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More farms, less specialized landscapes, and higher crop
diversity stabilize food suppliesLukas Egli^{1,2,3,*} , Zia Mehrabi^{4,5} and Ralf Seppelt^{2,6} ¹ UFZ—Helmholtz Centre for Environmental Research, Department of Computational Landscape Ecology, Permoserstr. 15, 04318 Leipzig, Germany² UFZ—Helmholtz Centre for Environmental Research, Department of Ecological Modelling, Permoserstr. 15, 04318 Leipzig, Germany³ University of Potsdam, Institute of Biochemistry and Biology, Maulbeerallee 2, 14469 Potsdam, Germany⁴ The UBC School of Public Policy and Global Affairs, University of British Columbia, Vancouver, British Columbia, Canada⁵ Institute for Resources, Environment and Sustainability, University of British Columbia, Vancouver, British Columbia, Canada⁶ Institute of Geoscience and Geography, Martin-Luther-University Halle-Wittenberg, 06099 Halle (Saale), Germany

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E-mail: lukas.egli@ufz.de**Keywords:** agroecology, climate variability, resilience, spatial heterogeneity, supply shocksSupplementary material for this article is available [online](#)

Abstract

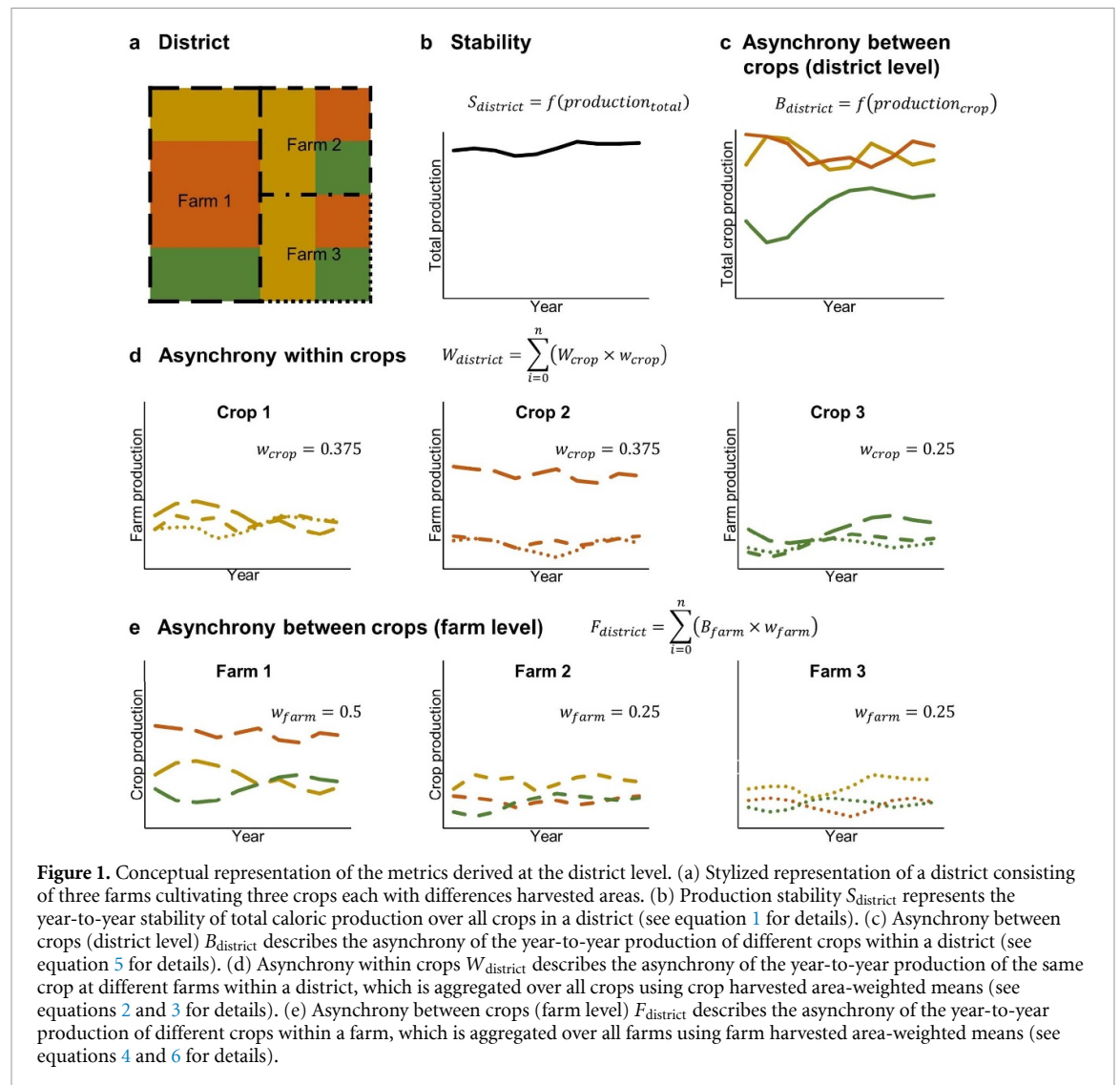
Theoretical and empirical studies show increased diversity in crops, supply chains, and markets helps stabilize food systems. At the same time global commodity markets and industrial agriculture have driven homogenization of local and regional production systems, and consolidated power in fewer larger specialized farms and distributors. This is a global challenge, with no obvious global solutions. An important question therefore, is how individual countries can build their own resilience through maintaining or increasing diversity within their borders. Here we show, using farm level data from Germany, that spreading production risk by growing the same crops across different farms carries stabilizing benefits by allowing for increased spatiotemporal asynchrony within crops. We also find that increasing asynchrony between the year-to-year production of different crops has stabilizing effects on food supply. Importantly, the benefits of increasing crop diversity are lower in specialized landscapes growing the same crop on large patches. Our results illustrate clear benefits of diversified crops, producers, and agricultural landscapes to buffer supply side shocks, and for incorporation in subsidies and other regulatory measures aimed at stabilizing food systems.

1. Introduction

Supply side variability and shocks driven by variable and extreme weather and pest outbreaks present a major challenge for food systems (Iizumi and Ramankutty 2016, Lesk *et al* 2016, Deutsch *et al* 2018, Mehrabi 2020). A key global concern is that ongoing and increasing homogenization of production systems, and agricultural landscapes, is rendering them vulnerable to these drivers (Kastner *et al* 2014, Ben-Ari and Makowski 2016, Ramankutty *et al* 2018, Nyström *et al* 2019). Increasing diversity in production systems has therefore been proposed as a key mechanism to offset these risks (Ramankutty *et al* 2018, Renard and Tilman 2019, Egli *et al* 2020). A key factor underpinning the stabilizing effects of diversification, is the impact effects of diversity on asynchronous

production dynamics. These effects can arise from either growing the same crops at different locations (leading to asynchrony within crops), or growing different crops at a given location (asynchrony between crops), such as across farms or regions (Mehrabi and Ramankutty 2019) (figure 1). However, in reality these two effects might trade-off with each other in practice, and the relative importance of each for the stability of production systems is poorly understood.

In the context of this study, asynchrony within crops describes the asynchrony of the year-to-year production of the same crop at different farms within a given region and time interval (figure 1(d)). It arises from differences in farmer decision making, and spatial heterogeneity in biophysical and social conditions (e.g. Kouadio and Newlands 2015). If differences



in crop management decisions, or climate, lead to asynchronous year-to-year production patterns in the same crop (e.g. with a production surplus in one place and a loss in the other), multiple producers can together stabilize the production system tied to that crop (Mehrabi and Ramankutty 2019). In general, larger areas with high spatial heterogeneity better buffer local variability and shocks, e.g. related to climate or weather events, political conditions and management (van Nes and Scheffer 2005, Suweis *et al* 2015, Cottrell *et al* 2019).

Asynchrony between crops describes the asynchrony of the year-to-year production of different crops within a given region (figure 1(c)) or farm (figure 1(e)). Increasing crop diversity stabilizes agricultural production if different crops show differential responses to climatic, economic and political variability and shocks, as well as differences in agricultural management (Rist *et al* 2014, Renard and Tilman 2019). This is the same stabilizing mechanism identified as ‘response diversity’ of different species found in biodiversity research (Elmqvist *et al* 2003). Across different regions or large geographic

units these differential physiological responses can be further increased by spatially heterogeneous biophysical or social conditions. Asynchrony between crops, is one important property that can explain why a higher crop diversity supports the stability of national food production (Egli *et al* 2020).

To foster stability of agricultural production, management approaches that increase asynchrony within and between crops need to be investigated in addition to other options. While crop diversification increases asynchrony between crops, asynchrony within crops also can be addressed by increasing the number and diversity of farms and production systems, and altering landscape configuration, e.g. by moving away from specialized landscapes with few large farms growing the same crop (Lin 2011). Beside their potential stabilizing effects for food supply, crop and landscape diversity can also benefit biodiversity and ecosystem services (Seppelt *et al* 2016, 2020, Kremen and Merenlender 2018, Garibaldi *et al* 2020, Li *et al* 2020), in particular if habitat for species is increased and dependency on agricultural inputs is reduced (Rist *et al* 2014).

While the effect of asynchrony within and between crops has been recently assessed individually at the global level, their relative importance to stabilize agricultural production for national production systems has not. In this study we include three approaches to better understand these mechanisms. First, we used farm level data in Germany to investigate the effect of asynchrony within crops across farms in a district, as well as the asynchrony between crops at the farm and district level, on the district-specific year-to-year stability of total caloric production (figure 1). Second, we empirically investigated the effect of increasing the number of farms and crops within a district on asynchrony within and between crops, respectively. Third, we simulated a model landscape with different management approaches (specialized, fragmented, diversified) to assess the effect and potential trade-offs of crop diversification on asynchrony within and between crops under variable temperature and precipitation regimes.

2. Materials and methods

2.1. Empirical analyses

For the empirical analyses, we extracted data for two time intervals (1999–2008, 2009–2018) from the ‘Testbetriebsnetz’ dataset, a comprehensive assessment of management and socioeconomic variables on more than 30 000 farms across Germany (table 1). To exclude farms where crop cultivation is of very minor relevance, we sorted them by the average cropland area over all reported years in descending order and divided it by the total cropland area of all farms and calculated the cumulative sum. We only included farms up to of 99.9% of the cumulative sum.

To calculate year-to-year production stability, several preparation steps were needed. We converted crop-specific production from tons to calories using standardized nutritive factors (table 1). We note that for the illustrative purposes of this paper this conversion assumes substitutability of supply but future applications may specify replaceable or substitutable goods for markets. We aggregated 16 crops to 10 major crops groups (supplementary table S1 (available online at stacks.iop.org/ERL/16/055015/mmedia)). For each time interval, we only included crops for which time series were complete and where both production and harvested area were reported. For each year, we then summed calorie production of all crops across all farms within each district (‘Regierungsbezirk’) to obtain overall production in kilocalories. To account for stability independent of long-term trends, we time-detrended annual production data by regressing annual total calorie production on year squared for each time interval (Renard and Tilman 2019). We calculated year-to-year production stability S_D as the non-time-detrended mean of total

caloric production divided by the time-detrended standard deviation of total caloric production for each district and time interval following Mehrabi and Ramankutty (2019)

$$S_D = \mu_D / \sigma_D \quad (1)$$

where μ_D is the non-time-detrended mean of the total caloric production of a district and σ_D is the time-detrended standard deviation of total caloric production of district D.

To confirm that production stability is directly related to supply shocks (Renard and Tilman 2019), we grouped all districts in both time intervals into four equally sized bins of increasing production stability and calculated how often annual production was at least 10% below the respective mean production of a given district and time interval.

For all three asynchrony metrics (asynchrony within crops, asynchrony between crops at farm and district level), we first calculated synchrony following Loreau and de Mazancourt (2008) and Mehrabi and Ramankutty (2019) with the ‘codyn’ package (version 2.0.3) in R (Hallett *et al* 2016) and subtracted it from 1 to receive asynchrony. We calculated within crop asynchrony W_c between the time-detrended production in farms where a given crop c was reported (equation (2))

$$W_c = 1 - \sigma_c^2 / \left(\sum_{i=0}^n \sqrt{f_{i,i}} \right)^2 \quad (2)$$

where σ_c^2 is the total variance of the time-detrended production of crop c in a district and the denominator reflects the sum of the respective variances within farms $f_{i,i}$ (the number of farms n ranges from 3 to 466 depending on the district).

By using harvested area-weighted means of these values we calculated the average asynchrony within crops in a district and time interval W_D over all crops

$$W_D = \sum_{i=0}^n (W_c \times w_c) \quad (3)$$

where w_c is the weight of each crop c based on the harvested area of this crop relative to the total harvested area of all ten crops.

To derive asynchrony between crops at the farm and the district level, we time-detrended crop-specific caloric production in each farm, or aggregated over all farms in a district, respectively. We then derived asynchrony between crops for each farm B_f (equation (4)) or district B_D (equation (5))

$$B_f = 1 - \sigma_f^2 / \left(\sum_{i=0}^n \sqrt{c_{i,i}} \right)^2 \quad (4)$$

Table 1. Datasets used in this study. Temporal extent reflects the years extracted for this study. Crop calories reflect standardized nutritive factors.

Data	Reference	Description	Resolution; temporal extent	Unit	URL
Area harvested	BMEL (2019)	Crop-specific harvested areas	Farm; 1999–2018	ha	www.bmel-statistik.de/landwirtschaft/testbetriebsnetz/testbetriebsnetz-landwirtschaft-buch-fuehrungsergebnisse/
Crop yields		Crop-specific yields	Farm; 1999–2018	dt/ha	
Crop calories	FAO (2001)	Food balance sheets	NA	kcal/100 g	www.fao.org/docrep/003/x9892e/X9892e05.htm#P8217_125315

where σ_f^2 is the total variance of the time-detrended production of farm f and the dominator reflects the sum of the respective variances within crops $c_{i,i}$ (the number of crops n ranges from 1 to 8 depending on the farm)

$$B_D = 1 - \sigma_D^2 / \left(\sum_{i=0}^n \sqrt{c_{i,i}} \right)^2 \quad (5)$$

where σ_D^2 is the total variance of the time-detrended production of district D and the dominator reflects the sum of the respective variances within crops $c_{i,i}$ (the number of crops n ranges from 4 to 9 depending on the district).

To aggregate farm level asynchrony between crops to the district level F_D we averaged asynchrony between crops for each farm over all farms in a district using harvested area-weighted means

$$F_D = \sum_{i=0}^n (B_f \times w_f) \quad (6)$$

where B_f is the asynchrony between crops in a farm and time interval, and w_f is the weight of each farm based on the harvested-area of this farm relative to the total harvested area of all farms.

The final dataset included 60 data points, reflecting 30 individual districts for two time intervals. Based on the derived metrics, we estimated the dependence of production stability on asynchrony within and between crops. We note that asynchrony between crops at the farm level can be seen as a scaling factor for district level production stability (Mehrabi and Ramankutty 2019). Here, instead of decomposing the variability into the contributing factors using theory, we undertook a statistical analysis to estimate the linear effect of the change in asynchrony within crops and either farm level or district level asynchrony between crops, on production stability for a given district. To do this we fit a linear mixed-effects model using the ‘nlme’ library in R (Pinheiro *et al* 2019) including a random intercept for the district to account for correlated errors between time intervals

$$S_D = \beta_0 + \beta_1 W_D + \beta_2 B_D + \beta_3 F_D + I_D + \varepsilon_D \quad (7)$$

where S_i is the year-to-year production stability of district D , β_0 is the intercept, β_1 , β_2 and β_3 are the regression coefficients for asynchrony within crops, district level asynchrony between crops and farm level asynchrony between crops, respectively, I_i is the random intercept for each district D and ε_D is the error term.

To assess distribution of the response variable, we used the ‘fitdistrplus’ package in R (Delignette-Muller and Dutang 2015). Production stability was clearly log-normally distributed ($\Delta AICc$ of -2 or less compared to a normal distribution). Once we had established this relationship between asynchrony and stability, we investigated the effect of having a greater number of different farms (diverse producers) growing the same crop on asynchrony within crops at the district level and the effect of the number of crops grown in a district on asynchrony between crops. We note that between 0 and 1, asynchrony is theoretically expected to increase with the number of farms and crops in a non-linear fashion, but here we estimate the empirical form of that relationship for our study region. Within each district we randomly and iteratively added farms from 1 to 500 and for each number of farms, we derived asynchrony within crops for each district as described above. Likewise, within each district, we randomly and iteratively added crops and derived asynchrony between crops as described above. To account for stochasticity in the sampling of farms and crops, we repeated this procedure ten times and derived mean values and standard deviation.

To assess the robustness of our results, we repeated all empirical analyses with splitting the data into two time intervals of only eight years (1999–2006, 2011–2018) and with a different function to time-detrend production data. Therefore, we used a loess function with a smoothing parameter of 0.75 to regress annual total or crop-specific calorie production on year for each time interval (Mehrabi and Ramankutty 2019).

2.2. Simulation

To explore the impacts of specialized farming on the stability of production, we simulated different management strategies in a model landscape. Here we simulate the effect of temperature and precipitation

on crop-specific suitability as a proxy for production (Zabel *et al* 2014), and use this to derive aggregated measures of asynchrony within and between crops for a set of management strategies. We did not attempt to simulate a particular geographical region but to investigate the general effects of random climate variability and different landscape management strategies on asynchrony within and between crops. While this is a simplification to illustrate general patterns, future studies could include more realistic climate dynamics including extreme events.

We first initialized a landscape with 5×5 , 9×9 or 33×33 pixels. Then, we randomly selected one to ten crops that were also present in the empirical analyses (table S1), and allocated them with equal area shares according to one of three landscape management strategies: specialized, fragmented and diversified. To create the specialized and fragmented landscape, we used the 'nlm_mdp' function in the 'NLMR' package with a roughness of 0 (clumped) and 1 (fragmented), respectively (Sciaini *et al* 2018). This function calculates the relative displacement (0–1) from a randomly selected pixel (figure S1). We then allocated the given number of crops with equal weights using the 'util_classify' function in the 'landscapepetools' package (Sciaini *et al* 2018). For the diversified landscape, we allocated each crop equally to each pixel.

We kept the crop distribution constant while we simulated annual temperature and precipitation for ten years with fixed mean values (20°C and 600 mm), were all crops considered showed relatively high suitability values. Each year we randomly sampled temperature and precipitation from a uniform distribution with the maximum deviation from the mean value set to 15°C and 450 mm, respectively. To simulate climate gradients, we used the 'nlm_mdp' function with a roughness of 0 (clumped) and transformed the resulting range (0–1) to the actual temperature and precipitation range (mean \pm deviation). We note that we implicitly assumed homogeneity regarding other landscape variables that would be relevant here (e.g. slope and soils).

For each pixel and allocated crop we computed annual temperature and precipitation related suitability using general crop-specific climate response functions that associate a suitability index from 0 (not suitable) to 1 (highly suitable) to each temperature or precipitation value (Zabel *et al* 2014) (figure S2). We selected the minimum of the resulting suitability values per crop (for either temperature or precipitation), as suitability is restricted by the lowest suitability in either. We used this suitability for crop growth as a simple proxy for production. We calculated crop-specific asynchrony between all pixels where a given crop was cultivated and averaged it over all crops to estimate asynchrony within crops (no weighting was needed because crop shares were similar). Next, we

calculated the total annual production of all pixels for each crop to derive asynchrony between crops as described above.

For each combination of landscape size, number of crops and management strategy ($n = 90$), we repeated the simulation for 100 times and calculated mean and standard deviation of the respective asynchronies within and between crops.

We used the statistical software R 3.5.1 (R Core Team 2019) run via RStudio (RStudio Team 2015) for analyses and simulations.

3. Results

3.1. Empirical analyses

Year-to-year production stability was closely related to supply side shocks, with the higher the stability the lower the frequency of shocks (figure S3). Year-to-year production stability, asynchrony within crops and district level asynchrony between crops were generally lower in Eastern Germany (figures 2 and S4). Farm level asynchrony between crops was particularly high in districts in Hesse, North Rhine-Westphalia and Baden-Wuerttemberg.

Both asynchrony within and between crops were positively related with production stability (figures 3 and S5; tables 2 and S2). However, unlike the effect of asynchrony between crops in a district, which had marked stabilizing effects on district level production, the effect of asynchrony between crops in a farm on production stability at the district was relatively small and highly uncertain (even though these effects were stabilizing for individual farm level stability, figure S7). We conclude that production stability is dependent on both asynchronous production within the same crops grown by different farms and between different crops at the district level, while between crop asynchrony effects at the farm level are less important for stabilizing district level production.

We also find that having multiple farms growing the same crop increased asynchrony within crops and maximum values were achieved with around 100 farms or more (figures 4(a) and S6(a)). Increasing the number of cultivated crops in a district increased asynchrony between crops (figures 4(b) and S6(b)). However, this effect saturated for the ten crops studied here and after seven crops the effect slightly decreased. We conclude that asynchronous production within the same crops and between different crops are increased when the number of producers growing the same and the number of crops is increased, respectively, but that these effects saturate.

3.2. Simulation

In the simulation we found that increasing crop diversity (number of crops) reduces asynchrony within crops in specialized landscapes, a negative

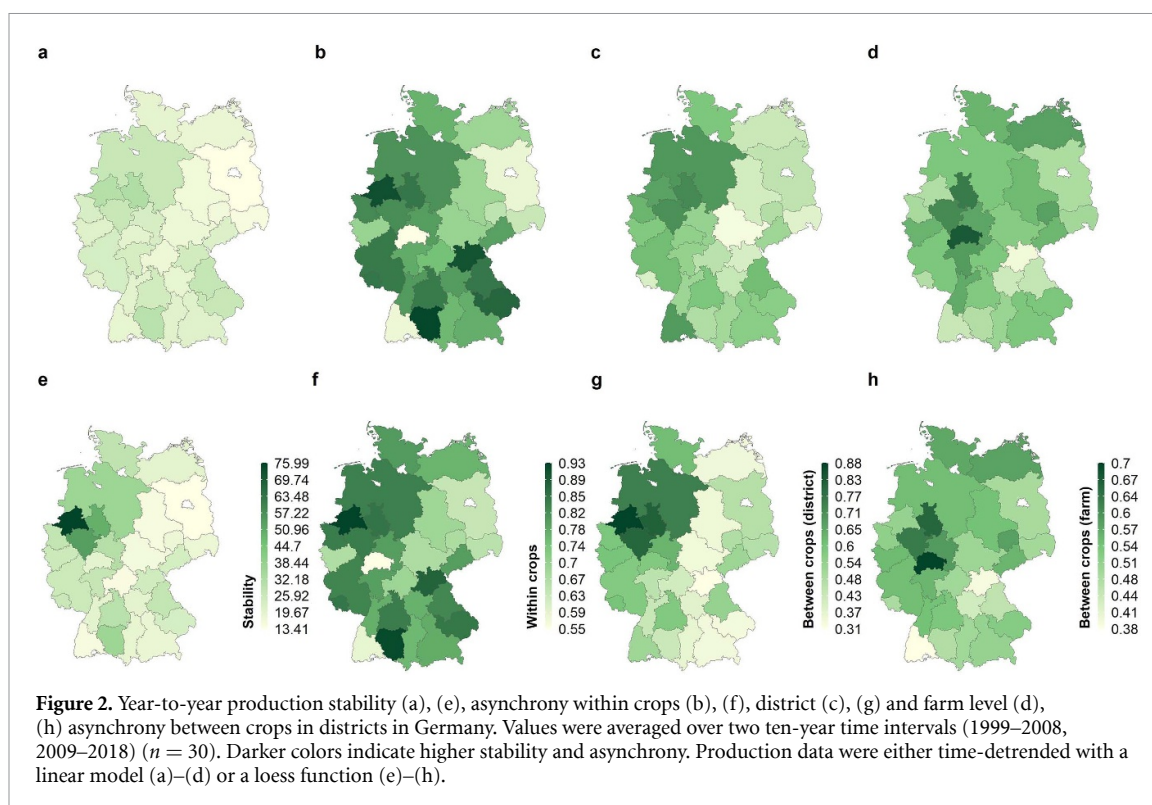


Table 2. Determinants of year-to-year production stability in districts in Germany for two ten-year time intervals (1999–2008, 2009–2018) ($n = 60$). Production stability was log-transformed. Regression coefficients are shown for fixed effects included in the linear mixed-effects models and indicate the change of year-to-year production stability by one unit of change in asynchrony within and between crops. Production data were either time-detrended with a linear model or a loess function. R^2 marginal refers to the variance explained by the fixed effects, R^2 conditional to the total variance explained including the random effect for the district. Due to the small sample size the Akaike's information criterion with small-sample correction (AICc) was computed.

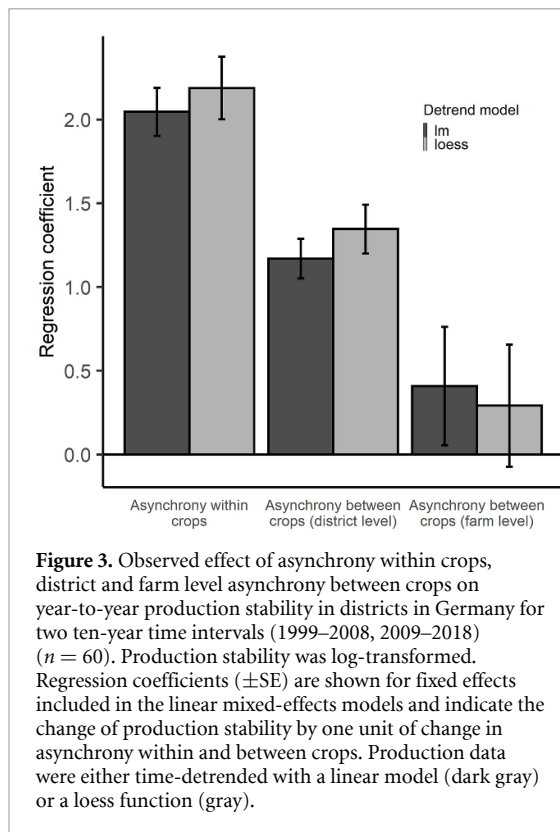
Variable	Linear model				Loess function			
	Estimate (SE)	DF	T	p -value	Estimate (SE)	DF	T	p -value
Intercept	0.3 (0.22)	29	1.35	0.19	0.62 (0.23)	29	2.73	0.01
Asynchrony within crops	2.05 (0.14)	27	14.27	<0.0001	2.19 (0.19)	27	11.74	<0.0001
Asynchrony between crops (district level)	1.17 (0.12)	27	9.92	<0.0001	1.35 (0.15)	27	9.27	<0.0001
Asynchrony between crops (farm level)	0.41 (0.35)	27	1.15	0.26	0.29 (0.36)	27	0.8	0.43
R^2 marginal	0.85	—	—	—	0.87	—	—	—
R^2 conditional	0.93	—	—	—	0.9	—	—	—
AICc	−63.03	—	—	—	−32.54	—	—	—

effect that is not present in diversified landscapes (with redundancy in production portfolios across space) (figure 5). In contrast, regardless of the management strategy, crop diversity consistently increased asynchrony between crops, with the effect decelerating after around six crops were added from our crop selection. This result was most convergent in larger landscapes. We conclude from these results that increasing crop diversity has stabilizing benefits regardless of the management strategy, due to increases in between crop asynchrony, but these benefits are constrained due to decreasing within crop asynchrony if landscapes are specialized. To maximize

the benefits of crop diversity, different crops have to be produced and landscapes must be diverse in their production portfolios.

4. Discussion

In the light of climate change, pest outbreaks, rising demands for food (Challinor *et al* 2014, Valin *et al* 2014) and the limits to food production (Seppelt *et al* 2014), increasing the resilience of agricultural systems is key to reduce supply side variability and shocks. Our results suggest that both asynchrony within and



between crops are important mechanisms to reduce variability and thus to stabilize agricultural production. Moreover, by using simulations, we identify trade-offs between increasing crop diversity and production stability that are introduced in highly specialized production landscapes.

Asynchrony within crops grown at different farms is a key mechanism to increase the year-to-year stability of agricultural production. This is because having more farms within a district leads to higher asynchrony within crops. This suggests that, despite high levels of conventional intensification in Germany (Václavík *et al* 2013, Levers *et al* 2018), farms do show heterogeneity, for example regarding decision making, biophysical and social conditions. However, in Eastern Germany for example, asynchrony within crops is generally lower than other regions, possible due to the emergence of relatively large, specialized and similar farms during the former German Democratic Republic (Bauerkämper 2004, Niedertscheider *et al* 2014, Dittrich *et al* 2017).

We found that asynchrony between crops is another important mechanism to stabilize agricultural production. While at the national level between crop asynchrony shows a high positive association with year-to-year production stability (Egli *et al* 2020), the effect of district level asynchrony between crops was weaker than the effect of asynchrony within crops in our study. Moreover, the positive effect of crop diversity turns slightly negative after seven crops,

indicating that some crops react similarly to variability and disturbances and thus experience similar year-to-year production dynamics. This pattern was also observed in the simulation. Nevertheless, our results show strategies to stabilize agricultural production also need to account for the asynchrony between crops.

The effect of farm level asynchrony between crops on stabilizing district level production was relatively small and highly uncertain. However, farm level asynchrony between crops is positively related to year-to-year production stability at the farm level (figure S7), which is likely important for farm viability, in particular in the light of the extreme droughts in 2018–2020, as well as increasing economic pressure and market fluctuations (Macholdt and Honermeier 2017). In addition our simulation indicates that diverse landscapes also avoid trade-offs between asynchrony within and between crops. In specialized landscapes, crop diversification negatively affects asynchrony within crops, because crop-specific spatial extent and heterogeneity are reduced.

Our findings clearly suggest that food system homogenization is risky (Ramankutty *et al* 2018, Nyström *et al* 2019) and production systems should be reversed by diversification from the field to the landscape scale (Lin 2011, Wanger *et al* 2020). Such large-scale perspective on managing farmland landscapes is a promising leverage. On the one hand, crop diversification at the farm level increases asynchrony between crops at both the farm and landscape level, without constraining asynchrony within crops. On the other hand, providing opportunities to incentive more farms in total, and more diversified farms could be a promising avenue to address asynchrony within crops and to avoid further homogenization of farms across large scales (with important implications for land consolidation policies). While the direct payments of the Common Agricultural Policy of the European Union have favored large-scale farms, greening measures and the programs related to rural development, for example subsidies for crop diversification and young farmers, could support such changes (Pe'er *et al* 2016, 2020).

Given the multiple challenges agriculture faces today, a fundamental transformation is needed to achieve productive, sustainable and resilient agricultural systems (Bailey *et al* 2015, Campbell *et al* 2017, Kremen and Merenlender 2018, Seppelt *et al* 2020). Diversification should be considered as a clear option for increasing and stabilizing production, while reducing negative externalities of conventional intensification (Beckmann *et al* 2019), such as the erosion of long-term resilience (Rist *et al* 2014). We think there are likely to be additional benefits to farmers and society. For example, intercropping has been found to increase both productivity and stability (Raseduzzaman and Jensen 2017, Martin-Guay *et al* 2018), and

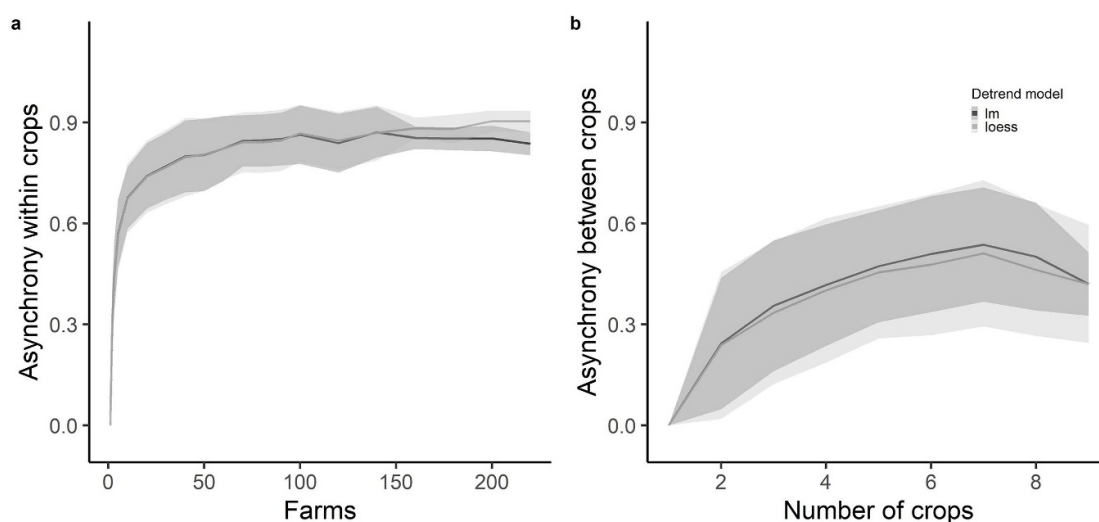


Figure 4. Effects of adding farms (a) and crops (b) on asynchrony between and within crops, respectively, in districts in Germany for two ten-year time intervals (1999–2008, 2009–2018). Within each district and number of randomly selected farms or crops asynchrony within and between crops was calculated. Lines show mean values over all districts and time intervals ± 1 standard deviation (shaded areas), only including estimates with at least three districts. Production data were either time-detrended with a linear model (dark gray) or a loess function (gray).

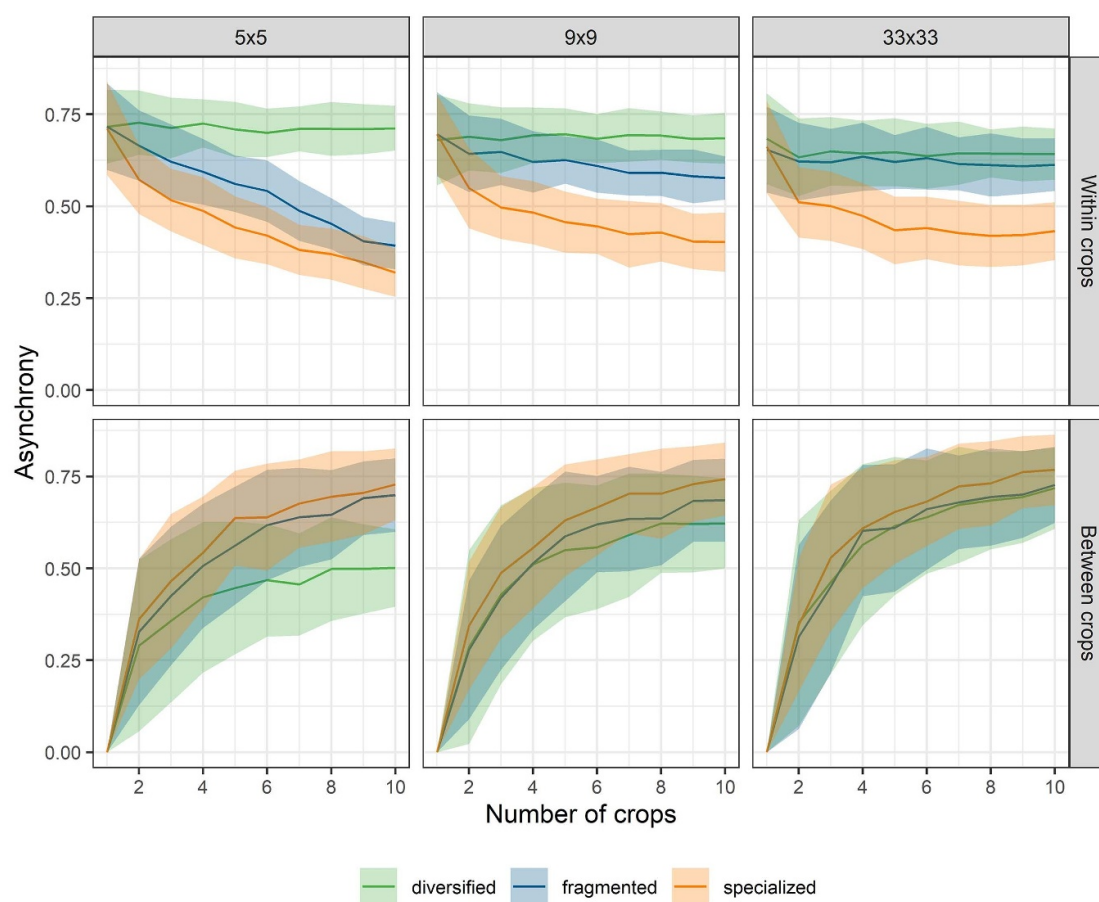


Figure 5. Simulated effect of increasing crop diversity (number of crops) in model landscapes of varying size and under different management strategies (diversified, fragmented, specialized) on asynchrony within and between crops. During each simulation (ten years), crop distribution was held constant while a random temperature and precipitation gradient was randomly simulated each year. Annual climate was used to derive crop-specific suitability and asynchrony within and between crops. Lines show mean values over all 100 repetitions ± 1 standard deviation (shaded areas).

diversification at multiple scales can promote biodiversity and ecosystem services (Kremen and Miles 2012, Kremen and Merenlender 2018). Therefore, integrated approaches at multiple scales could potentially achieve higher production and stability with lower environmental impacts than today (Seufert et al 2012, Iverson et al 2014, Tschardt et al 2015, Muller et al 2017, Knapp and van der Heijden 2018, Sirami et al 2019).

5. Conclusion

Our study suggests that both asynchrony within and between crops are important mechanisms to stabilize agricultural production. Cultivating the same crops across distinct farms increases asynchrony within crops, while increasing the number of crops grown enhances asynchrony between crops. A combination of crop and landscape diversification further helps avoids trade-offs between these two stabilizing mechanisms. Our findings demonstrate a need for integrated management approaches from the farm to the landscape level to foster resilient farming systems in the light of climate change, rising demands for agricultural products and risks of agricultural specialization. Further studies could incorporate other aspects of asynchrony and its underlying drivers, for example related to growing crops in multiple seasons, differences in agricultural management, farms and disturbance types (Reidsma et al 2010, Cottrell et al 2019, Egli et al 2020). Parametrizing computer simulations for different regions and future climate scenarios is needed to understand these mechanisms in the context of climate change. Further studies could also investigate the role of trade in stabilizing domestic food supply (Kummu et al 2020). Uncovering a wide range of mechanisms working at different levels of organization, scales and time horizons will be needed to identify comprehensive pathways towards productive, sustainable and resilient farming systems (Battisti and Naylor 2009, Valin et al 2014, Lesk et al 2016, Weise et al 2020).

Data availability statement

For data protection reasons, the farm level data is only available at the Johann Heinrich von Thünen-Institut, Braunschweig, Germany. All other data that support the findings of this study are openly available at the following URL: <https://github.com/legli/AsynchronyGermany>.


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
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