Divergent impacts of crop diversity on caloric and economic yield stability

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Abstract

Food security and the agricultural economy are both dependent on the temporal stability of crop yields. To this end, increasing crop diversity has been suggested as a means to stabilize agricultural yields amidst an ongoing decrease in cropping system diversity across the world. Although diversity confers stability in many natural ecosystems, in agricultural systems the relationship between crop diversity and yield stability is not yet well resolved across spatial scales. Here, we leveraged crop area, production, and price data from 1981 to 2020 to assess the relationship between crop diversity and the stability of both economic and caloric yields at the state level within the USA. We found that, after controlling for climatic instability and differences in irrigated area, crop diversity was positively associated with economic yield stability but negatively associated with caloric yield stability. Further, we found that crops with a propensity for increasing economic yield stability but reducing caloric yield stability were often found in the most diverse states. We propose that price responses to changes in production for high-value crops underly the positive relationship between diversity and economic yield stability. In contrast, spatial concentration of calorie-dense crops in low-diversity states contributes to the negative relationship between diversity and caloric yield stability. Our results suggest that the relationship between crop diversity and yield stability is not universal, but instead dependent on the spatial scale in question and the stability metric of interest.

1. Introduction

Ensuring the temporal stability of agricultural production is critical to regional and global food security and sustained rural economic well-being (Schmidhuber and Tubiello 2007, Ben-Ari and Makowski 2014). Recently, several studies have suggested that increasing the diversity of cropping systems at the national level has the potential to increase the stability of total agricultural yields (Renard and Tilman 2019, Egli et al 2020, Redhead et al 2020). Over the course of the past century, cropping system diversity has declined worldwide (Khoury et al 2014, Ramankutty et al 2018), a trend that is particularly pronounced in industrialized countries such as the United States, where between 2002 and 2012 there occurred a 15-fold increase in the spatial concentration of cropping species (Aguilar et al 2015, Crossley et al 2021). Because high levels of spatial specialization can lead to increased risk of crop failure from climatic stressors (Ortiz-Bobea et al 2018), potential for synchronous failure of global breadbasket regions has also been linked to increasingly homogeneous agricultural landscapes (Tigchelaar et al 2018, Mehrabi and Ramankutty 2019, Egli et al 2020). Given that declines in cropping system diversity are coinciding with heightened climatic threats to production stability (Gaupp et al 2020, Mehrabi 2020),
it is increasingly important to understand how the relationship between diversity and stability operates in an agricultural context.

Experimental and observational work on the diversity-stability relationship, largely conducted in natural ecosystems, has primarily identified positive effects of diversity on ecosystem stability (Tilman et al 2006, Isbell et al 2009, Zhang et al 2018, Xu et al 2021), though negative (Pfisterer and Schmid 2002, Sasaki and Lauenroth 2011), and climate-dependent (Hallett et al 2014, García-Palacios et al 2018) relationships have also been reported. Variability in outcomes may be in part associated with differences in the definitions of diversity (such as taxonomic versus functional diversity; e.g. García-Palacios et al 2018) and stability (such as temporal variability versus resilience or resistance; e.g. Isbell et al 2015). Positive diversity-stability outcomes are often attributed to the portfolio effect (also termed the insurance hypothesis), whereby diversity buffers against stressors via temporal asynchrony and niche separation (Doak et al 1998, Yachi and Loreau 1999, Wilcox et al 2017).

In agricultural systems, these relationships have been most closely studied at the field to landscape scale. Rotational diversity (Borrelli et al 2014, Gaudin et al 2015, Bowles et al 2020) and intercropping (Rasheduzzaman and Jensen 2017) have been shown to improve yield stability, including under drought stress (Leuthold et al 2021). Mechanisms by which this relationship operates include an increase in the prevalence of beneficial insects (Weibull et al 2000, Hemberger et al 2021), increased soil moisture retention (Leuthold et al 2021), and differential sensitivity to stressors (Gaudin et al 2015). At the national scale, crop diversity has been found to stabilize yields due to portfolio effects associated with concurrent cropping systems (Renard and Tilman 2019, 2020). Temporal asynchrony in crop production, or variability in the timing of growth stages and stress exposure, has been invoked as one key mediator of this relationship (Egli et al 2020, 2021). In addition to the biophysical factors that influence caloric yield stability, price responsibility associated with global supply and demand, regional production variability (Urruty et al 2016), and government subsidy programs (Berardi et al 2011) all play a role in determining the stability of economic returns to farmers.

Although the stabilizing effect of diversity operates via different mechanisms at different scales, this relationship has not yet been evaluated at a subnational level. As the United States is one of the most agriculturally productive countries in the world (FAOSTAT 2022), contains a wide range of environmental conditions and crop production systems, and has experienced a rapid contraction in crop diversity (Aguilar et al 2015, Crossley et al 2021), it presents a useful test case of these patterns at the subnational scale. In addition, the benefits of local yield stability (and the costs of instability) are distinct from those associated with national yield stability and have direct relevance for agricultural communities. Understanding these relationships at a smaller spatial scale may also have relevance for agricultural policies affecting crop choice, as many of these decisions are made at the subnational scale. Previous work on landscape diversity and yield stability that has been conducted at the subnational scale has focused on stability of individual crops (Redhead et al 2020, Nelson and Burchfield 2021, Nelson et al 2022), failing to capture impacts on the stability of total economic and caloric production. Here, we tested the hypothesis that crop diversity has a stabilizing effect on caloric and economic yields at the state scale in the United States. We leveraged annual, state-level records of crop production, area, and prices spanning 1981–2020 to calculate caloric and economic yields for 90 crops and assess the impact of diversity on interannual yield stability, controlling for decade, weather instability, and irrigation. Finally, we quantified the de/stabilization potential of each crop across state-years to determine which crops have the strongest influence on subnational yield stability.

2. Methods

2.1. Crop area, production, and price data

Annual, state-level data on crop areas, total production, and prices received by farmers were acquired from the U.S. Department of Agriculture (USDA) National Agricultural Statistics Service (NASS) surveys for 90 unique crops in the contiguous United States from 1981 to 2020 (see table S1 for a complete list of crops) (USDA QuickStats 2022). Area data were based on the harvested area for field crops and on the area bearing for tree crops. Data from the Census of Agriculture, conducted once every five years, were generally not included because of differences in coverage between the Survey and Census programs. However, area data for several tree crops were not available in the surveys. Because tree crop areas were relatively static, we used area data from the census for these crops when survey data was not available and filled gaps via linear interpolation. All area data were converted to hectares, and all production data were converted to kilograms. Volume-to-weight conversion factors were obtained as needed from USDA documentation for cranberries, citrus fruits, and select grain and oilseed crops (table S2). Missing production and area data were gap-filled using linear interpolation between observations from the preceding and following years. Gaps longer than five years in length were not filled, and data were not extrapolated beyond the endpoints of the timeseries. Unless otherwise specified, we used the complete, gap-filled dataset for all further analyses. Livestock were omitted from this study because of substantial challenges related to area-based calculations of yields, data availability around stocking rates, movement of livestock.
between states, and double-counting of feed crop calories. Similarly, we were unable to conduct the analysis at the county level because of limited data availability due to withholding for producer privacy.

State-level annual production and yield were calculated in terms of both calories and US dollars (USDs). The human-available caloric contents of each crop, excluding inedible refuse, were calculated using data from the USDA Nutrient Database (USDA FoodData 2019). Caloric conversions, refuse percentages, and data processing details are available in table S1. Cotton, tobacco, hay, and hops were excluded from caloric production and caloric yield calculations as they do not contain human-available calories. Total caloric production was calculated by multiplying the caloric content by production in kilograms and summing across crops. Price data were converted to USD per kilogram, adjusted for inflation relative to a base year of 2010 using the Producer Price Index for farm products (Series ID WP01) from the U.S. Bureau of Labor Statistics (US BLS 2022), and gap-filled using the average price in states for which data were available for that crop and year. Total economic production was calculated by multiplying the adjusted price by the production in kilograms. Finally, state-level economic and caloric yields were calculated by dividing total economic and caloric production by the total crop area. The aggregated data and all associated code are available via Zenodo (Driscoll et al 2022).

2.2. Irrigated area
State-level data on total harvested area and irrigated harvested area were acquired at five year intervals for 1982–2017 from the USDA Census of Agriculture. For the 1997 Census and all subsequent censuses, data were accessed via the NASS QuickStats API. Data for the 1982, 1987, and 1992 censuses were accessed via the historical archive hosted by the Albert R. Mann Library at Cornell University (Census of Agriculture 2019). The average proportion of irrigated area was calculated by dividing irrigated harvested area by total harvested area and averaging across each decade.

2.3. Climate data
Gridded daily data for mean temperature and total precipitation were obtained from the PRISM Climate Group for 1981–2020 (4 km resolution). Data were aggregated to the county level by weighting each PRISM grid cell by the proportion of area classified as cropland by the GFSAD30NACE product from NASA EarthData (30 m resolution) (Massey et al 2017). We then aggregated these data to monthly, state-level values by weighting each county by its average cropland area across USDA Censuses from 1992 to 2017. We removed months with a minimum temperature less than 0 °C to approximate the growing season and calculated the average temperature and total precipitation. Finally, we calculated a unitless index of state-level temperature and precipitation instability as the temporal standard deviation divided by the average annual value for each decade.

2.4. Crop diversity
We calculated crop diversity in each state (s) and year (j) with respect to caloric production and economic production (hereafter caloric diversity and economic diversity, respectively). To do so, we used the total number of different crops (c) and the proportion (p) of total caloric or economic production attributable to each crop as inputs to the equation for Shannon’s diversity index. Shannon’s diversity index is a widely used indicator of species diversity that accounts for both species richness (the number of species within a designated region) and evenness (a measure of the relative abundance of each species; Lande 1996). In addition to economic and caloric diversity, we also calculated diversity with respect to crop area using the same formula because area-based crop diversity is commonly utilized in other studies (Renard and Tilman 2019, Crossley et al 2021). In our data set, both caloric and economic diversity were positively correlated with area-based diversity (r = 0.88 and 0.93, respectively; p < 0.0001 for both). We utilized caloric and economic diversity for further analyses as they incorporate differences in caloric content and price across crops,

\[
d_s,j = -\sum_{i=1}^{c} p_i \ln (p_i).
\]

(1)

2.5. Yield and production stability
We quantified the stability of caloric and economic yields at the state level, defined as the average yield divided by the standard deviation of the residuals from a linear regression of yield by a quadratic function of year, calculated at decadal intervals. We fit a linear regression model (equation (2)) to estimate the sensitivity of yield stability (y) at the state (s) and decade (t) level to average crop diversity (d_s,t), temperature instability (h_s,t), precipitation instability (r_s,t), and the proportion of irrigated area (a_s,t). We included a categorical variable for decade to account for technological and policy change over time. We used the caloric measure of crop diversity in the models of caloric yield stability and the economic measure of crop diversity in the models of economic yield stability. We conducted an analogous analysis for crop production stability with qualitatively similar results, reported in the supplementary information (figures S1 and S2).

\[
y_{s,t} = \beta_0 + \beta_1 d_{s,t} + \beta_2 h_{s,t} + \beta_3 r_{s,t} + \beta_4 a_{s,t} + \epsilon.
\]

(2)

2.6. Crop-level analyses
To further clarify the role of individual crops in driving the observed diversity-stability relationships, we conducted additional analyses at the crop level. First, we calculated the calorie-to-price ratio of each crop.
using the calories per kilogram and the average price of the crop. We also calculated a crop-level indicator of diversity as the average diversity of the state-years that produced each crop, weighted by the proportion of total production in each state-year. We then performed a leave-one-out analysis in which stability was recalculated for each state-year after iteratively dropping each crop from the dataset. Leave-one-out analysis and associated log response ratio (LRR) are commonly used in meta-analyses (Hedges et al 1999) and have been applied in similar analyses of cropping system stability (Renard and Tilman 2019). State-years in which a crop was not grown were removed from the analysis after the calculation of stability. The modified LRR of stability (LRR\(c,s,t\)) was calculated for each crop \(c\), year \(t\), and state \(s\) according to equation (3), in which \(\gamma_{c,s,t}'\) represents either the economic or caloric stability calculated without crop \(c\) in the dataset, and \(\gamma_{c,s,t}\) represents the stability calculated using the complete dataset. Values were then aggregated across state-years to determine the average response to each crop for the period surveyed,

\[
\text{LRR}_{c,s,t} = -\ln \left( \frac{\gamma'_{c,s,t}}{\gamma_{c,s,t}} \right). \tag{3}
\]

We extended our calculations of the LRR to determine the likelihood that, within a given state-year in our dataset, including a certain crop would lead to a lower economic or caloric yield stability. We termed this destabilization potential and calculated it for each crop as the proportion of LRRs that were negative across all state-years in which the crop was present. Due to the potential divergent response between economic and caloric stability, we calculated destabilization potential separately for both stability metrics, and further refer to them as economic destabilization potential and caloric destabilization potential, respectively. In both instances, increasing destabilization potential for a given crop indicates that, within our dataset, that crop was more likely to decrease the economic or caloric yield stability of a given state year than crops with lower destabilization potentials. Linear regression was used to quantify the relationship between caloric destabilization potential and crop-level diversity.

3. Results and discussion

3.1. Patterns in crop diversity and yield stability

State-level crop diversity assessed with respect to caloric production (figure 1(a)) and economic production (figure 1(b)) were positively correlated with one another \((r = 0.84, p < 0.0001)\). In all but three states (NV, UT, and WY), economic production diversity was higher than caloric production diversity. This state-level pattern was also reflected nationally: the top five crops with respect to caloric production (corn, soybeans, wheat, sorghum, and rice) contributed 94% of total caloric production across the study period, whereas the top five crops with respect to economic production (corn, soybeans, hay, wheat, and cotton) contributed only 73% of total economic production. This higher economic diversity relative to caloric diversity arises because, in this dataset, the average price of a crop was unrelated to its caloric content \((p = 0.60; \text{figure S3})\). Supply and demand forces may partially drive this lack of a relationship, as some crops with the highest average prices are labor-intensive to cultivate and have substantially lower production areas than crops with lower average prices. For instance, averaged across our dataset, asparagus accounted for 16 431 ha of arable land and commanded a price of 2.46 USD kg\(^{-1}\), reflecting both the cost of inputs and labor as well as the inherent scarcity of a specialty crop. In contrast, corn grown for grain, one of the most abundant crops, was grown on 29 927 934 ha on average and had an average price of only 0.15 USD kg\(^{-1}\). These differences in the costs of production and overall supply have a marked influence on the economic value of a given crop. However, the caloric content of a given crop is a static value, unresponsive to economic forces; the caloric content of asparagus is an order of magnitude lower than that of corn for grain (106 kcal kg\(^{-1}\) vs. 3650 kcal kg\(^{-1}\)). In our data, many fruit and vegetable crops have low caloric values, but due to their overall scarcity, they command high prices. Other high-value crops such as cotton, hops, and tobacco provide no caloric value, further adding to the divergence. Conversely, staple crops such as grains and oilseeds, which are abundant and as such are typically priced relatively low, have high caloric contents. These patterns in distribution and cost likely drive the divergence between the metrics that we observed. Moreover, the crop calorie-to-price ratio was negatively related to the diversity of the state-years in which they were grown (figure S4; \(r = -0.66, p < 0.0001\)). In other words, crops with a high calorie-to-price ratio tended to be grown in less diverse states. The effects of this decoupling were particularly pronounced in states such as MI, TN, NC, SC, and VA, which have high economic diversity but low caloric diversity.

An analysis of temporal trends in crop diversity identified a recent and dramatic reduction in area-based crop diversity in the U.S. at the county scale when considering 18 dominant crops (Crossley et al 2021). Despite this overall contraction in crop diversity, driven primarily by economic incentives and federal policy (Crossley et al 2021, Lark et al 2022), the spatial distribution of crop diversity across states has remained relatively consistent across decades within the study period (figure S5). States in the Central and Eastern Corn Belt and in the Northeast tended to have lower diversity, while states in the South and West tended to have higher diversity. California had the highest crop diversity with respect to both caloric and economic metrics, and TX, AZ, and ND also had consistently high diversity.
Various biophysical, policy, and sociocultural factors have been identified as important drivers of spatial patterns of crop diversity within the United States. Goslee (2020) was able to explain a large proportion (>57%) of spatial variability in crop diversity based on soil quality, temperature, precipitation, and irrigation, while Socolar et al (2021) found that areas of high biophysical crop suitability were associated with lower levels of crop diversity in the Midwestern US. Within this data set, temperature was positively associated with caloric (p = 0.0032, r = 0.42) and economic (p = 0.025, r = 0.32) diversity. Precipitation was negatively associated with caloric diversity (p = 0.0063, r = −0.39), but unrelated to economic diversity (p = 0.40). Management, economic, and policy factors, including farm proximity to a biofuel plant, transportation infrastructure, labor availability, and policies around land conservation and agricultural trade have also been highlighted as important drivers of diversity (Crossley et al 2021, Socolar et al 2021). Here, caloric diversity, but not economic diversity, was positively associated with the proportion of cropland that was irrigated (p = 0.0004, r = 0.49 for caloric; p = 0.28 for economic). In addition to these structural factors, many interactive socio-cultural and economic factors drive field-scale farmer decision-making, including market availability, access to capital, equipment needs, farmer values, cultural norms, and others (Roesch-McNally et al 2018).

On average, decadal stability was higher for caloric yields (mean = 11.3) than economic yields (mean = 8.9), which is perhaps unsurprising given that prices vary from year-to-year but crop caloric content is fixed. We identified greater variation between states in caloric yield stability (standard deviation = 4.9), which tended to be lowest in the Southeast and Appalachia and highest through the Intermountain West and Southwest, than economic yield stability (standard deviation = 2.2). Economic yield stability was high in PA, VA, and NC, and low in much of the Northeast, IA, and AZ. Patterns in yield stability were variable across decades (figure S6), particularly for economic yields. Notably, economic yield stability was not significantly correlated with caloric yield stability on average over the study period (p = 0.13), nor within any individual decade. This divergence between economic and caloric yield stability is consistent with the results of previous work indicating increasing variability in the total amount of food produced (Ben-Ari and Makowski 2014, Lobell and Azzari 2017) and

![Maps of crop diversity and yield stability](https://example.com/maps.png)
decreasing volatility in total farm income (Key et al 2017).

3.2. Drivers of yield stability
Linear regressions of state-level yield stability by decade, crop diversity, the proportion of cropland that is irrigated, and precipitation and temperature instability indicated that crop diversity significantly influenced both caloric and economic yield stability (figure 2). However, crop diversity was positively related to economic yield stability ($\beta = 0.19 \pm 0.07$, $p = 0.011$) but negatively related to caloric yield stability ($\beta = -0.30 \pm 0.07$, $p < 0.0001$). Precipitation instability was negatively related to caloric yield stability ($\beta = -0.17 \pm 0.07$, $p = 0.014$), but not economic yield stability ($p = 0.58$). Temperature instability had no effect on either caloric or economic yield stability ($p = 0.52$ and $p = 0.47$, respectively). The proportion of area irrigated stabilized caloric yields ($\beta = 0.27 \pm 0.09$, $p = 0.002$), but not economic yields ($p = 0.58$). Economic yield stability may be less sensitive to irrigation because of compensatory price increases during periods of drought stress. Both models explained a relatively small proportion of the total variance in yield stability (Adj. $R^2 = 0.23$ for caloric yield stability and 0.13 for economic yield stability).

We tested two additional subsets of data to assess the robustness of the results to various crop inclusion criteria and found that these effects were qualitatively similar across subsets (figure S7).

Our finding that economic yield stability was positively associated with crop diversity is consistent with previous work (Renard and Tilman 2019, Egli et al 2020, 2021). However, the observed negative relationship between crop diversity and caloric yield stability contrasts with previous findings. We propose that differences in geographic scale and potential for temporal asynchrony may explain the differences. A recent study of scale-dependency in crop diversity in the United States found that, at the state scale and smaller, diversity is determined predominantly by within-farm, rather than between-farm, diversity (Merlos and Hijmans 2020). In contrast, national-scale diversity is driven by variability in crops between farms and regions. Because the US has low crop diversity relative to most other countries (Aizen et al 2019), and state-scale diversity is inherently limited relative to national-scale diversity, it is possible that the observed diversity is simply insufficient to provide stability benefits. Additionally, the temperate climate of the U.S. limits the potential benefits of temporal asynchrony because there are fewer areas suitable for winter cultivation. If temporal asynchrony is the primary driver of stabilization via differential exposure to stressors, the benefits of diversity will be limited in temperate environments.

3.3. Crop-specific contributions to yield stability
To better understand the mechanism underlying the unexpected divergent response of caloric and economic stability to increasing diversity, we quantified the contributions of crops to economic and caloric stability in each state-year using a leave-one-out analysis to calculate the LRR of stability to each crop. Positive values of the LRR indicate that the crop increases yield stability, while negative values indicate that the crop decreases yield stability. The magnitude of the absolute value of the
LRR indicates the relative strength of its influence on stability. Of the crops included, 26% had a mean LRR that indicated little to no effect on economic yield stability, and 36% showed little to no effect on caloric yield stability (|LRR| < 0.001). However, several crops demonstrated outsized influence on economic and caloric stability (figure 3(a)). Hay had the largest positive effect on economic yield stability (LRR = 0.192), though oranges (LRR = 0.165), almonds (LRR = 0.118), hazelnuts (LRR = 0.0625), and tobacco (LRR = 0.0423) also demonstrated a strong tendency to increase economic yield stability. Cranberries (LRR = −0.0757), romaine lettuce (LRR = −0.0356) and maize grown for grain (LRR = −0.0325) also demonstrated the highest destabilizing tendencies for economic yields. Rice (LRR = 0.154) had the largest positive impact on caloric stability, while almonds (LRR = −0.103) had the largest negative impacts. Wheat (LRR = 0.0656), peanuts (LRR = 0.0510), oranges (LRR = 0.483), potatoes (LRR = 0.0325) and cranberries (LRR = 0.0275) also had a stabilizing effect on caloric yields, whereas corn grown for grain (LRR = −0.0593), sweet corn (LRR = 0.0574), and walnuts (LRR = −0.0569) had destabilizing effects.

The spatial arrangement of different crop species across a state or region can play an important role in determining relative yield stability. For example, the consolidation of crop cultivation into highly specialized areas of production (Crossley et al 2021) can increase instability when a region that produces the bulk of a certain crop species experiences widespread crop failure or bumper crop years. High-yielding crops tend to exhibit increased volatility, exacerbating this risk (Ben-Ari and Makowski 2016). In contrast, price support programs may have artificially inflated the economic stability of some crops. For instance, the LRR for tobacco dropped from 0.103 to 0.0433 following the end of the federal tobacco quota system in 2004 (Kirwan et al 2012).

Interestingly, some crops with the biggest influence on stability exhibited divergent stabilization tendencies (e.g. stabilizing economic yield stability, but destabilizing caloric yield stability, or vice versa). For example, almonds decreased caloric yield stability, but increased economic yield stability. To better understand these differential impacts, we examined the relationship between the caloric destabilization potential and the natural log transformed ratio of kilocalories per kilogram to USD price per kilogram ($r^2 = 0.27$, $p < 0.0001$).

**Figure 3.** (a) Log response ratios (LRRs) of the 15 crops with the most influence on economic and/or caloric yield stability. Bars indicate the mean LRR of caloric stability (red) and economic stability (green) across state-years, while points indicate individual state-year observations. Positive values reflect a stabilizing effect, while negative values reflect a destabilizing effect. (b) Linear relationship between caloric destabilization potential and the natural log transformed ratio of kilocalories per kilogram ($r^2 = 0.27$, $p < 0.0001$).

4. Conclusions

Our analysis demonstrated that, at the state level in the US, crop diversity is associated with increased economic yield stability but decreased caloric yield stability. This finding runs counter to previous global-scale...
studies that identified positive relationships between crop diversity and both caloric and economic yield stability and has important implications for the incentive structures that inform the design of agricultural landscapes. We attribute our findings to several mechanisms, including: (a) limited potential for temporal asynchrony in production due to the temperate climate of the lower 48 states examined here; (b) the concentration of specialty crops in highly diverse states, which command high prices but have low caloric value; and (c) the contribution of price responses to changes in production to economic stability, a mechanism that is not available for caloric output. These results, particularly in light of their contrasts with previous work conducted at different scales, highlight that multiple approaches are needed to develop a comprehensive understanding of the role of crop diversity in improving food and economic security.

Several recent studies have considered the yield stability of major crops individually, finding that increased landscape complexity can decrease volatility of corn, soybean, and wheat yields (Redhead et al 2020, Nelson and Burchfield 2021, Nelson et al 2022) through benefits such as increased water availability, nutrient retention, and pest management (Martin et al 2019). Given that total agricultural production reflects a mosaic of different crops grown simultaneously across space, single-crop analyses may fail to capture trends in the consistency of overall food production or economic gain from a given area. Further to that point, the ability to assess mechanisms such as the insurance hypothesis or portfolio effect is lost when a single crop is examined, instead of aggregating outcomes across different systems (Nelson et al 2022). Our results indicated that this is especially relevant for specialty and horticultural crops, which are often omitted or lumped together in multi-crop analyses of diversity and yield stability (e.g. (Weigel et al 2018)). Specialty crops lack the support framework (i.e. hyper localized fertilizer recommendations, genetically modified crop varieties, crop-specific pesticide regimens) that row crops often have, often resulting in lower yield stability on a caloric basis. However, they command prices that are both higher and often more responsive to changes in supply (Bowman and Zilberman 2013), making them highly relevant to economic yield stability, even at relatively low production volumes.

Given that the direction and magnitude of the benefit of crop diversity for yield stability seem to vary depending on location and spatial scale, policies to improve yield stability and/or promote crop diversity must be made with local factors in mind. In countries such as the US where caloric production outstrips caloric demand, improvements in economic yield stability may be a higher policy priority than improvements in caloric yield stability. In this context, incentive programs that promote and enable the transition to systems with increased spatial and temporal crop diversity may be desirable (Sirami et al 2019, Tscharrntke et al 2021). In addition to increased economic yield stability, crop diversity also provides environmental benefits such as bolstered pollinator abundance, improved water quality, and healthier soils, ecosystem services that are not typically internalized into the price of agricultural products. Furthermore, livestock are critical to caloric and economic value production on US farms, and crop-livestock integration has been shown to provide numerous benefits (Sanderson et al 2013). Future research incorporating the role of livestock in stabilizing the economic and caloric production of agricultural systems presents an interesting opportunity for improving the understanding of this topic. Similarly, inclusion of additional environmental and socioeconomic variables, such as soil parameters (Socolar et al 2021), input costs (Brunelle et al 2015), and management decisions (Knapp and van der Heijden 2018), may improve potential for broad applicability across scales and regions.

Spatial patterns of diversity are not temporally static and are likely to be affected by climate-related changes in suitability (Baldocchi and Wong 2008, Parker et al 2021), as is overall crop productivity (Ray et al 2015). Incorporation of projected crop migration patterns (Sloat et al 2020) and global change effects on state-level diversity in future analyses of crop diversity and yield stability will aid in the development of forward-looking policy recommendations. Our research here indicated that the relationship between crop diversity and yield stability is nuanced, and that a range of factors must be considered in order to optimize the benefits of increased crop diversity. Continued analysis of changing trends in these relationships by scientists, economists and policymakers is paramount to ensuring the stability of our food supply and agricultural economy.

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: 10.5281/zenodo.7332106.

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