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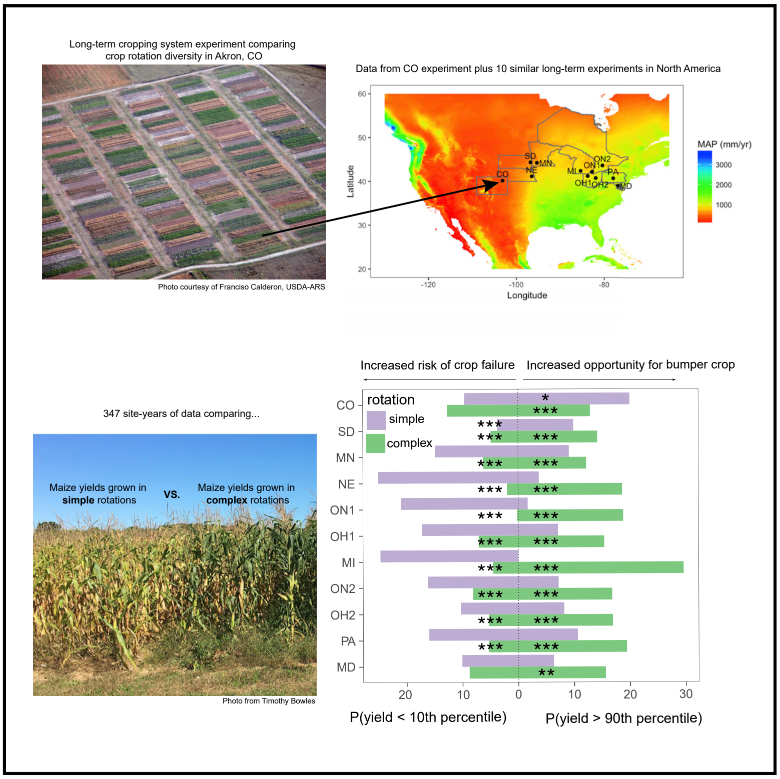
Long-Term Evidence Shows that Crop-Rotation Diversification Increases Agricultural Resilience to Adverse Growing Conditions in North America

Graphical Abstract



Highlights

- 347 site-years of yield data from 11 experiments show benefits of diversification
- Rotation diversification increased maize yields under putative droughts
- More diverse rotations also showed yield benefits across all growing conditions
- Diverse rotations accelerated maize yield gains over time

Authors

Timothy M. Bowles, Maria Mooshammer, Yvonne Socolar, ..., Marty R. Schmer, Jeffrey Strock, A. Stuart Grandy

Correspondence

timothy.bowles@berkeley.edu

In Brief

Diversifying cropping systems improves environmental health and has the potential to reduce risk from climate-change-related threats, but empirical evidence remains sparse. In this study, we found that maize yields were higher during adverse weather, including droughts, when maize was grown as part of a more diverse rotation. Rotation diversification also increased maize yields over time and under better growing conditions. Policies that support more diversified cropping systems could help reduce risk from increasingly stressful weather.

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Long-Term Evidence Shows that Crop-Rotation Diversification Increases Agricultural Resilience to Adverse Growing Conditions in North America

Timothy M. Bowles,[1,16,*] Maria Mooshammer,[1] Yvonne Socolar,[1] Francisco Calderón,[2] Michel A. Cavigelli,[3] Steve W. Culman,[4] William Deen,[5] Craig F. Drury,[6] Axel Garcia y Garcia,[7] Amélie C.M. Gaudin,[8] W. Scott Harkcom,[9] R. Michael Lehman,[10] Shannon L. Osborne,[10] G. Philip Robertson,[11] Jonathan Salerno,[12] Marty R. Schmer,[13] Jeffrey Strock,[14] and A. Stuart Grandy[15]
[1]Department of Environmental Science, Policy, and Management, University of California, Berkeley, Berkeley, CA 94720, USA
[2]USDA-ARS Central Great Plains Research Station, Akron, CO 80720, USA
[3]USDA-ARS Sustainable Agricultural Systems Laboratory, Beltsville, MD 20705, USA
[4]School of Environment and Natural Resources, Ohio State University, Wooster, OH 44691, USA
[5]Department of Plant Agriculture, University of Guelph, Guelph, ON N0G2K0, Canada
[6]Agriculture & Agri-Food Canada, Harrow, ON N0R1G0, Canada
[7]Department of Agronomy and Plant Genetics and Southwest Research and Outreach Center, University of Minnesota, Lamberton, MN 56152, USA
[8]Department of Plant Sciences, University of California, Davis, Davis, CA 95616, USA
[9]Department of Plant Science, Pennsylvania State University, University Park, PA 16802, USA
[10]USDA-ARS North Central Agricultural Research Laboratory, Brookings, SD 57006, USA
[11]W.K. Kellogg Biological Station and Department of Plant, Soil and Microbial Sciences, Michigan State University, Hickory Corners, MI 49060, USA
[12]Department of Human Dimensions of Natural Resources, Colorado State University, 1480 Campus Delivery, Fort Collins CO 80523, USA
[13]Agroecosystem Management Research Unit, USDA-ARS, Lincoln, NE 68583-0937, USA
[14]Department of Soil, Water and Climate and Southwest Research and Outreach Center, University of Minnesota, Lamberton, MN 56152, USA
[15]Department of Natural Resources and the Environment, University of New Hampshire, 56 College Road, Durham, NH 03824, USA
[16]Lead Contact
*Correspondence: timothy.bowles@berkeley.edu
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SCIENCE FOR SOCIETY A grand challenge facing humanity is how to produce food for a growing population in the face of challenges from climate change while also improving environmental sustainability. Prior research has shown the potential for more biodiversified farming systems to provide substantial environmental benefits, but to what extent they also reduce risks from stressful weather conditions likely to occur more often in the future remains unclear. We use the most comprehensive synthesis to date of crop rotation, or the diversity of crops through time, to show that increasing rotational diversity in maize-based North American cropping systems improves maize yields over time and across all growing conditions, including during droughts. Agricultural systems that increase reliance on biodiversity can reduce risks from climate-change challenges and should be considered an essential component of meeting the grand challenge.

SUMMARY

A grand challenge facing humanity is how to produce food for a growing population in the face of a changing climate and environmental degradation. Although empirical evidence remains sparse, management strategies that increase environmental sustainability, such as increasing agroecosystem diversity through crop rotations, may also increase resilience to weather extremes without sacrificing yields. We used multilevel regression analyses of long-term crop yield datasets across a continental precipitation gradient to assess how temporal crop diversification affects maize yields in intensively managed grain systems. More diverse rotations increased maize yields over time and across all growing conditions (28.1% on average), including in favorable conditions (22.6%). Notably, more diverse rotations also showed positive effects on yield under unfavorable conditions, whereby yield losses were reduced by 14.0%–89.9% in drought years. Systems approaches to environmental sustainability and yield resilience, such as crop-rotation diversification, are a central component of risk-reduction strategies and should inform the enablement of policies.

INTRODUCTION

To avoid widespread disruptions of food supplies in the future,[1] agricultural production must grow more resilient to climate variability while simultaneously meeting food security goals.

However, the paradigm of input intensification and specialization that has contributed to large yield gains in staple crops has also led to dramatic declines in crop diversity,[2,3] which is recognized for field-level benefits such as improving crop yields, soil health, and input use efficiency,[4] and at the national scale for increasing the stability of food production.[5] In regions such as the central US, where intensive cropping of grains and oilseeds predominates, at least 90% of the 55 million ha in production is composed of maize and soybean, and up to ~30% contains just maize or soybean for at least two consecutive years.[6–8] To sustain yields in such biologically simplified cropping systems, substantial inputs of agrochemicals supplant services traditionally supplied by biodiversity,[9–11] leading to many well-documented tradeoffs, such as soil degradation and water pollution.[12,13]

Specialization in maize and soybean production, together with sensitivity of rain-fed crop production to climatic factors, makes regions such as the central US increasingly sensitive to extreme weather events such as drought.[14,15] For example, the 2012 drought in the central US reduced maize yields by ~25% and caused significant related water-quality issues.[16] Totaling $18.6 billion, 2012 was also the US government's most expensive year for crop-insurance payouts.[17] Without risk-reduction strategies that increase climate-change adaptation, indemnity costs will continue to rise given projections of more frequent and intense heat waves and altered precipitation patterns.[18] Policies to enhance agricultural resilience, and the information to support policy development, are thus urgently needed.

Crop diversity is increasingly recognized for its potential to reduce risk from climate-change-related threats.[5] At the farm scale and beyond, crop diversity reduces economic and production risks due to the "portfolio effect," whereby different crops respond differently to stress. Few studies have addressed another potentially important form of risk reduction at the field scale: how crop diversity affects yield resilience of individual crops across time, including resistance to yield declines in the face of stress.[19] Farmers have used temporal crop diversity, e.g., crop rotation (the sequence of crops grown over time), for millennia to improve yields by regenerating soil health[20,21] and breaking cycles of herbivores, weeds, and pathogens.[22] In the US, such well-studied benefits of crop rotation often lead to 5%–10% higher maize yields on average in even just a two-crop rotation of maize and soybean,[6] despite the monoculture system typically requiring more inputs.[23] Going beyond average yield increases, far less is known regarding how diversified crop rotations (beyond just two crops) affect yield resilience,[6,11,22,24–26] especially in intensive agricultural systems in which inputs supplant some of the functions that rotations provide in low-input systems.[27] In diversified rotations, increased yield resilience to drought and other types of stressful growing conditions may result from improved soil properties, such as increases in soil water capture and storage and abundance of beneficial soil microbes. One study recently showed 7% higher maize yields during hot and dry years in a diversified five-crop rotation than in a maize-soybean rotation,[24] but whether this is a general effect of rotation diversification or a site-specific effect due to particular environmental conditions or crop-rotation composition is not known.

It is important to examine other aspects of how diversified crop rotations perform in tandem with yield resilience in order to assess potential tradeoffs or synergies. If, for example, yield benefits of diversified rotations are mainly concentrated in more stressful growing conditions, there may be opportunity costs to adopting them in ideal growing conditions. If, on the other hand, improvements in soil with diversified rotations contribute to greater yield increases over time than those provided by simplified systems, they may help to close yield gaps as yield potential increases with improved genotypes.[28] Although yield gains with crop rotation are well known, whether these gains are mainly due to short-term effects or whether they continue to increase over time remains an important knowledge gap.

To assess how diversified rotations can help agriculture adapt to increasingly stressful growing conditions while contributing to sufficient food production, we require analysis of long-term yield trends encompassing a range of crop rotations, key management practices such as fertilization, and climate and soil type. Although such integrated knowledge has urgent policy relevance, it has been hindered by a lack of adequate long-term agroecosystem research networks that synthesize cross-site results. Here, we evaluate the impacts of crop-rotational diversity on several aspects of maize yields on a greater spatiotemporal scale than has previously been done. In particular, we consider how diversified maize rotations affect yield responses to stressful conditions, an essential element of agroecosystem resilience,[19] together with other aspects of cropping system performance, including yields under more productive conditions and yield trends over time. We focus on maize responses in maize-based rotations because it is one of the most important cash crops in the world, and disruptions to maize yields due to climate-change-driven heat waves and droughts could lead to widespread impacts on food production.[1]

We obtained historic maize yield data from 11 long-term experiments spanning a wide precipitation gradient across the US and Canada (Figure S1), much of which corresponds to an east-west productivity gradient.[29] We compared maize monoculture or two-crop rotations against more diverse rotations (Table 1), comprising 347 site-years in total, to address two main questions: how crop-rotational diversity in intensively managed systems affects (1) yields in stressful and productive growing conditions and (2) changes in yields over time. These sites represent the major maize-producing regions of the US and Canada. To quantify and compare changes associated with increasing crop-rotational diversity, we calculated a rotational complexity index (RCI) for each rotation at each site,[20] which allows for testing the extent to which rotation diversification leads to yield resilience and yield gains over time. We used an environmental index (EI), defined as the mean detrended yield across all rotations at a given site in a given year, as an indicator of growing conditions in which low EI values signal poor growing conditions.[11,30] This approach is often used in multilocation crop variety trials because it can provide a localized indicator of growing conditions that account for differences in factors such as genotypes, soils, and management that vary across sites and over time. Since this approach does not indicate the cause of stressful or productive growing conditions, we complemented this analysis by comparing yields in diversified versus simplified rotations

Table 1. Characteristics and Management of Included Long-Term Experiments on Crop-Rotational Diversity in the US and Canada

Site	Latitude, Longitude	MAP (mm $year^{-1}$)	Lowest Diversity Rotation (RCI)	Highest Diversity Rotation (RCI)	Total Years of Data	Nitrogen Fertilization[a] (kg N ha^{-1}) and Tillage
Akron, Colorado (CO)	40.2, −103.1	406	C-F-W (2.45)	C-M-Pea-W (4)	23	synthetic N (variable: soil test); NT
Brookings, South Dakota (SD)	44.4, −96.8	582	C-S (2)	eight rotations with four crops (4)	16	synthetic N (~73); NT
Lamberton, Minnesota (MN)	44.2, −95.3	664	C-S (2)	C-S-O/A-A (4)	27	zero; synthetic N (2-year: 31–58; 4-year: 96–131); organic N (manure, 2-year: 264; 4-year: 298); CT
Mead, Nebraska (NE)	41.1, −96.5	777	C (1)	C-O/rc-Sorg-S (4.47); C-S-Sorg-O/rc (4.47)	31	zero; synthetic N (90, 180); NT
Woodslee, Ontario (ON1)	42.2, −82.7	849	C (1)	C-O/A-A-A (3.46)	58	zero; synthetic N (129); CT
Hoytville, Ohio (OH1)	41.2, −83.8	863	C (1)	C-O-P (3)	51	synthetic N (202); NT, RT, CT
Hickory Corners, Michigan (MI)	42.4, −85.4	911	C (1)	C/rc + rye-S-W/rc + rye (3.87)	16	zero; CT
Elora, Ontario (ON2)	43.6, −80.4	927	C (1)	C-C-O/rc-B/rc (4)	37	synthetic N (160–180); RT, CT
Wooster, Ohio (OH2)	40.8, −81.9	947	C (1)	C-O-P (3)	52	synthetic N (202); NT, RT, CT
Rock Springs, Pennsylvania (PA)	40.7, −78.0	996	C (1)	C-O/W-rc/tim-rc/tim (4)	17	synthetic N (variable: soil test) and organic N (manure); CT
Beltsville, Maryland (MD)	39.0, −76.9	1074	C/rye-S/v (2.83)	C/rye-S-W-A-A-A (5.48)	19	organic N (variable: animal and green manure); CT

Abbreviations are as follows (lowercase abbreviations indicate cover crops): A, alfalfa; B, spring barley; C, maize; F, fallow; O, oats; P, pasture (mixed grass, alfalfa, or clover); rc, red clover; rye, cereal rye; S, soy; Sorg, sorghum; tim, timothy; v, hairy vetch; W, winter wheat; CT, conventional till; NT, no till; RT, reduced till; MAP, mean annual precipitation; RCI, rotational complexity index (see Experimental Procedures for calculation).
[a]Synthetic nitrogen fertilization rates are for the maize year of the rotation.

during putative drought years identified with crop-insurance indemnity data. Analyses employing Bayesian multilevel statistical models (the conceptual scheme of which is given in Figure S2) and probability analysis allowed us to test the hypotheses that more rotationally diverse systems provide yield benefits across a broad range of growing conditions, including drought events, while also enhancing yields over time in intensive grain systems.

RESULTS

Crop-Rotational Diversity Increases Maize Yields across Growing Conditions

Crop-rotational diversity increased maize yields in 9 of the 11 sites when site-specific differences were accounted for, such that the two most arid sites showed no changes in yields (Figure 1A). Notably, model estimates incorporating both the site-level varying effects and the global mean (95% credibility interval for RCI global mean: [−1.93, 1.97]) reflect how crop-rotational complexity affected maize yields across sites contrasting in climate and soil conditions (Table 1) (throughout the text and figures, state and province abbreviations, numbered when there is more than one site in a state or province, are used as site names; see Table 1 for definitions). Where site-specific RCI effects were credibly greater than zero, maize yields were 7.7% (ON2) to 80.5% (ON1) higher in the most diverse rotations than in the simple rotations, with an average increase of 28.1%. Crop-rotational diversity also affected how maize yield responded to growing conditions (Figure S3), as inferred from model-estimated effects across the EI. In two sites, rotational diversity increased the capacity of maize to take advantage of favorable growing conditions, as shown by positive effects in the site-level diversity (RCI) × environment (EI) interaction (Figure 1B; 95% credibility interval for RCI × EI global mean: [−0.05, 0.06]). Positive, but not statistically clear, interactions were estimated in an additional six sites. The largest interaction effect was estimated at NE with a value of 0.089 (95% credibility interval: [0.054, 0.123]). This means that, as growing conditions improve, for each unit increase in EI of 1,000 kg ha^{-1}, maize in the maize-oats/red-clover-sorghum-soybean rotation (RCI = 4.47) has a predicted yield 398 kg ha^{-1} greater than that of the maize monoculture system.

Additionally, we assessed the impact of nitrogen fertilization on crop-rotation effects by considering fertilization treatments separately within sites. We found that these effects tended to be reduced with higher nitrogen (N) inputs but remained positive even in treatments with relatively high synthetic N (e.g., 180 kg N ha^{-1} in the high nitrogen treatment at site NE) (Figure S4). The one exception was MN, at which only the organic N fertilization treatment showed higher yields in more productive environments with more diverse rotations.

Crop-Rotational Diversity Accelerates Yield Increases over Time

Across all rotations, maize yields at all sites either increased over time or remained stable, with the exception of two sites, MI and CO (Figure S5). For the sites with increasing maize yields,

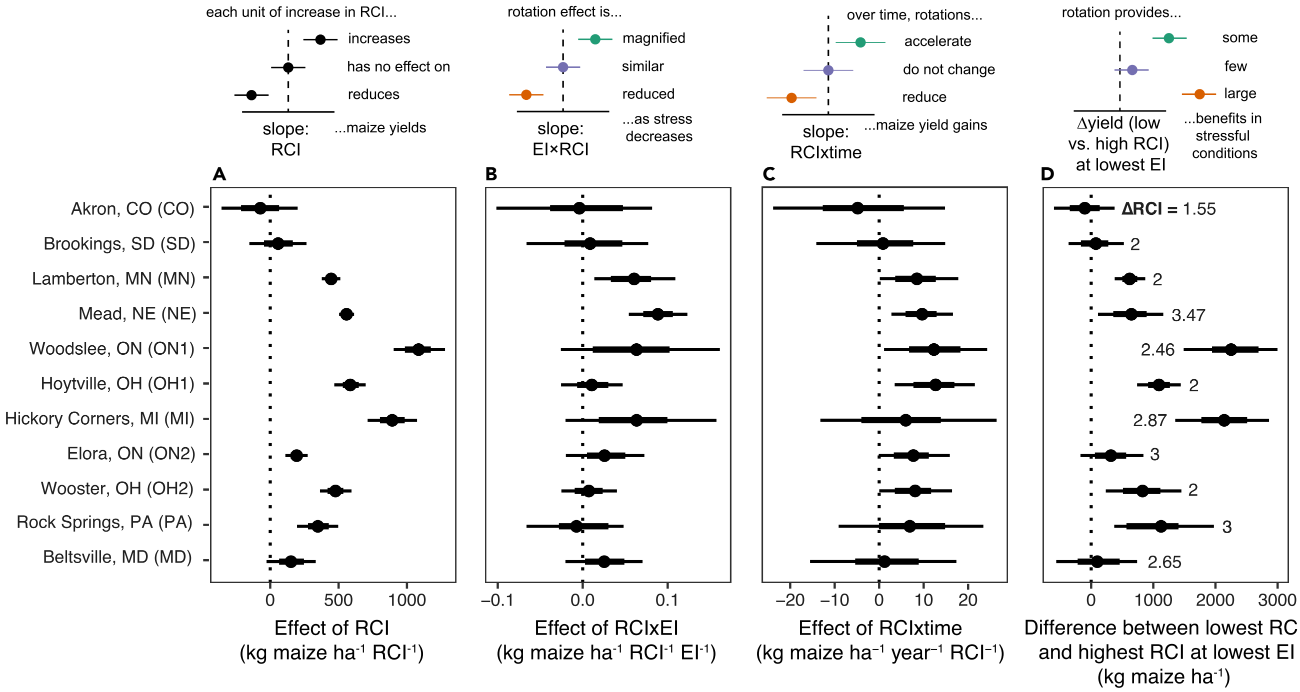

Figure 1. Effects of Crop-Rotational Diversity on the Productivity and Resilience of Maize Yields

Results from two multilevel regression models show that maize yields are predicted by rotational complexity index (RCI). Detrended maize yield is predicted by RCI (A) and RCI interacted across gradient of environmental conditions (environmental index [EI]) (B). To examine impacts over time, maize yield is predicted by RCI interacted with year (C). To examine relationships specifically under adverse growing conditions, RCI effects from the detrended maize yield model are plotted as differences in maize yields between the lowest and highest EI values within each site (D). Interpretations of results are shown above each panel, where colors correspond to hypotheses in Figure S2. The site-level effects displayed are additive of the global mean and the varying effect for the site. The dashed vertical line represents a slope of zero (A–C) or no difference in yields between low and high RCI rotations (D). Regression results are shown as site-level coefficient estimates from the multilevel model, adjusted for the mean fixed effect. Posterior mean estimates (points) are displayed in terms of their effect on maize yields with 95% (thin lines) and 68% (thick lines) credibility intervals. Coefficients and credibility intervals are drawn from the joint posterior distribution of the model.

increases ranged from 74 kg ha^{-1} $year^{-1}$ (OH1) to 210 kg ha^{-1} $year^{-1}$ (PA). Model estimates of the RCI × year interaction demonstrate how crop-rotation diversification altered these changes over time. Although the overall effect of RCI on yield over time was not different from zero (model estimate of 0.52 kg ha^{-1} $year^{-1}$; 95% credibility interval on global mean of RCI × year: [−1.45, 2.53]), rotation diversification did increase the rate of yield growth in 6 of the 11 sites (Figure 1C). This means that at six sites, yield growth was accelerated in the more diverse crop rotations, for instance, by 12.70 kg ha^{-1} $year^{-1}$ (95% credibility interval: [3.49, 21.51]) for each additional unit of RCI at OH1. Thus, compared with the continuous maize system (RCI = 1), predicted maize yields in the maize-oats-pasture rotation (Table S1, RCI = 3) increased an additional ~38.1 kg ha^{-1} $year^{-1}$ beyond the positive yield trend across all rotation systems at the site for a total of ~1,905 kg ha^{-1} for the ~50-year study.

Crop-Rotational Diversity Reduces Yield Loss and Risk of Crop Failure under Stress

One key measure of resilience in agricultural systems is the ability to withstand or recover from stress to avoid low yields or crop failure. Comparing yields in low- versus high-diversity rotations at the lowest EI, i.e., the most stressful growing conditions at a site, shows the contribution of crop-rotational diversity to resilience in the face of stressful growing conditions regardless of the specific stressor. More diverse rotations increased yields in 7 of the 11 sites during the most stressful conditions (Figure 1D), as estimated by the detrended maize yield model. These effects were greatest for sites with large differences in diversity among systems and/or treatments with no fertilizer inputs, e.g., ON1, where the maize-oats/alfalfa-alfalfa-alfalfa rotation had 2,252 kg ha^{-1} (95% credibility interval: [1,488, 2,998]) greater maize yield than the monoculture maize system under the most stressful growing conditions. However, the differences for well-fertilized systems were large as well, for instance, 1,091 kg ha^{-1} (95% credibility interval: [739, 1,442]) at OH1.

To identify the main causes of low yields, we used a US-county-level database of crop-insurance indemnity payments corresponding to each site, which serves as an annual record of what causes the agricultural shocks experienced by farmers.[17] We found that since 2000, drought and excess moisture were the most common reasons that farmers received insurance payouts in these counties (Figure 2A). During the worst putative drought years at each site (identified with the use of indemnity payments for the county in which the site is located; Table S3), maize yields were between

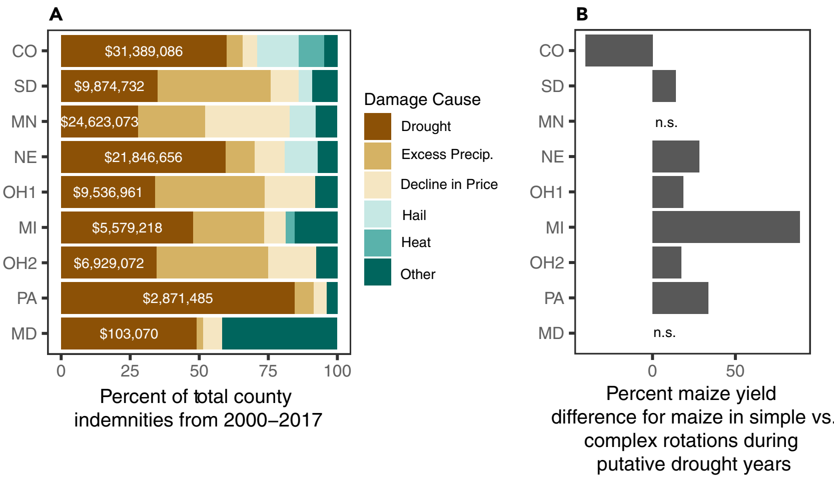

Figure 2. Causes of Low Yields and Yield Performance during Putative Drought Years

Sources of stress in each of the nine US sites are based on causes of crop-insurance indemnity payments at the county level (A). Total county-level insurance payments (2000–2017) are inset on the graph. The difference in yield for maize grown in simple versus complex rotations during the worst putative drought years at each site is shown in (B) (see Table S2). n.s., not significant.

14.0% and 88.9% higher in more diverse rotations than in simplified rotations (Figure 2B). At these sites, rotations thus confer substantially greater yield resilience by reducing the impact of drought on maize yield.

As a complementary approach to assess the potential of rotational diversity to lower the risk of crop failure as well as to increase the upside yield potential, we used historical yield data to compute probabilities of obtaining yields below the 10th percentile and above the 90th percentile within each site. Compared with simple rotations, more diverse rotations considerably lowered risks of yield failure (yields below the 10th percentile) at 8 of 11 sites and increased the upside potential of yield (yields above the 90th percentile) in most cases (Figure 3).

DISCUSSION

Responses to Adverse Growing Conditions

Analysis of 11 long-term experiments comprising 347 site-years and ~11,000 observations across the US and Canada showed that crop-rotational diversity can reduce the risk of low maize yields during stressful growing conditions, including droughts. Increasing crop-rotational diversity could thus help ameliorate the impacts of an increasing frequency and intensity of droughts and heat waves that will likely affect maize production in the future[18] and have subsequent impacts on farmers' livelihoods and the food system.[1] These results complement recent work showing how national-level crop diversity stabilizes food production[5] through a portfolio effect by quantifying how crop diversity at the field level can lead to more stress resistance (i.e., less intense yield declines during stressful conditions).

Several candidate mechanisms may explain greater stress resistance from rotational diversity. Water stress related to low precipitation and/or high vapor pressure deficits during heat waves is the most important abiotic factor limiting maize yields globally.[31,32] Changes in soil driven by rotational diversity could ameliorate water stress, such as even small increases in soil water storage capacity due to higher soil organic matter concentrations and porosity[33–36] and higher water retention with greater infiltration rates in more complex rotations.[37,38] Other changes due to rotation diversification, such as changes in soil physical structure that affect water dynamics,[39] crop rooting characteristics,[40] and soil microbial community composition and functioning,[41,42] could also play a role in stress resistance and require further research.

Yield Increases during Productive Growing Conditions and over Time

Rotation diversification also increased yields during more productive growing conditions, as shown by the positive RCI × EI interactions at most sites and higher probabilities of obtaining yields greater than the 90% percentile in diversified versus simple rotations at all sites but CO. These benefits extended beyond maize-soybean rotations, the dominant maize-based rotation in the US and Canada and the focus of most studies on maize yields in rotation (e.g., the studies by Seifert et al.[6] and Snapp et al.[26]). Together, this confirms our hypothesis that inputs such as N fertilizer cannot entirely substitute for the positive effects of crop rotation.[22,43] Synthetic N fertilization did diminish the positive RCI × EI interaction, but like others,[11] we did not find that maize yields in simple and diverse rotations converged in better growing conditions.

The acceleration of yield gains over time in more diverse rotations (i.e., positive RCI × time interaction at over half the sites) has important implications for maize productivity gains. Globally, world cereal yield growth rates have slowed dramatically since the 1960s, when they peaked at ~2.5% per year,[44] and have hovered between 1% and 1.5% in recent years. In the US, average yield gains of maize at a rate of 121 kg ha^{-1} year^{-1} were observed between 1987 and 2015 from state-level data,[45] similar to the range of increases we observed at sites with increasing yield trends (74–210 kg ha^{-1} year^{-1}). Although increases over time have mainly been attributed to breeding and technology,[28] we demonstrate a further role for crop-rotational diversity to increase yield trends. Relative to simplified rotations, diversified rotations increased maize yield gains by 16–34 kg ha^{-1} year^{-1} at six sites (as shown by the positive RCI × time interaction) or up to nearly one-third of the annual average yield gain in the US. Simplified rotations thus come with opportunity costs for maize yields that accumulate over time. Although increasing rotational diversity leads to less total maize production since maize is grown in fewer years, alternative cropping systems can optimize annual maize yields and ultimately support similar or higher levels of profitability for producers.[9]

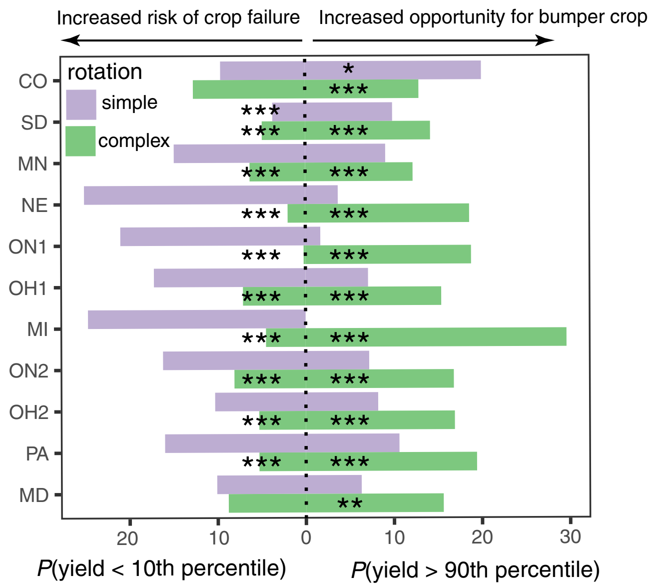

Figure 3. Probability Analysis of Low and High Yields in Simple versus Complex Rotations

Probabilities (%) of obtaining yields below the 10th percentile or above the 90th percentile according to probability densities from yield distributions within a site. The stars represent the significance level when comparing rotation treatment densities with a randomized distribution without treatment effects using bootstrapping iterations. Significant differences indicate that rotation diversity affects the probabilities of high and/or low yields compared with a randomized distribution at the 95% confidence level beyond the determined percentiles.

Improvements in soil health and reductions in plant pathogens, insect pests,[46] and weed pressure[47] have all been proposed as explaining the "rotation effect" on yield. Higher yields in more diverse rotations have been linked to enhanced soil N cycling and a greater supply of plant-available N during critical periods,[23,46,48] although this mechanism has been called into question.[49] As for responses to adverse conditions, we speculate that the beneficial effects of crop rotation over time and in productive conditions likely occurred through improvements in soil, such as increases in soil organic matter that occurred at several of the sites in this study[20,25,50–53] and/or possibly increases in abundance and diversity of beneficial soil biota.

Variation across Sites

Variation in crop-rotation benefits across these 11 sites may be due to a variety of factors, such as differences in inputs, the other crops in rotation, inherent soil quality, the magnitude of the yield gap, and climatic constraints. Since these differences are all implicitly included in the varying effects for sites included in the multilevel analyses, we cannot readily tease them apart, but we speculate here on the role of precipitation. The driest site, CO, with a mean annual precipitation (MAP) of 406 mm year^{-1}, lacked any positive yield benefit from crop-rotational diversity in this analysis, and the more diverse rotations at the second driest site, SD (582 mm year^{-1}), showed yield benefits only during recent putative drought years. At CO, the rotations with the highest RCI lacked a fallow period, and this could have negatively affected yields because of the reduced soil profile moisture recharge.[54] More diverse rotations did improve certain soil properties at these sites, e.g., increasing organic carbon in surface soil.[50,51] However, very dry conditions in these environments may overwhelm the capacity of improvements in soil to reduce yield losses. Especially at CO, water in the soil profile is not necessarily recharged between cash crops, so yields of maize depend strongly on the water use of the previous crop and summer precipitation during key growth stages.[55,56] In semi-arid environments with highly variable rainfall and potential for withering droughts, opportunity cropping based on soil moisture near the time of planting,[57] organic matter amendments,[58] alternative drought-resistant crops, retaining and increasing surface crop residues,[59] and other adaptive strategies with potential to enhance water availability[60] may be needed to supplement rotational diversity. Few benefits of rotational diversity for MD mirror previous studies,[61,62] perhaps because all rotation treatments include organic matter amendments, and even the lowest diversity rotation at the site contains two cash crops and two cover crops within 2 years.

There are several limitations for our study, including our ability to draw conclusions about the impact of crop diversity per se on the yield advantages shown here. Using rotation studies that follow established local practices precludes testing the effects of crop diversity versus the composition of crops in rotation. Using crop-insurance indemnity data to identify putative drought years estimates drought impacts, relative to producers' expectations in the local area, and could be complemented by also assessing local meteorological data. Other management changes, such as reductions in agrochemical inputs, occur alongside rotation diversification.[9] These limitations do not undermine our aim, which is to draw conclusions about the impacts of how crop diversity manifests in agricultural systems and involves decisions to optimize crop functional diversity, concurrent management changes, local conditions, and market opportunities.

Policy Implications

The central US continues on a trajectory toward greater homogenization of cropping systems and loss of crop diversity, including an increased prevalence of maize monocultures over the past two decades.[2,7,8] Although these decisions may be economical in the short term[63] for an individual farmer during periods of greater expected market returns for maize such as the biofuel boom,[8] monocultures and short two-crop rotations often require more non-renewable inputs than more complex rotations, which contribute to well-documented negative environmental consequences.[9,10,64] Here, we show that loss of crop-rotational diversity can undermine resilience to stressful conditions, possibly contributing to the observed increases in weather sensitivity of maize production in the central US.[14,15] US federal policies such as biofuel mandates and crop insurance help make shifts to monocultures more profitable than they otherwise would be, and other factors such as availability of markets for alternative crops and farmers' land tenure[65] constrain farmers' ability to expand crop-rotational diversity where it is low,[7] even when their values tend toward environmental stewardship.[66] For farmers and society to realize the potential benefits of crop-rotational diversity, policies and strategies are needed to help farmers overcome adoption costs, spur development of alternative markets for small grains and other crops, and/or support reintegration of crops and livestock.[66] For instance, lower crop-insurance premiums for diversified crop rotations and other practices that build soil health could incentivize farm management that reduces risks. However, several aspects of the US Federal Crop Insurance Program disincentivize crop diversification, such as temporary deductible and insurance cost increases when new crops are incorporated into rotations, long waiting periods to establish field-specific yield histories for new crops, and the lack of coverage availability for some alternative crops.[67]

Conclusions

This study shows that long-term crop-rotational diversity should be considered a fundamental component of risk reduction for climate-change adaptation that also allows for taking advantage of opportunities in favorable conditions and over time. Increasing crop diversity where highly specialized commodity production now predominates will be contingent on enabling factors across a range of socioeconomic levels.[66,68] Since soil properties that likely underpin many benefits of crop-rotational diversity only change slowly, this transition is urgent and should be supported for the long term.

EXPERIMENTAL PROCEDURES

Long-Term Experiments on Crop Rotation

This study involved 11 long-term rain-fed experiments on crop rotation that were located in the US and Canada (Table 1). These experiments included all those existing that could be identified, through literature searches (e.g., "crop rotation" AND yield AND [corn OR maize]) and personal communications from experts, and met our criteria in these two countries: at least three full rotation cycles of data, including maize monoculture or two-crop maize rotations as well as more complex rotations; rain-fed conditions; and no other treatments confounded with rotation (e.g., farming-system comparisons). Beyond maize, other crops in rotation varied depending on suitability for local conditions (Tables 1 and S1). Between 16 and 58 years of data were available from the experiments, and all had numerous complete rotation cycles. In all experiments, each phase of every rotation was present every year, so maize yields were measured from every rotation every year. Maize genotypes were the same across rotations within a given site in a given year. Site-specific management (e.g., genotypes, inputs, and field operations), can be found in site references (see Table S1). With one exception (Woodslee, Ontario), rotations were replicated in an experimental design similar to a randomized complete block design. Historical data on maize yields were requested from researchers at each experiment during spring and summer of 2016 and subsequently processed to allow for cross-site analyses.

Data Processing

Data from the first full rotation cycle of each experiment were removed so that only effects of "established" rotations are considered (n = 10,424). Maize yield data were then linearly detrended for each site separately. For the analysis of changes in yield over time, raw yields (i.e., not detrended) were used, and the first rotation cycle was included (n = 11,868). To estimate how crop-rotational diversity mediates yield responses to growing conditions, we calculated two indices. First, as a metric of stress, an EI was calculated for each year within each site as the mean detrended maize yield across all rotations at that site. Crop-breeding programs commonly use this approach for assessing environmental conditions across sites and years to compare yield stability,[30] and it is well suited to comparing crop rotations.[11] High EI values indicate productive growing conditions, whereas low EI values indicate stressful growing conditions. Second, an indicator of crop-rotational diversity was calculated for each rotation at each site. This RCI was defined as the square root of the number of cash and cover crop species (richness) in a rotation multiplied by the length of the rotation. These characteristics—richness and length—represent two fundamental properties that can be calculated for any rotation without subjectivity. The square root of their product was taken to remove the multiplicative relationship between richness and length, making the index comparable across the range of RCI values. The resulting RCI transformed the crop-rotation treatments into a variable that indicates the degree of diversification within a rotation, which could be compared across sites and used as a predictor variable in a linear model, as in other crop-rotation studies.[20] Including both the length of the rotation and the number of species assigns a higher RCI both to rotations that have more species per year, such as when cover crops are included, and to rotations that have one or more years of perennial crops, such as alfalfa. For example, a continuous maize monoculture would have an RCI of 1 (1 crop × 1-year rotation), whereas a 3-year rotation of maize, soybean, and wheat would have an RCI of 3 (square root of 3 crops × 3-year rotation).

Statistical Analysis

We used a Bayesian multilevel statistical modeling approach to estimate the association between maize yield, RCI, EI, and time. Specifically, Gaussian multilevel models were fitted to test how crop-rotational diversity mediated yield responses to growing conditions and how diversity affected yields over time. Since the data were hierarchically structured, with yield-in-plot-by-year observations clustered in the same block within the same site, varying (i.e., random) intercept effects were included for blocks and site. These effects control for unobserved differences in the outcome variable shared by blocks-within-site and sites.[69] To allow for different effects on yield across sites, varying slopes for site were included on all plot-level fixed effects in both models. These effects allow for a site-specific adjustment to the sample-wide mean fixed effects estimates. Maize yields were thus modeled as follows:

$$\text{yield\_detr}_{p,b,s} = \alpha + B_b + S_s + \beta_{[s]}\text{EI}_p + \gamma_{[s]}\text{RCI}_p + \delta_{[s]}\text{EI}_p \times \text{RCI}_p + \varepsilon_{p,b,s}, \quad \text{(Equation 1)}$$

$$\text{yield}_{p,b,s} = \alpha + B_b + S_s + \epsilon_{[s]}\text{year}_p + \gamma_{[s]}\text{RCI}_p + \zeta_{[s]}\text{year}_p \times \text{RCI}_p + \varepsilon_{p,b,s} \quad \text{(Equation 2)}$$

where, for Equation 1, yield_detr is the observation of detrended maize yield for one annual harvest in a given plot within block and site; $\alpha$is an intercept shared by all observations (i.e., grand or global intercept); B_b and S_s are varying intercepts for block-within-site and site, respectively; and $\beta_{[s]}$, $\gamma_{[s]}$, and $\delta_{[s]}$ represent the varying slope adjustments specific to each site, s, on the plot-level fixed effect coefficients for EI, RCI, and their interactions, respectively. Equation 2 estimates raw yield in a given plot, block, and site in a given year. α is an intercept shared by all observations (i.e., grand or global intercept); B_b and S_s are varying intercepts for block-within-site and site, respectively; and $\epsilon_{[s]}$, $\gamma_{[s]}$, and $\zeta_{[s]}$ represent the varying slope adjustments specific to each site, s, on the plot-level fixed effect coefficients for year, RCI, and their interactions, respectively.

All predictor variables were centered.[70] Model estimation was conducted in Stan[71] and called through R, which implements Hamiltonian Monte Carlo procedures. Model computation consisted of a 50,000-iteration burn-in and 50,000-iteration joint posterior sample. Conservative priors on coefficients of all fixed effects were specified as highly diffuse Gaussian densities with mean of zero and standard deviation of 1, i.e., weakly informative priors that improve inference.[72] Priors on all varying effects were specified as Gaussian and multivariate Gaussian with mean zero, respectively, and hyperparameters for standard deviations had half-Cauchy priors, a weakly informative prior suitable for standard deviations.[72] Varying-effects priors were specified to adaptively regularize varying intercepts (block, sites), varying slopes, and their correlations by constructing variance-covariance matrices with the LKJ onion method for correlation matrix distribution.[72] Models were coded according to McElreath[72] with the map2stan() function from the rethinking package in R. Diagnostics, including traceplots and kernel densities, confirmed adequate mixing. The number of effective samples (n_eff) was not substantially lower than the value of samples of the posterior distribution, indicating that the chains were efficient.[72] The Gelman-Rubin convergence diagnostic values were 1, indicating that the chains converged.[73] Plots of residual and predicted values within each site did not show any discernible pattern, indicating that the Gaussian model was appropriate. Posterior predictions from the models were overlaid on actual data and shown in Figures S3 (Equation 1) and S5 (Equation 2). Furthermore, we performed predictive posterior checks on both models by using the post-check() function in the rethinking package and found no systematic deviation between actual data and 95% credibility intervals for each case. A representative plot of this check is shown in Figure S6.

The two research questions—how crop-rotational diversity affects (1) yields in stressful and productive environments and (2) changes in yields over time—were evaluated through the focal coefficient estimates drawn from the joint posterior density of the statistical model (estimates reported with 68% and 95% credibility intervals).

As a complementary but separate analysis, probability densities of maize yield at each site were estimated via kernel density estimation with a Gaussian smoothing kernel and a smoothing bandwidth following.[24] We then conducted probability analyses of low and high yields in rotations at each site. To compare performance of simple versus diversified rotations within sites, we calculated three metrics based on the probability distribution of maize from pooled, within-site detrended data (i.e., including all rotations): (1) probability of high yields, defined as the estimated probability of achieving yields above the 90th percentile; (2) probability of lower-than-median yields, defined as the estimated probability of achieving yields below the 50th percentile; and (3) probability of low yields, defined as the estimated probability of achieving yields below the 10th percentile. Rotation treatment densities were compared with a randomized distribution originating from bootstrapping without treatment effects. Probabilities of high and low yields were defined as estimated probabilities of achieving yields above the 90th percentile and below the 10th percentile, respectively. 1,000 randomizations were sufficient to stabilize the p values. Rotation diversity effects on the probability of high or low yields were identified when observed results were significantly different from the randomized distribution at the 95% confidence level beyond the determined percentiles.

To identify likely sources of stress affecting maize production, we used historical records on crop-insurance indemnity payments for each of the nine sites in the US. Publicly available county-level data from 2000 to 2017 on reasons for indemnity payments for maize (i.e., Cause of Loss Historical Data Files) were obtained from the USDA Risk Management Agency (https://www.rma.usda.gov/SummaryOfBusiness/CauseOfLoss). Damage causes were tallied by dollar amount (adjusted to 2018 dollars) for each county over the 18-year period. The three worst years for drought were identified by the highest payouts for drought in each county. We consider these to be putative drought years for the long-term experiment located in the same county. We compared these years identified with crop-insurance indemnity payouts with years with low EIs (Table S3). In years with putative drought, we compared crop yields in simple, intermediate, and complex rotations at each rotation by using ANOVA and calculated percent differences in sites and years where there were significant differences across the systems.

DATA AND CODE AVAILABILITY

Corn-yield data are available in the Dryad repository: https://doi.org/10.6078/D1H409.

SUPPLEMENTAL INFORMATION

Supplemental Information can be found online at https://doi.org/10.1016/j.oneear.2020.02.007.

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AUTHOR CONTRIBUTIONS

T.M.B. conceptualized the research; T.M.B. and A.S.G. acquired funding; T.M.B., J. Salerno, and Y.S. analyzed data; F.C., M.A.C., S.W.C., W.D., C.F.D., A.G.y.G., A.C.M.G., W.S.H., R.M.L., S.L.O., G.P.R., M.R.S., and J. Strock provided data from long-term experiments; T.M.B. and M.M. wrote the original draft; and all authors contributed to reviewing and editing the manuscript.

DECLARATION OF INTERESTS

The authors declare no competing interests.

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One Earth, Volume *2*

Supplemental Information

Long-Term Evidence Shows that Crop-Rotation Diversification Increases Agricultural Resilience to Adverse Growing Conditions in North America

Timothy M. Bowles, Maria Mooshammer, Yvonne Socolar, Francisco Calderón, Michel A. Cavigelli, Steve W. Culman, William Deen, Craig F. Drury, Axel Garcia y Garcia, Amélie C.M. Gaudin, W. Scott Harkcom, R. Michael Lehman, Shannon L. Osborne, G. Philip Robertson, Jonathan Salerno, Marty R. Schmer, Jeffrey Strock, and A. Stuart Grandy

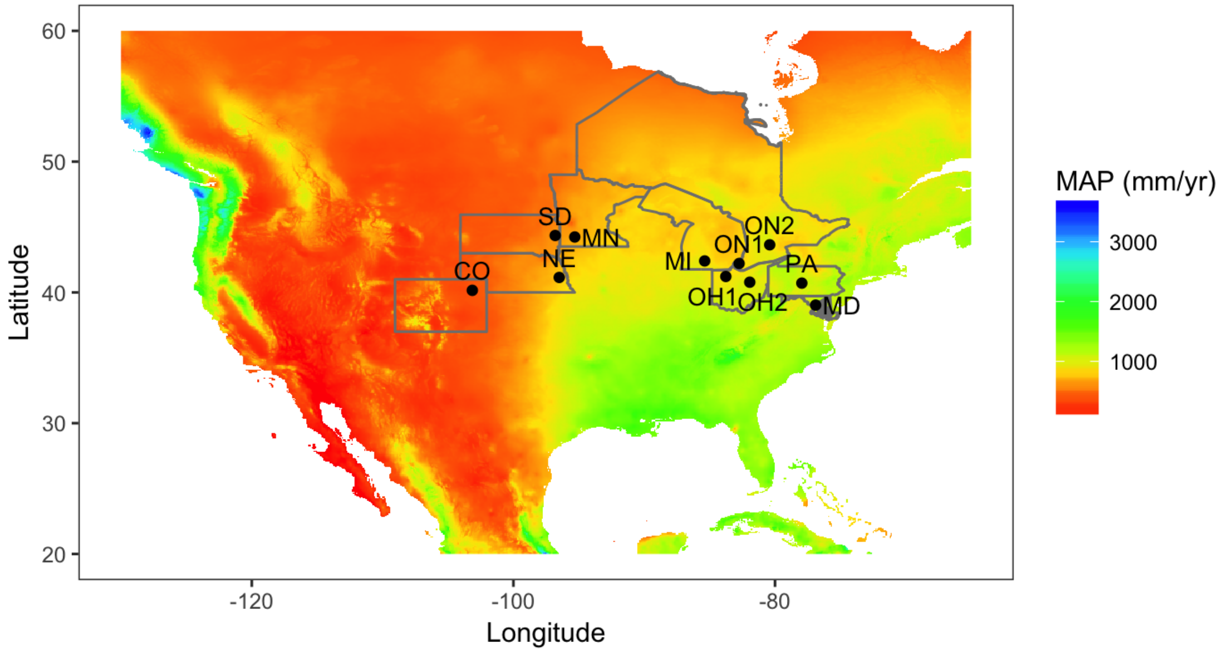


Fig. S1: Map of long-term experiments included in the analysis. MAP: mean annual precipitation. The gray lines correspond to the state and province boundaries of each site.

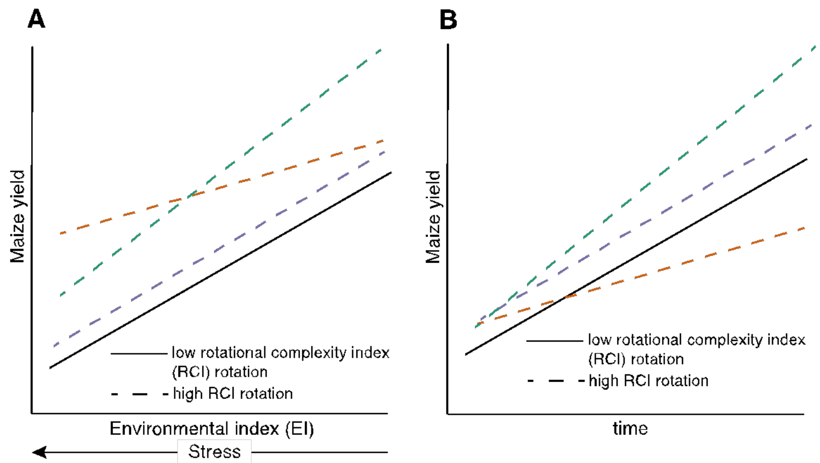
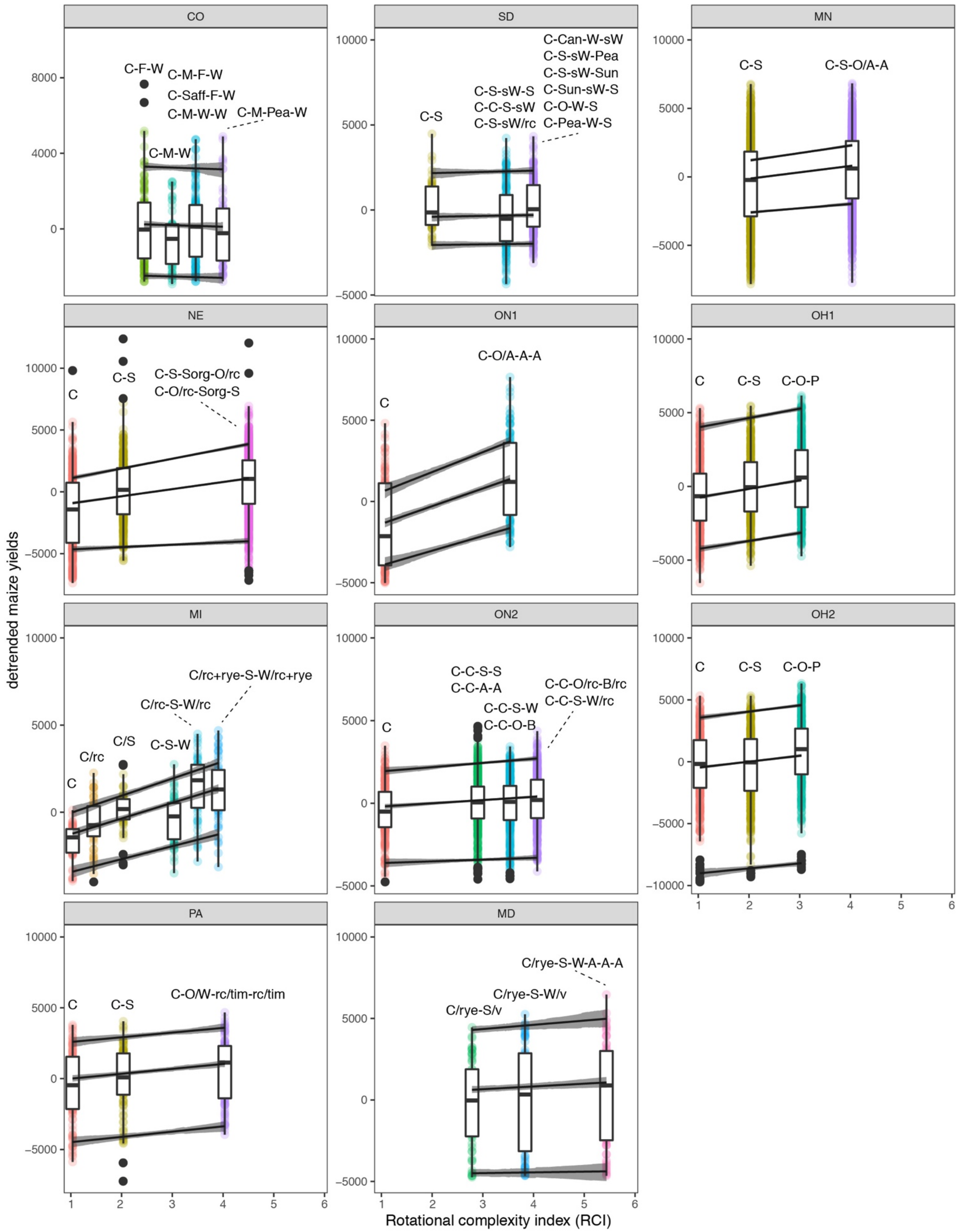


Fig. S2. Hypothetical relationships among maize yields, rotational complexity (RCI), and environmental conditions (EI) (A). Hypothetical relationships among maize yields, rotational complexity, and time are shown in (B). For instance, the green dashed line shows a hypothetical rotation that provides some yield benefit when stress is high (low EI) but increasingly higher yields as growing conditions improve (high EI). By contrast, the orange line shows a hypothetical rotation that provides large yield benefits during the most stressful conditions, but these benefits diminish as growing conditions improve. The blue line shows a hypothetical rotation that provides little maize yield benefit that does not shift across environmental conditions.



CO
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C-M-F-W
C-Saff-F-W
C-M-W-W
C-M-Pea-W
C-M-W
SD
C-Can-W-sW
C-S-sW-Pea
C-S-sW-Sun
C-Sun-sW-S
C-O-W-S
C-Pea-W-S
C-S-sW-S
C-C-S-sW
C-S-sW/rc
C-S
MN
C-S
C-S-O/A-A
NE
C
C-S
C-S-Sorg-O/rc
C-O/rc-Sorg-S
ON1
C
C-O/A-A-A
OH1
C
C-S
C-O-P
MI
C
C/rc
C/S
C-S-W
C/rc-S-W/rc
C/rc+rye-S-W/rc+rye
ON2
C
C-C-S-S
C-C-A-A
C-C-S-W
C-C-O-B
C-C-O/rc-B/rc
C-C-S-W/rc
OH2
C
C-S
C-O-P
PA
C
C-S
C-O/W-rc/tim-rc/tim
MD
C/rye-S/v
C/rye-S-W/v
C/rye-S-W-A-A-A
detrended maize yields
Rotational complexity index (RCI)

Fig. S3. Maize yields (detrended) as a function of the rotational complexity index (RCI) (see Methods), from 11 long-term experiments on crop rotational diversity. Shown are actual plot-level data (points) (n = 10,424), with colors corresponding to the RCI value (x-axis) to aid in comparing across sites. Overlaid on the points are box plots summarizing the distribution of the data. Specific crop rotations are labeled over each RCI position in each site. See Table S1 for definitions of crop rotation abbreviations. Posterior predictions from the hierarchical model at three levels of the environmental index (EI) are shown to illustrate the interaction between RCI and EI. These predictions are at the lowest, median, and highest values of EI, shown as the bottom, middle, and top lines in each graph. Shading along lines is the 95% credibility interval of the mean. Note that that the maize yields (y-axis) are detrended (including removal of intercept), which is why negative values appear.

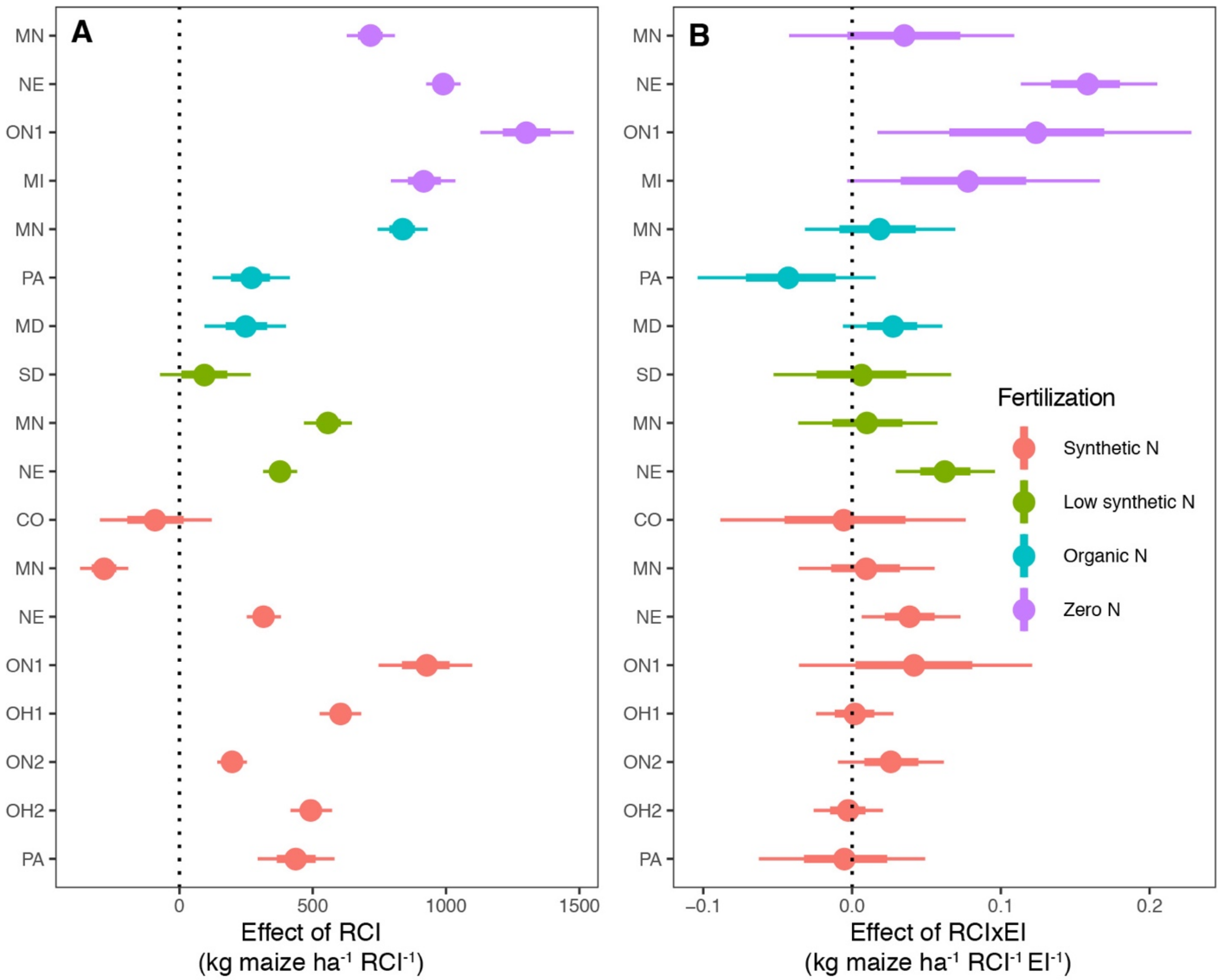
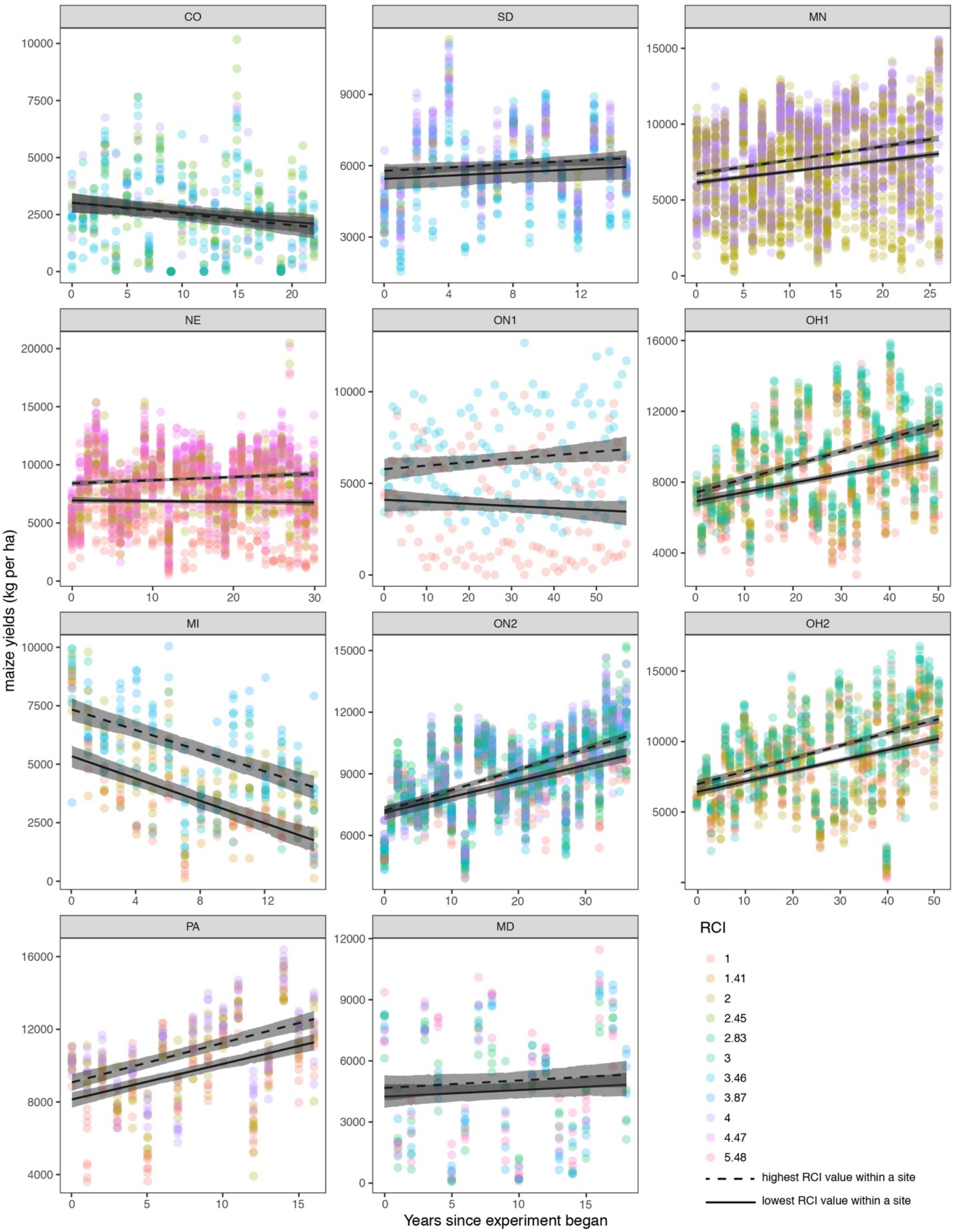


Fig. S4: Results of a model in which nitrogen (N) fertilization treatments in a given site were considered separately. Site-level coefficient estimates from the multilevel model predicting how crop rotational complexity affects yields (A) and how these effects differ depending on environmental stress B). See Table 1 for information on N fertilizer application rates. Fertilizer was categorized as "synthetic N" if the amount of N added was not expected to be yield limiting according to site references, and "low synthetic" if N rate could be yield limiting according to site references. Posterior mean estimates (points) of these site-level fixed effects are displayed in terms of their effect on maize yields, with 95% (thin lines) and 68% (thick lines) credibility intervals. Coefficients and credibility intervals are drawn from the joint posterior distribution of the model.



CO
SD
MN
NE
ON1
OH1
MI
ON2
OH2
PA
MD
maize yields (kg per ha)
Years since experiment began
RCI
1
1.41
2
2.45
2.83
3
3.46
3.87
4
4.47
5.48
highest RCI value within a site
lowest RCI value within a site

Fig. S5. Maize yields as a function of time (years) since the long-term experiment at each site began. Shown are actual data (points) (n = 11,868), with color corresponding to RCI value. Posterior predictions from the hierarchical model are shown with dotted lines representing the most diverse rotation in each site and solid lines representing the least diverse rotation in every site. Shading along lines is the 95% credibility interval of the mean.

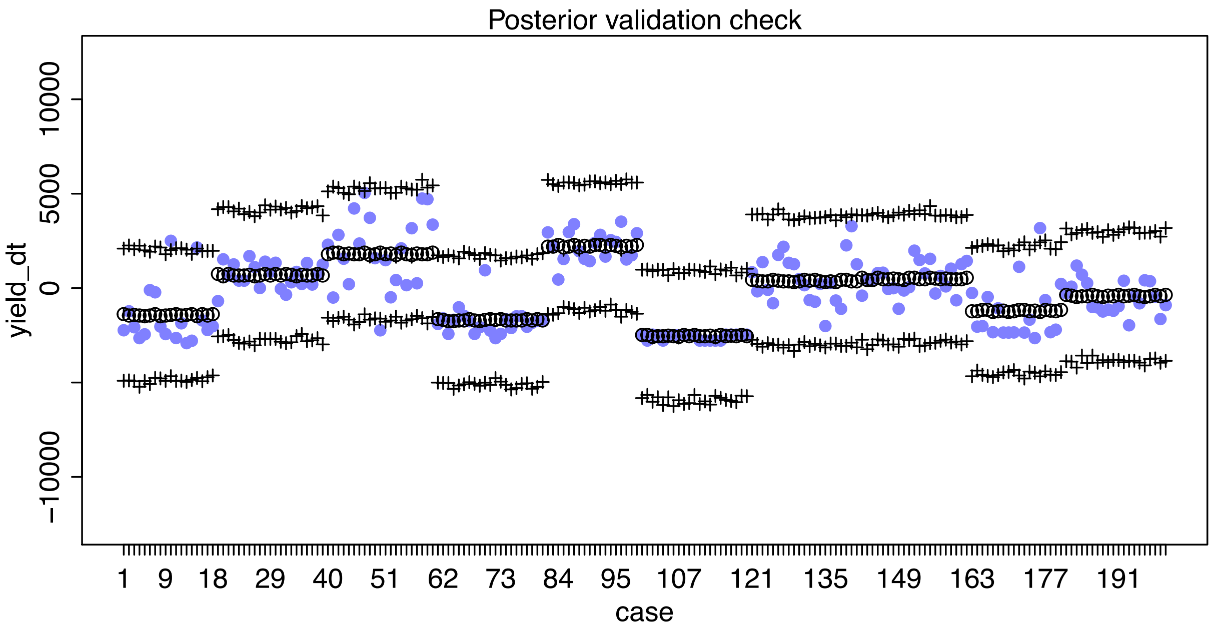


Fig. S6. Representative predictive posterior check (first 200 cases) of the RCIxEI model [1] showing actual data (blue dots) with 95% credibility intervals (cross hatches) from the posterior.

SI Table 1: Additional site characteristics and key references.

Site	Soil type	Rotations (length in years)	MAP CV (%)	MAT (ºC)	Years of data (total)	Key references[1]
Akron, CO	Weld silt loam	C-F-W (3); C-M-W (3); C-M-F-W (4); C-M-W-W (4); C-Saff-F-W (4); C-M-Pea-W (4)	72	9.5	1993–2015	(1, 2)
Brookings, SD	Barnes sandy clay loam	C-S (2); C-S-sW/rc (3); C-O-W-S (4); C-S-sW-Pea (4); C-C-S-sW (4); C-S-sW-Sun (4); C-Can-W-S (4); C-Pea-W-S (4); C-S-sW-S (4); C-Sun-sW-S (4)	60	6.5	2001–2016	(3)
Lamberton, MN	Normania clay loam, Revere clay loam, Ves clay loam, and Webster clay loam	C-S (2); C-S-O/A-A (4)	51	7.0	1989–2015	(4, 5)
Mead, NE	Yutan silty clay loam and Tomek silt loam complex	C (1); C-S (2); C-O/rc-Sorg-S (4); C-S-Sorg-O/rc (4)	52	10.3	1983–2013	(6, 7)
Woodslee, ON (ON1)	Brookston clay loam	C (1); C-O/A-A-A (4)	16	9.2	1959–2016	(8, 9)
Hoytville, OH (OH1)	Hoytville clay loam soil	C (1); C-S (2); C-O-P (3)	23	9.7	1963–2013	(10)
Hickory Corners, MI	Kalamazoo loam, and Oshtemo sandy loam	C (1); C/rc (1); C-S (2); C-S-W (3); C/rc-S-W/rc (3); C/rc+rye-S-W/rc+rye (3)	24	8.8	2000–2015	(11, 12)
Elora, ON (ON2)	Woolwich silt loam	C (1); C-C-A-A (4); C-C-S-S (4); C-C-O-B (4); C-C-S-W/rc (4); C-C-O/rc-B/rc (4)	12	6.4	1980–2016	(13, 14)
Wooster, OH (OH2)	Wooster silt loam soil	C (1); C-S (2); C-O-P (3)	21	9.8	1962–2013	(10)
Rock Springs, PA	Hagerstown silt loam	C (1); C-S (2); C-O/W-rc/tim-rc/tim (4)	15	9.3	1990–2006	(15)
Beltsville, MD	Christiana, Matapeake, Keyport, and Mattapex silt loams	C/rye-S/v (2); C/rye-S-W/v (3); C/rye-S-W-A-A-A (6)	12	13.0	1996–2015	(16, 17)

A: Alfalfa; B: spring barley; C: Maize; Can: Canola; F: Fallow; O: Oats; P: pasture (mixed grass, alfalfa, or clover); rc: Red clover; rye: cereal rye; S: Soy; Saff: safflower; Sorg: sorghum; Sun: Sunflower; sW: spring wheat; tim: timothy; v: Hairy vetch; W: winter wheat. Lower case abbreviations indicate cover crops. MAP: mean annual precipitation; MAT: mean annual temperature; CV: coefficient of variation.

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SI Table 2: Average yields in contrasting crop rotations in likely drought years identified through U.S. crop insurance indemnity payments at the county level, in the county where the experiment is located. Only U.S.-based sites are included. The three years with the highest levels of indemnity payments due to drought in the county were selected for each site. Within a crop rotation, yields are averaged across other treatments (e.g. fertilization, tillage) that are included at a site. Significant differences between rotations within a site are indicated by superscript letters, based on results of a mixed-effects ANOVA including all putative drought years and subsequent means separation. EI rank is the ranking (from most to least stressed in the dataset) to which the putative drought year identified with crop insurance indemnity payouts corresponds.

		Maize yield (kg ha^{-1})			
Site	Years with highest indemnity payments for drought in county, ordered in payment amount (EI rank)	Least diverse rotation	Mid- diverse rotation	Most diverse rotation	Percent difference (least to most diverse)
CO	2013 (10), 2012 (2), 2004 (14)	2468^{a} (C-F-W)	1653^{ab} (C-M-W-W)	1466^{ab} (C-M-Pea-W)	-40.6%
SD	2012 (4), 2008 (5)	5297^{ab} (C-S)	4991^{a} (C-S-sW/rc)	6037^{bc} (C-Sun-sW-S)	14.0%
MN	2013 (9), 2008 (3), 2012 (5)	6954 (C-S)	NA	7505 (C-S-O/A-A)	ns
NE	2012 (3), 2002 (2), 2003 (14)	5669^{a} (C)	6053^{a} (C-S)	7260^{b} (C-O/rc-Sorg-S)	28.1%
OH1	2008 (7), 2002 (6), 2012 (5)	6435^{a} (C)	6761^{a} (C-S)	7597^{b} (C-O-P)	18.6%
MI	2012 (11), 2007 (1), 2008 (2)	2156^{a} (C)	3558^{b} (C-S)	4073^{b} (C/rc+rye-S-W/rc+rye)	88.9%
OH2	2002 (1), 2012 (14)	5201^{ab} (C)	4874^{a} (C-S)	6113^{b} (C-O-P)	17.5%
PA	2002 (1)	6507^{a} (C)	6308^{a} (C-S)	8694^{b} (C-O/W-rc/tim-rc/tim)	33.6%
MD	2007 (2), 2010 (4), 2002 (1)	1320 (C/rye-S/v)	689 (C/rye-S-W/v)	1376 (C/rye-S-W-A-A-A)	ns

SI Table 3: Probabilities (%) of obtaining yields above or below certain thresholds based on probability densities from yield distributions within a site. Statistical significance is based on randomized *p*-values and indicated by (*) 5%, (**) 1%, and (***) 0.1% for metrics that are higher or lower than randomized metrics.

	Crop rotational complexity index		P(yield < 10th percentile)		P(yield < 50th percentile)		P(yield > 90th percentile)	
Crop rotational diversity	simple	complex[a]	simple	complex	simple	complex	simple	complex
CO	C-F-W	C-M-Pea-W	9.6	12.7	36.7***	54.9	20.0*	12.9***
SD	C-S	C-Sun-sW-S	3.7***	4.9***	47.1	35.4***	9.9	14.2***
MN	C-S	C-S-O/A-A	14.9	6.3***	55.7	44.6***	9.1	12.2***
NE	C	C-O/rc-Sorg-S	25.1	2.0***	68.5	35.2***	3.7	18.6***
ON1	C	C-O/A-A-A	21.0	0.2***	62.9	36.1***	1.7	18.8***
OH1	C	C-O-P	17.2	7.1***	59.2	40.8***	7.1	15.4***
MI	C	C/rc+rye-S-W/rc+rye	24.7	4.5***	96.6	23.0***	0.0	29.6***
ON2	C	C-C-O/rc-B/rc	16.2	8.1***	61.6	45.1***	7.2	16.8***
OH2	C	C-O-P	10.3	5.3***	53.3	39.7***	8.2	16.9***
PA	C	C-O/W-rc/tim-rc/tim	16.0	5.3***	57.7	40.5***	10.6	19.4***
MD	C/rye-S/v	C/rye-S-W-A-A-A	10.1	8.8	53.8	48.1	6.3	15.6**

[a]When rotations at a given site were tied for highest crop rotational complexity, the rotation with the highest cumulative ordinal rank for each probability metric was selected. At all sites but CO, the highest ranked rotation was the most diverse, or tied for the most diverse. At CO, the highest ranked rotations were C-F-W and C-M-F-W (tied).

Site References (different numbering from main text)

1. Nielsen DC, Halvorson AD, Vigil MF (2010) Critical precipitation period for dryland maize production. *F Crop Res* 118(3):259–263.
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One Earth, Volume *2*

Supplemental Information

Long-Term Evidence Shows that Crop-Rotation Diversification Increases Agricultural Resilience to Adverse Growing Conditions in North America

Timothy M. Bowles, Maria Mooshammer, Yvonne Socolar, Francisco Calderón, Michel A. Cavigelli, Steve W. Culman, William Deen, Craig F. Drury, Axel Garcia y Garcia, Amélie C.M. Gaudin, W. Scott Harkcom, R. Michael Lehman, Shannon L. Osborne, G. Philip Robertson, Jonathan Salerno, Marty R. Schmer, Jeffrey Strock, and A. Stuart Grandy

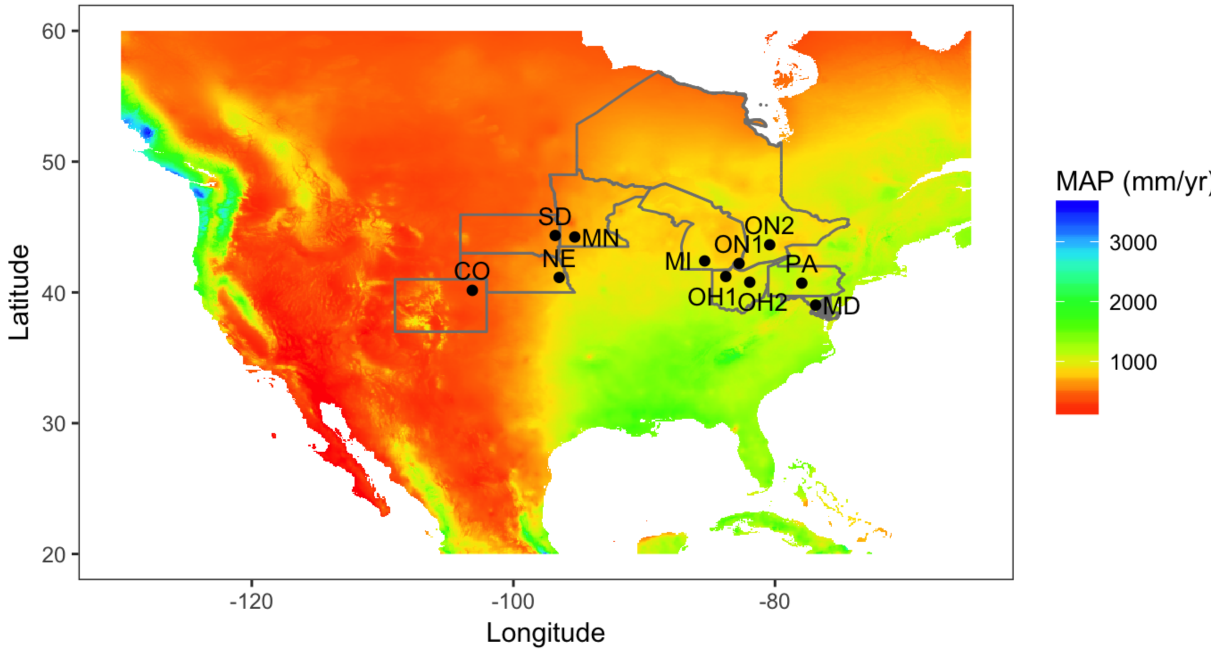


Fig. S1: Map of long-term experiments included in the analysis. MAP: mean annual precipitation. The gray lines correspond to the state and province boundaries of each site.

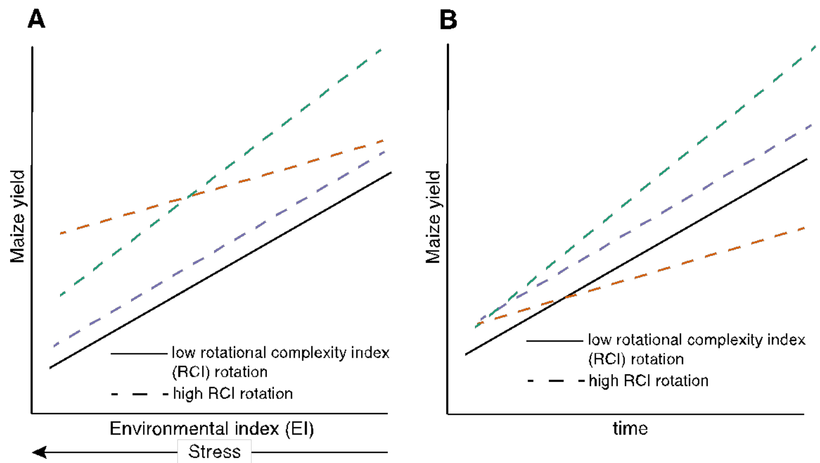
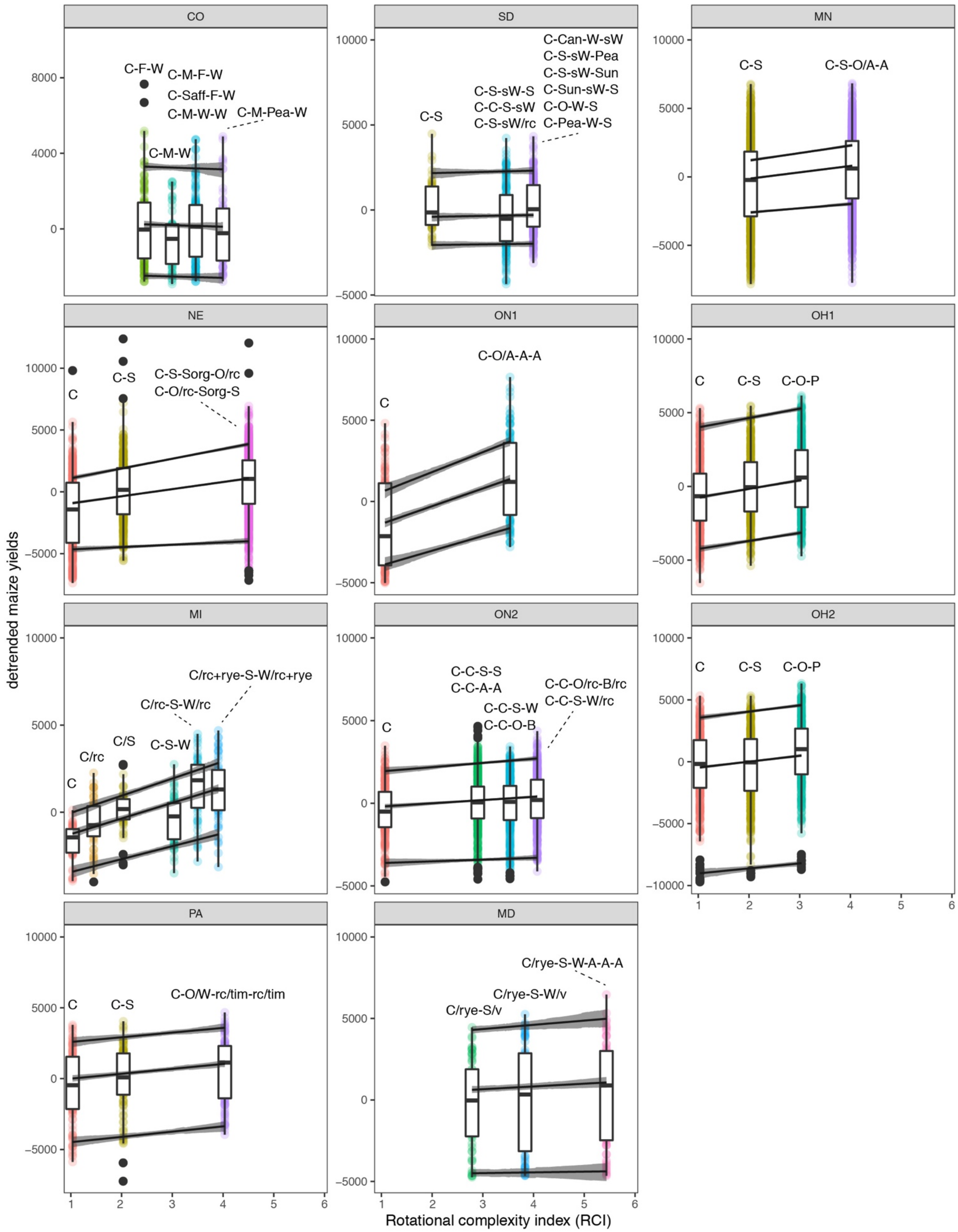


Fig. S2. Hypothetical relationships among maize yields, rotational complexity (RCI), and environmental conditions (EI) (A). Hypothetical relationships among maize yields, rotational complexity, and time are shown in (B). For instance, the green dashed line shows a hypothetical rotation that provides some yield benefit when stress is high (low EI) but increasingly higher yields as growing conditions improve (high EI). By contrast, the orange line shows a hypothetical rotation that provides large yield benefits during the most stressful conditions, but these benefits diminish as growing conditions improve. The blue line shows a hypothetical rotation that provides little maize yield benefit that does not shift across environmental conditions.


CO
C-F-W
C-M-F-W
C-Saff-F-W
C-M-W-W
C-M-Pea-W
C-M-W
SD
C-Can-W-sW
C-S-sW-Pea
C-S-sW-Sun
C-Sun-sW-S
C-O-W-S
C-Pea-W-S
C-S-sW-S
C-C-S-sW
C-S-sW/rc
C-S
MN
C-S
C-S-O/A-A
NE
C
C-S
C-S-Sorg-O/rc
C-O/rc-Sorg-S
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C-O-P
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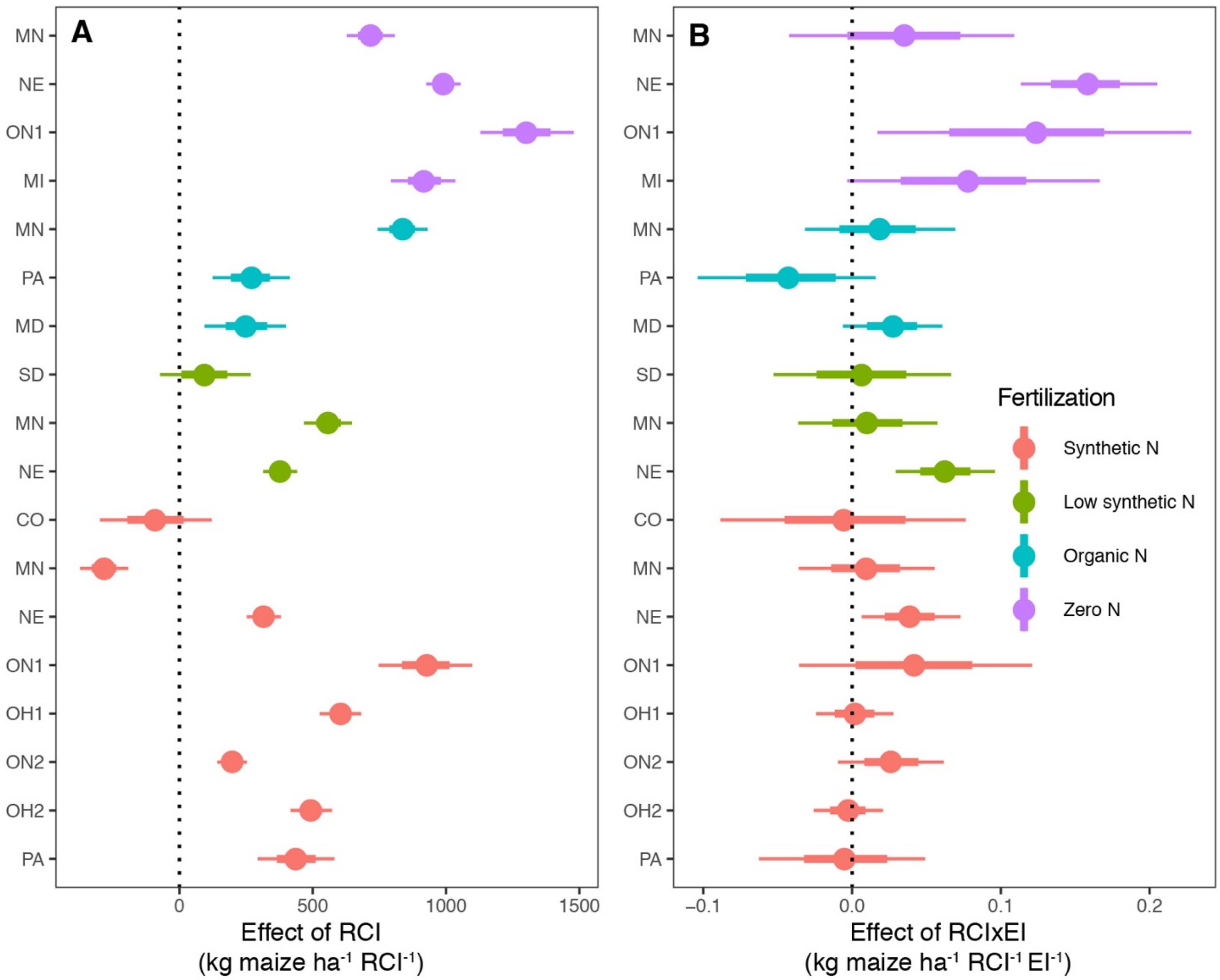

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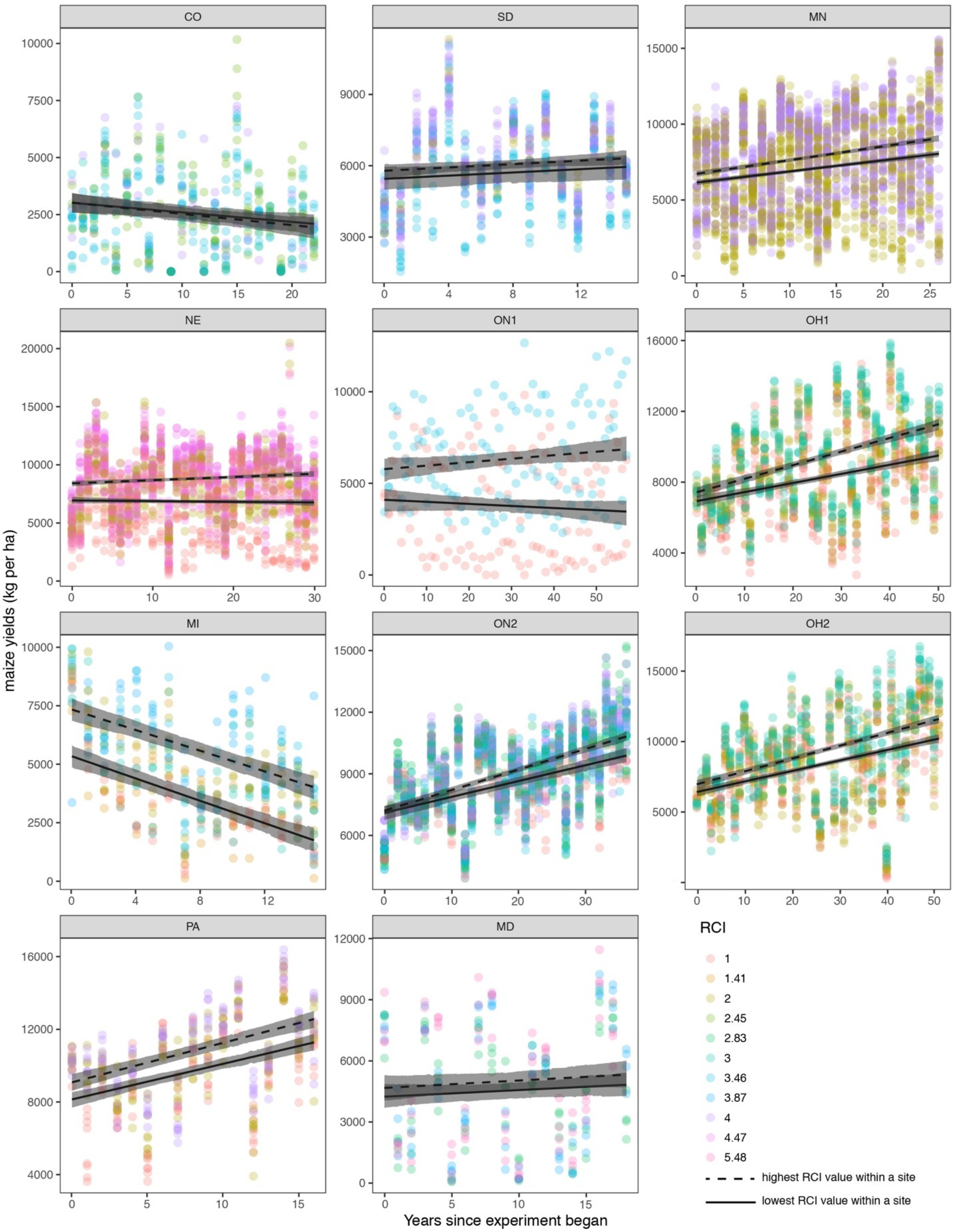
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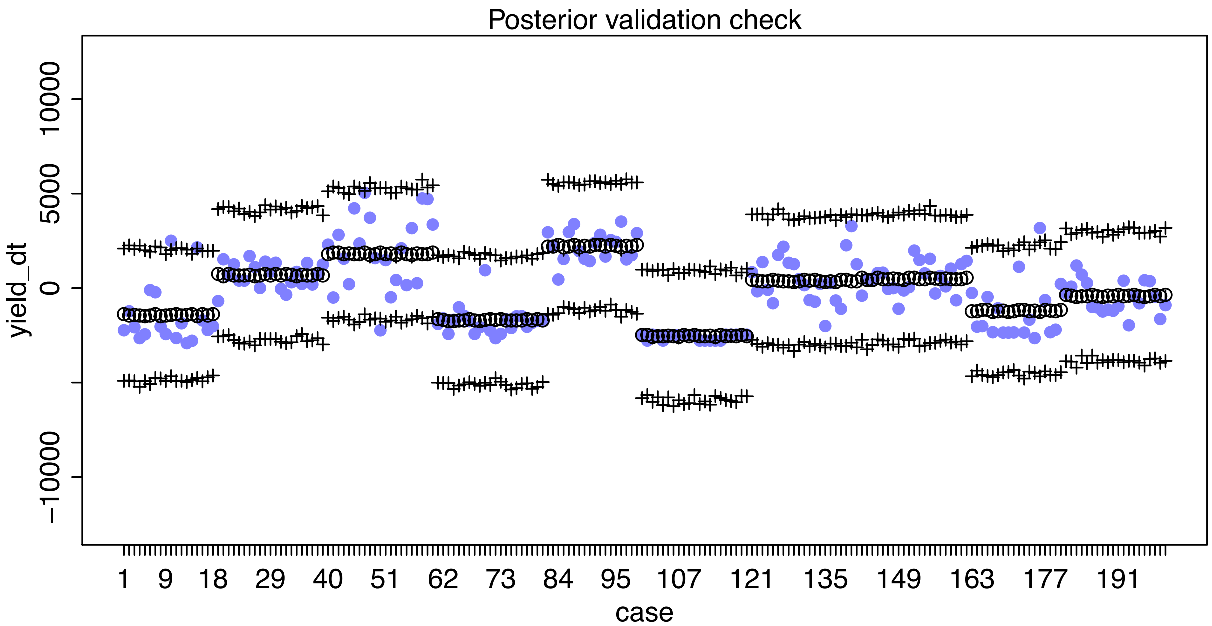

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SD	2012 (4), 2008 (5)	5297^{ab} (C-S)	4991^{a} (C-S-sW/rc)	6037^{bc} (C-Sun-sW-S)	14.0%
MN	2013 (9), 2008 (3), 2012 (5)	6954 (C-S)	NA	7505 (C-S-O/A-A)	ns
NE	2012 (3), 2002 (2), 2003 (14)	5669^{a} (C)	6053^{a} (C-S)	7260^{b} (C-O/rc-Sorg-S)	28.1%
OH1	2008 (7), 2002 (6), 2012 (5)	6435^{a} (C)	6761^{a} (C-S)	7597^{b} (C-O-P)	18.6%
MI	2012 (11), 2007 (1), 2008 (2)	2156^{a} (C)	3558^{b} (C-S)	4073^{b} (C/rc+rye-S-W/rc+rye)	88.9%
OH2	2002 (1), 2012 (14)	5201^{ab} (C)	4874^{a} (C-S)	6113^{b} (C-O-P)	17.5%
PA	2002 (1)	6507^{a} (C)	6308^{a} (C-S)	8694^{b} (C-O/W-rc/tim-rc/tim)	33.6%
MD	2007 (2), 2010 (4), 2002 (1)	1320 (C/rye-S/v)	689 (C/rye-S-W/v)	1376 (C/rye-S-W-A-A-A)	ns

SI Table 3: Probabilities (%) of obtaining yields above or below certain thresholds based on probability densities from yield distributions within a site. Statistical significance is based on randomized *p*-values and indicated by (*) 5%, (**) 1%, and (***) 0.1% for metrics that are higher or lower than randomized metrics.

	Crop rotational complexity index		P(yield < 10th percentile)		P(yield < 50th percentile)		P(yield > 90th percentile)	
Crop rotational diversity	simple	complex[a]	simple	complex	simple	complex	simple	complex
CO	C-F-W	C-M-Pea-W	9.6	12.7	36.7***	54.9	20.0*	12.9***
SD	C-S	C-Sun-sW-S	3.7***	4.9***	47.1	35.4***	9.9	14.2***
MN	C-S	C-S-O/A-A	14.9	6.3***	55.7	44.6***	9.1	12.2***
NE	C	C-O/rc-Sorg-S	25.1	2.0***	68.5	35.2***	3.7	18.6***
ON1	C	C-O/A-A-A	21.0	0.2***	62.9	36.1***	1.7	18.8***
OH1	C	C-O-P	17.2	7.1***	59.2	40.8***	7.1	15.4***
MI	C	C/rc+rye-S-W/rc+rye	24.7	4.5***	96.6	23.0***	0.0	29.6***
ON2	C	C-C-O/rc-B/rc	16.2	8.1***	61.6	45.1***	7.2	16.8***
OH2	C	C-O-P	10.3	5.3***	53.3	39.7***	8.2	16.9***
PA	C	C-O/W-rc/tim-rc/tim	16.0	5.3***	57.7	40.5***	10.6	19.4***
MD	C/rye-S/v	C/rye-S-W-A-A-A	10.1	8.8	53.8	48.1	6.3	15.6**

[a]When rotations at a given site were tied for highest crop rotational complexity, the rotation with the highest cumulative ordinal rank for each probability metric was selected. At all sites but CO, the highest ranked rotation was the most diverse, or tied for the most diverse. At CO, the highest ranked rotations were C-F-W and C-M-F-W (tied).

Site References (different numbering from main text)

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