "user's accuracy" and hypothetical "producer's accuracy" (48) of crop-switching determinations, by propagating crop-level uncertainty to estimate probabilities of correctly classifying crop switching in a given pixel. See *SI Appendix*, Fig. S1for details.

All analysis was done in Google Earth Engine (49) and R (50).

Data, Materials, and Software Availability. Data (code and results) have been deposited in Zenodo (DOI:10.5281/zenodo.11977899). Previously published data were used for this work (25).

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