The Pennsylvania State University The Graduate School Department of Plant Science

SUSTAINABLE INTENSIFICATION AND CLIMATE RESILIENCE: COVER CROPS, SOIL IMPROVEMENT, AND DROUGHT

A Dissertation in Agronomy

by Mitchell Clayton Hunter © 2018 Mitchell Clayton Hunter

Submitted in Partial Fulfillment of the Requirements for the Degree of Doctor of Philosophy

August 2018

The dissertation of Mitchell Clayton Hunter was reviewed and approved* by the following:

David A. Mortensen Distinguished Professor of Weed and Applied Plant Ecology The Pennsylvania State University Dissertation Advisor Chair of Committee

David M. Eissenstat Professor of Woody Plant Physiology The Pennsylvania State University

Jason P. Kaye Professor of Soil Biogeochemistry The Pennsylvania State University

Armen R. Kemanian Associate Professor of Production Systems and Modeling The Pennsylvania State University

Meagan E. Schipanski Assistant Professor of Cropping Systems Colorado State University Special Signatory

Erin L. Connolly Professor of Plant Science Head of the Plant Science Department The Pennsylvania State University

*Signatures are on file in the Graduate School

ABSTRACT

New agricultural production strategies are needed to 1) deliver nutritious, affordable, and accessible food; 2) maintain high and stable yield in the face of climate change; and 3) maintain or restore ecosystem integrity. This dissertation aims to address this challenge at multiple scales.

Chapter 2 reevaluates the dominant narrative that food production must double by 2050 to meet world demand. This narrative creates an urgency around increasing production that tends to mute concern about resulting environmental impacts. An updated analysis of food demand projections showed that demand will increase only 26-68% between 2014 and 2050 (rather than 100%). A review of published goals for agricultural greenhouse gas emissions and nutrient losses to water bodies showed that, at the same time, agricultural pollution must decrease rapidly to maintain ecosystem integrity. Together, these quantitative targets for production and environmental impacts provide a more balanced set of priorities for "sustainable intensification" in agricultural research and policy.

The subsequent chapters explore opportunities for improving yield stability at the farm level through diversification and conservation practices. Chapter 3 analyzes the effects of multi-species cover crop mixtures on the mean levels and spatiotemporal stability of cash crop yield and soil N supply in an organically-managed three-year rotation of maize (*Zea mays* L.), soybean (*Glycine max* L.), and wheat (*Triticum aestivum* L.) in central Pennsylvania. Results show that cover crop mixtures that produced biomass with a low carbon:nitrogen (C:N) ratio increased both soil N supply and maize yield, while high-C:N ratio cover crops reduced both N supply and maize yield. Soil N supply explained 23.0% of the variation in maize yield. Cover crop mixtures did not affect soybean or wheat yield. A novel stability metric developed here (the Consistent Performance Index) showed that the stability of soil N supply was a strong predictor of the stability of maize yield ($R^2 = 0.849$). These results suggest that low-C:N ratio cover crops can promote maize yield stability.

Chapter 4 evaluates the potential for cover crops to mitigate a specific climate change impact: increased drought stress. Cover crops may affect cash crop drought physiology by transpiring soil water in the spring and influencing soil N dynamics following termination. Both water- and N-stress may impair yield formation by reducing radiation interception (RI), radiation use efficiency (RUE), and harvest index (HI). Nitrogen limitation may also help crops tolerate drought by reducing transpirative demand and stimulating root growth. In contrast, high N supply may reduce drought stress directly by enabling osmotic adjustment. Rainout shelters were deployed in maize grown following functionally-diverse cover crops and maize response was evaluated with multiple repeated ecophysiological measures over two growing seasons. Results indicate that cover crop N supply is critical for yield formation under both drought and ambient conditions. Drought reduced maize yield by 23.2 %, while the cereal rye (*Secale cereale* L.) cover crop reduced yield by 33.6%, likely due to N immobilization. A red clover (*Trifolium pratense* L.) cover crop resulted in high and stable maize yield across years and drought conditions. Ecophysiological measurements indicate that cover crop N supply was critical for canopy formation and chlorophyll content, enhancing RI and RUE. N limitation did not confer drought adaptation, nor did N supply substantially improve osmotic adjustment. Due to consistent rains, there was no effect of cover crop transpiration on soil moisture at termination.

Chapter 5 extends this question by evaluating the drought-mitigating effects of long-term soil improvement using the Cycles cropping system model. Management practices that improve soil infiltration rate (IR) and available water capacity (AWC) may reduce yield losses under drought, but this effect has not been rigorously assessed. Maize yield under a range of historical and future climate conditions was simulated in soils parameterized based on the results of a long-term (49-year) field study of four different soil disturbance regimes, which led to substantial differences in IR and AWC. Future conditions were simulated based on the RCP8.5 high-greenhouse gas emissions scenario using data from the CCSM4 climate model downscaled with the MACAv2METDATA methodology. Overall, reduced soil disturbance increased simulated yield by up to 13.3% in moderate drought conditions and up to 11.7% in severe drought. Improved AWC increased yield more (8.52%) than improved IR (3.33%). The benefit of improved AWC was shown to depend on the retention of crop residues, which reduced surface evaporation. Simulations indicate that improving soil hydraulic properties may help reduce yield losses under drought, but yield will still decline due to increased temperature and reduced growing season precipitation under climate change.

Overall, these results indicate that cover cropping and reduced soil disturbance may help achieve high and stable maize yield while improving environmental quality, thereby contributing to sustainable intensification. However, to avoid maize yield losses, cover crops must be managed to ensure that they do not reduce N supply, especially in organic systems. Future work is needed to understand the interacting effects of long-term soil improvement and short-term nutrient dynamics on maize drought physiology.

TABLE OF CONTENTS

LIST OF FIGURES	vii
LIST OF TABLES	xi
PREFACE	xiv
ACKNOWLEDGEMENTS	xv
Chapter 1 Introduction	1
1.1 The Challenge	1
1.2 Clarifying Goals for Sustainable Intensification	4
1.3 Diversification and Stability	5
1.4 Conclusion	8
1.5 References	8
Chapter 2 Agriculture in 2050: Recalibrating Targets for Sustainable Intensification	14
2.1 Introduction	14
2.2 Food Demand Projections	15
2.2 Environmental Goals	19
2.3 Agriculture's Path to 2050	
2.4 Conclusion	
2.5 References	
Chapter 3 Cover Crop Mixtures: Effects on Crop Yield and Yield Stability	27
3.1 Introduction	
3.1.1 Effects of Cover Crop Mixtures on Cash Crop Yields	
3.1.2 Cash Crop Yield Stability	
3.1.3 Biodiversity Effects in Cover Crop Mixtures	
3.1.4 Hypotheses.	
3.2 Methods	
3.2.1 Site Characteristics	
3.2.2 Experimental Design and Management	32
3.2.3 Cash Crops	
3.2.4 Cover Crops	
3.2.5 Data Collection	
3.2.6 Stability Metrics	
3.2.7 Statistical Analyses	39
3.3 Results	
3.3.1 Weather Conditions	
3.3.2 Cover Crop Performance	
3.3.3 Soil Inorganic Nitrogen – Prior to Maize	
3.3.4 Soil Inorganic Nitrogen – Prior to Sovbean	51
3.3.5 Maize Silage Yield	

3.3.6 Soybean Yield	58
3.3.7 Wheat Yield	61
3.4 Discussion	62
3.4.1 Cover Crop Effects on Crop Yields	62
3.4.2 Cover Crop Effects on Crop Yield Stability	64
3.5 Conclusions	66
3.6 References	67
Chapter 4 Cover Crop Effects on Maize Physiology Under Experimental Drought Conditions	73
4.1 Introduction	73
4.1.1 Cover Crop Effects on Crop Water Balance	74
4.1.2 Water and Nitrogen Stress	75
4.2 Methods	77
4.2.1 Experimental Design and Management	78
4.2.2 Cover Crop Treatments	79
4.2.3 Rainout Shelters	80
4.2.4 Ambient Weather and Shelter Microclimate	81
4.2.5 Cover Crop and Soil Measurements	83
4.2.6 Maize Ecophysiology	84
4.2.7 Maize Height, Yield, Yield Components, and Tissue Nitrogen	87
4.2.8 Statistical Analysis	88
4.3 Results and Discussion	90
4.3.1 Cover Crops	90
4.3.2 Ambient Weather Conditions in the Maize Growing Season	92
4.3.3 Shelter Microclimate	92
4.3.4 Cover Crop Effects on Spring Soil Water Content	97
4.3.5 Cover Crop N Provisioning	
4.3.6 Maize Nitrogen Status	
4.3.7 Radiation Capture and Use Efficiency	104
4 3 8 Osmotic Adjustment	107
4 3 9 Maize Development and Yield	109
4 3 10 Vield Components	115
4 3 11 Integrative Regression Model	116
4 3 12 Vield Stability	117
4 4 Conclusions	118
4.5 References	119
Chapter 5 Drought-Resistant Soil: An Initial Scoping Analysis	127
5.1 Texture describes	107
5.1 Introduction	127
5.2 Methods	129
5.5 Kesuits and Discussion	133
5.4 Kelerences	142
Chapter 6 Epilogue	149
Appendix Root Pit Data	151

LIST OF FIGURES

Figure 2-1: Food demand is projected to climb while environmental impacts must plummet. Calls to double crop production from a recent baseline imply growth rates outside of the range of empirical projections. Meanwhile, agriculture's environmental impacts need to fall rapidly to protect critical ecosystem functions. (a) Historical and projected global cereal production and demand. (b) Historical and projected direct greenhouse has (GHG) emissions from agriculture and 2050 goal. (c) Historical total phosphorous loading in the Mississippi-Atchafalaya River Basin and 2035 goal. Note: Historical data is shown in solid lines and future projections and goal trajectories are shown in dashed or dotted lines1	18
Figure 2-2: Decrease in world cereal yield growth rate over time. To double by 2050 from a 2005 baseline, yield growth would have to be maintained at 1.5% per year. Doubling from a 2014 baseline would require yield growth of 1.9% per year. Each point represents the compound annual growth rate of global average cereal yields over the five previous years (FAO 2016). To smooth interannual variation, growth rates were calculated using five-year moving average cereal yields.	19
Figure 3-1 : Monthly a) precipitation and b) mean temperature for 2013, 2014, and 2015, in comparison to monthly averages for 1980 to 2016 (horizontal black bars). Data is from NLDAS (Xia et al. 2012)	41
Figure 3-2 : Cover crop biomass production in fall (A, C) and spring (B, D) in the planting windows prior to maize (A, B) and prior to soybean (C, D). Clusters of bars represent results from the 2012-2013, 2013-2014, and 2014-2015 cover cropping seasons, respectively. Note the different scale in the expanded portion of C. Adapted from Murrell et al. (2017).	45
Figure 3-3 : Cover crop biomass carbon:nitrogen ratio in the fall (A) and spring (B) prior to maize (mean and standard deviation). C:N ratio is not reported for the fallow treatment since weeds were controlled with tillage	46
Figure 3-4 : Cover crop biomass carbon:nitrogen ratio in the spring prior to soybean (mean and standard deviation).	16
Figure 3-5 : Soil inorganic nitrogen in nitrate (NO ₃ ⁻) and ammonium (NH ₄ ⁺) in the top 20 cm of soil in plots planted to maize in 2013, 2014, and 2015. Downward arrows indicate the dates of cover crop termination, which were closely followed by manure application and tillage. Upward arrows indicate the dates of maize planting.	47
Figure 3-6 : Area-under-the-curve of soil inorganic nitrogen (SIN _{auc}) in nitrate (NO ₃ ⁻) and ammonium (NH ₄ ⁺) in the top 20 cm of soil in plots planted to maize between early June and late July pooled across 2013, 2014, and 2015 (mean and standard deviation)	1 9

Figure 3-7: Spatiotemporal stability of the area under the curve of soil inorganic nitrogen (SIN _{auc}) in nitrate (NO ₃ ⁻) and ammonium (NH ₄ ⁺) in the top 20 cm of soil in plots planted to maize. Environmental index is the mean SIN _{auc} of all treatments in each block of four blocks in three years. A slope of one indicates mean stability for this set of treatments, lower slope indicates greater stability, and higher slope indicates lower stability	. 51
Figure 3-8 : Soil inorganic nitrogen (SIN) in nitrate (NO ₃ ⁻) and ammonium (NH ₄ ⁺) in the top 20 cm of soil in plots planted to soybean in 2013, 2014, and 2015. Downward arrows indicate the dates of cover crop termination, which were closely followed by tillage. Upward arrows indicate the dates of soybean planting. Note that SIN was sampled on only two dates in 2013.	. 52
Figure 3-9 : Soil inorganic nitrogen (SIN) in nitrate (NO ₃ ⁻) and ammonium (NH ₄ ⁺) in the top 20 cm of soil in plots planted to soybean in mid-June of 2014 and 2015 ($6/11/2014$ and $6/24/2015$; mean and standard deviation).	. 53
Figure 3-10 : Maize silage yield (Mg ha ⁻¹ dry matter) following cover crop monocultures and mixtures (mean and standard deviation).	. 54
Figure 3-11: Relationship between maize silage yield (Mg ha ⁻¹ dry matter) and the area-under- the-curve of soil inorganic nitrogen (SIN _{auc}) in nitrate (NO ₃ ⁻) and ammonium (NH ₄ ⁺) in the top 20 cm of soil under maize between early June and late July.	. 54
Figure 3-12 : Spatiotemporal stability of maize silage yield. Environmental index is the mean yield of all treatments in each block of four blocks in three years.	. 57
Figure 3-13 : Relationship between spatiotemporal consistent-performance index of SIN _{auc} (CPI _{sin}) and maize silage yield (CPI _{Zm}). Each point represents one cover crop treatment. CPI score for a given value (yield or SIN _{auc}) corresponds to the mean rank for that value across three years and four blocks.	. 58
Figure 3-14 : Soybean yield (13% moisture) following cover crop monocultures and mixtures (mean and standard deviation).	. 59
Figure 3-15 : Spatiotemporal stability of soybean yield. Environmental index is the mean yield of all treatments in each block of four blocks in three years. A slope of one indicates mean stability for this set of treatments, lower slope indicates greater stability, and higher slope indicates lower stability.	. 60
Figure 3-16 : Wheat yield (13.5% moisture) following cover crop monocultures and mixtures (mean and standard deviation).	. 61
Figure 4-1: Rainout shelter shortly after installation during early maize growth	. 81
Figure 4-2: Timeline of ecophysiological measurements (θ_v , soil volumetric water content; Ψ_L , leaf xylem water potential; SPAD, SPAD meter; SIN, soil inorganic nitrogen; LAI, leaf area index; g_s , stomatal conductance).	. 84

Figure 4-3: Monthly precipitation (A) and mean temperature (B) for the growing season (May to September) in 2014 and 2015, in comparison to monthly averages for 1980 to 2016 (horizontal black bars). Data is from NLDAS (Xia et al. 2012).	93
Figure 4-4: Volumetric water content in ambient (blue) and drought (red) maize plots at 10, 20 and 40 cm depth in 2014 and 2015	94
Figure 4-5: Pre-dawn leaf xylem water potential by cover crop, drought treatment, and year (readings taken on 8/19/14 and 8/14/15; mean and standard deviation)	94
Figure 4-6 : Soil volumetric water content just prior to cover crop termination (5/2/2014 and 4/29/2015; 20 cm depth; mean and standard deviation).	98
Figure 4-7: Soil inorganic nitrogen in nitrate (NO ₃ ⁻) and ammonium (NH ₄ ⁺) in the top 20 cm of soil under maize in 2014 and 2015. Downward arrows indicate the dates of cover crop termination, which were closely followed by manure application and tillage. Upward arrows indicate the dates of maize planting.	99
Figure 4-8 : Maize SPAD meter reading (A), leaf area index (B), stomatal conductance (C), and height (D) by cover crop, drought treatment, and year	100
Figure 4-9 : Final SPAD readings by cover crop, drought treatment, and year (sampling dates: 9/3/14 and 9/11/15; mean and standard deviation)	101
Figure 4-10 : Hemispherical leaf area index by cover crop, drought treatment, and year (measured on 8/15/14 and 8/13/15; mean and standard deviation).	105
Figure 4-11: Seasonal solar radiation interception by cover crop, drought treatment, and year (mean and standard deviation).	106
Figure 4-12 : Maize radiation use efficiency by cover crop, drought treatment, and year (mean and standard deviation).	107
Figure 4-13 : Mid-August leaf stomatal conductance by cover crop, drought treatment, and year (readings taken on 8/14/14 and 8/14/15; mean and standard deviation)	108
Figure 4-14 : Relationship between final SPAD reading and stomatal conductance in mid- August by drought treatment and year (readings taken on 8/14/14 and 8/14/15 between 11:00 and 16:00).	109
Figure 4-15 : Maize kernel biomass by cover crop, drought treatment, and year (mean and standard deviation).	110
Figure 4-16 : Maize kernel yield loss due to drought by cover crop and year (mean and standard deviation).	115
Figure 4-17 : Kernel yield stability analysis for the two years and drought treatments. Environmental index is the mean yield of all treatments in an environment. The order of environments across the X axis is 2014 drought, 2014 ambient, 2015 drought, 2015 ambient. A slope of one indicates mean stability for this set of treatments, lower slope	

indicates greater stability, and higher slope indicates lower stability. The dashed black line has a slope of one and an intercept of zero.	. 118
Figure 5-1: Maize grain yield (A) and standardized precipitation-evapotranspiration index (B; SPEI) for historical (1950-2005) and projected future (2006-2099) climate conditions. The simulation in A was run with crop residues retained. The shaded area in B represents the 95% confidence interval.	. 134
Figure 5-2: Soil management effects on maize grain yield (A) and yield relative to conventional tillage (B) across the range of standardized precipitation-evapotranspiration index (SPEI) values simulated for 1950-2099. The simulation was run with crop residues retained. The shaded areas in B represent the 95% confidence intervals, which were adjusted for multiple comparisons with a Tukey correction.	. 135
Figure 5-3 : Percent of years in each moisture category between the beginning (2000-2029) and end (2070-2099) of the 21 st century.	. 137
Figure 5-4: Sensitivity analysis of maize yield response to available water capacity (AWC) in the top 40 cm of soil and infiltration rate (IR) as determined by the curve number (CN). Mean yield is from all years from 1950-2099 in which moderate-to-severe drought occurred in June-August (values of the standardized precipitation-evapotranspiration index less than or equal to -0.5). Values of AWC reflect the legacy of four long-term soil management regimes. Curve numbers represent the range between the highest (woodlot) and lowest (conventional tillage) infiltration rates for these management regimes. (Note: IR increases as CN decreases.) The simulation was run with crop residues retained	. 138
Figure 5-5: Soil management effects on maize grain yield with crop residue retained (A) and crop residue removed (B) across the range of standardized precipitation-evapotranspiration index values simulated for 1950-2099. Best-fit lines from B are plotted in gray on A for comparison, and vice versa.	. 139
Figure 5-6 : Soil management effects on maize grain yield across the range of standardized precipitation-evapotranspiration index (SPEI) values simulated for 1950-2099 with crop residue removed and equal infiltration rate for all soils (curve number = 80)	. 140
Figure A-1: Root intersections per square inch of vertical soil face under the maize row, by cover crop and drought treatment. Root pits were dug following maize harvest in 2015 (10/6-10/15).	. 152

х

LIST OF TABLES

Table 3-1: Field management details.	. 34
Table 3-2: Cover crop treatment species diversity and seeding rates.	. 36
Table 3-3 : Aboveground biomass (kg ha ⁻¹ dry matter) and carbon-to-nitrogen (C:N) ratio by year of cover crops grown prior to maize (PM). Biomass and C:N values both include weeds. C:N ratio mean is weighted by the biomass of each replicate. Means within years that share a letter are not significantly different at the alpha = 0.05 level with a Tukey correction for multiple comparisons. Cover crop biomass values were previously reported in Murrell et al. (2017) and Baraibar et al. (2018).	. 43
Table 3-4 : Aboveground biomass (kg ha ⁻¹ dry matter) and carbon-to-nitrogen (C:N) ratio by year of cover crops grown prior to soybean (PS). Biomass and C:N values both include weeds. C:N ratio mean is weighted by the biomass of each replicate. Means within years that share a letter are not significantly different at the alpha = 0.05 level with a Tukey correction for multiple comparisons. Fall biomass and C:N ratio are not reported for the fallow treatment due to missing data.	. 44
Table 3-5 : Area-under-the-curve of soil inorganic nitrogen (SIN _{auc}) in nitrate (NO ₃ ⁻) and ammonium (NH ₄ ⁺) in the top 20 cm of soil in plots planted to maize between early June and late July. Means within years that share a letter are not significantly different at the alpha = 0.05 level with a Tukey correction for multiple comparisons.	. 48
Table 3-6 : Mean area-under-the-curve of soil inorganic nitrogen (SIN _{auc}) and spatiotemporal stability metrics of SIN _{auc} (consistent performance index (CPI _{sin}), coefficient of variation (CV), and slope of the environmental index (EI)), by cover crop treatment. Values represent all three years of the study. Means within columns that share a letter are not significantly different at the alpha = 0.05 level with a Tukey correction for multiple comparisons. An EI slope of one indicates mean stability for this set of treatments, lower slope indicates greater stability, and higher slope indicates lower stability. There were no statistical differences among EI slopes.	. 50
Table 3-7: Soil inorganic nitrogen (SIN) in nitrate (NO ₃ ⁻) and ammonium (NH ₄ ⁺) in the top 20 cm of soil in plots planted to soybean in mid-June. Means within years that share a letter are not significantly different at the alpha = 0.05 level with a Tukey correction for multiple comparisons.	. 52
Table 3-8 : Maize silage, soybean, and wheat yields by cover crop and year. Means within or across years that share a letter are not significantly different at the alpha = 0.05 level with a Tukey correction for multiple comparisons. There are no pairwise differences among cover crop treatments for soybean or wheat yield.	. 56
Table 3-9 : Mean maize silage yield and spatiotemporal stability metrics of yield (consistent performance index (CPI_{Zm}), coefficient of variation (CV), and slope of the environmental index (EI)), by cover crop treatment. Values represent all three years of the study. Means within columns that share a letter are not significantly different at the alpha = 0.05 level	

with a Tukey correction for multiple comparisons. An EI slope of one indicates mean stability for this set of treatments, lower slope indicates greater stability, and higher slope indicates lower stability. There were no statistical differences among EI slopes	. 57
Table 3-10 : Mean soybean yield and spatiotemporal stability metrics of yield (consistent performance index (CPI _{<i>Gm</i>}), coefficient of variation (CV), and slope of the environmental index (EI)), by cover crop treatment. Values represent all three years of the study. There were no statistical differences among values in any of the columns. An EI slope of one indicates mean stability for this set of treatments, lower slope indicates greater stability, and higher slope indicates lower stability.	60
Table 4-1: Management dates, manure rate, and manure plant-available N.	. 79
Table 4-2: Cover crop treatments, treatment abbreviations, number of species per treatment, target plant populations, and expected level of functional traits.	. 79
Table 4-3: Dates of ecophysiological measurements.	. 85
Table 4-4 : Cover crop dry matter (kg ha-1) and C:N ratio in the fall and spring of the 2013-2014 and 2014-2015 cover crop growing seasons. Means within columns and years that share a letter are not significantly different at the alpha = 0.05 level with a Tukey correction for multiple comparisons.	91
Table 4-5: Shelter microclimate measurements. Soil volumetric water content was measured with time domain reflectometry probes installed horizontally at 10, 20, and 40 cm depths. Air temperature was measured with temperature loggers suspended 1 m above the ground in the maize canopy. Minimum, maximum, and mean temperatures reflect the entire 24-hour cycle. Day and night temperatures are the means for 06:00 to 20:00 and 20:00 to 06:00, respectively. Pre-dawn leaf temperature was measured with an infrared radiometer. Overall means within columns and years are significantly different at the alpha = 0.05 level when they do not share a letter. There were no differences by cover crop treatment for any of the measurements reported here. There were also no significant differences in air temperature between the ambient and drought conditions.	95
Table 4-6 : Select ecophysiological measures of maize grown following cover crops under either ambient conditions or in rainout shelters. Across both years, means within a column are significantly different at the alpha = 0.05 level when they do not share a letter. Capital letters distinguish between ambient and drought conditions. Lower-case letters distinguish among cover crops, with a Tukey correction for multiple comparisons	102
Table 4-7: Height, yield and yield components of maize grown following various cover crop treatments under either ambient or imposed drought conditions. Results are reported for 2014, 2015, and the two years pooled. Across both years, means within a column are significantly different at the alpha = 0.05 level when they do not share a letter. Capital letters distinguish between ambient and drought conditions. Lower-case letters distinguish among cover crops, with a Tukey correction for multiple comparisons	111
Table 4-8: Relative drought stress effects (DS_{rel}) caused by rainout shelters for maize grown	

following various cover crop treatments. Negative values indicate a reduction relative to

r c c	naize grown under ambient conditions. For all DS_{rel} measures, means are not significantly different by cover crop at the alpha = 0.05 level with a Tukey correction for multiple comparisons.	114
Table s	4-9 : Mean maize kernel yield estimated marginal mean and stability analysis regression slope by cover crop treatment. Means within columns that share a letter are not significantly different at the alpha = 0.05 level with a Tukey correction for multiple	
С	comparisons	117
Table c	5-1 : Hydraulic properties in the top 40 cm of soils following 49 years of contrasting listurbance regimes.	130
Table t c V s	5-2 : Mean maize grain yield by residue management scenario, soil management reatment, and moisture category for 1950-2099. Values in parentheses represent percent differences in mean yield between each soil management category and conventional till. Within each residue-management scenario, means within each moisture category that share a letter are not significantly different at the alpha = 0.05 level with a Bonferroni	
С	correction for multiple comparisons	136

PREFACE

Chapter 2 has already been published in *BioScience* (67: 386–391) as a multi-author paper. Mitchell Clayton Hunter conceived of the approach, performed the data analysis, and led the writing and editing processes. Richard G Smith, Meagan E. Schipanski, and Lesley W. Atwood contributed to the development of the approach and to writing and editing. David A. Mortensen convened the authors; posed the original question; and contributed to the development of the approach and to writing and editing.

ACKNOWLEDGEMENTS

I am grateful to all the people who have helped me grow as a scholar and a person over the past six years. I am not sure what twist of fate led me to connect with my advisor, Dr. David Mortensen, at the PASA conference in 2012, but I know that this was a profound meeting. Over the last six years, Dave has been an incredibly caring mentor, a stimulating intellectual partner, a farsighted guide—and he has become a very good friend. Dave is endowed with an extraordinary complement of humanity. Though I have benefited greatly from his technical training, academic guidance, and career wisdom, the most important thing I will take forward with me is the example of his unfailing propensity to engage deeply and genuinely with the people around him. This instinct not only makes Dave a joy to work with, it makes him a better teacher and scholar as well. I will do my best to emulate this quality in my own life. I have been called "little Dave" on more than one occasion—a high compliment that I will try to live up to.

I certainly cannot thank everyone by name or in full, but I will try to hit some highlights. Dr. Meagan Schipanski served as a second advisor in my first year or two, showed me the ropes of field work, got me started thinking about diversity and resilience, and is yet another example of extreme humanity. I am grateful to Dr. Jason Kaye for leading the vibrant multidisciplinary Cover Crop Cocktails (CCC) project team, which was one of the most important intellectual experiences of my PhD process, and for building such a comprehensive research program around nitrogen. My work has benefited immensely from understanding the nitrogen cycle; it really does explain everything. Drs. Dave Eissenstat and Armen Kemanian inspired my interest in ecophysiology and equipped me with a large toolbox to draw on. Dave Eissenstat also motivated a focus on clearly-articulated hypotheses, while Armen has both helped me develop modeling skills and cursed (actually blessed) me with the habit of seeing the whole world in terms of exchanges of energy and mass. Finally, Drs. Erin Connolly and Marvin Hall put in lots of time and effort supporting my many scholarship applications. The list could go on.

This job has been fun because of the people I've gotten to work with, especially the research technicians, postdocs, and fellow grad students. From the early days with Al and Mac (properly speaking, Dr. Macdonald Burgess), to the Jim/Dayton era, to the new regime of Brosi and Dayton, the CCC field crew has been a joy to work with. Brosi has been the rock, the rudder, the ballast, the chassis and the steering wheel all at the same time (and a great inspiration to play more volleyball). I couldn't have done it without her, especially since the Kaye lab biweekly soil nitrogen samples proved critical for half of my chapters. Denise (now Dr. Denise Finney) was an awesome rainout

shelter design-build partner. The weed lab was a great home thanks to Bill, Dwight, Art, Franklin, Katy, Clair, Eli, Kat, Kelly, Mark, Rachel, Abbe, Tosh, Matt, Melanie, Jess, Rebecca, Erik, Annie, etc. Drs. John Wallace, Barbara Baraibar, Ebony Murrell, Charlie White, and Glenna Malcolm—not to mention Meagan and Mac—have variously been great officemates, stats gurus, co-authors, and friends, and have given me excellent models of postdoc-dom to follow. All (well, most) of my summer research assistants were awesome as well, so here's a special "4 Rows!" shout out to Anna, Elyse, Sadie, Sara, David, Keirstan, Wingyi, Evan, Emily, Julian, Sonia, Cassidy, Jeep, Brendan, Mary, Matthew and everyone else who helped dig TDR holes. (Listing so many names is dangerous – I'm sure I've forgotten some. Apologies!)

Through it all I've been supported by an awesome and ever-changing group of friends here in State College, as well as some who've known me for decades. Thanks to my brother and sister and their families for their love and support, and for coming to State College for my defense. Finally, my deepest and most lasting thanks go to my parents. They always taught me that hard work pays off, especially when you're doing something interesting and challenging. After six years, the evidence supports their hypothesis. Mom and Dad, your example of decency and perseverance guides me every day, and your unwavering love has been a subtle wind at my back for as long as I can remember. Thank you.

Now for the obligatory part: This work was supported by the USDA National Institute of Food and Agriculture, Organic Research and Extension Initiative under Project PENW-2015-07433, Grant No. 2015-51300-24156 and Accession No. 1007156. This material is based on work supported by the National Science Foundation under Grant no. DGE1255832. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation. "What more delightful avocation than to take a piece of land and by cautious experimentation to prove how it works."

Aldo Leopold Unpublished Manuscripts 1928-1948

Chapter 1

Introduction

1.1 The Challenge

Agriculture sits at the nexus of ecology and society. It is a critical human life-support system, a major economic sector, a dominant land use, and a leading contributor to numerous environmental problems, including deforestation, greenhouse gas emissions, and eutrophication. Going forward, growing population and wealth will increase demands on agriculture while global climate change threatens to disrupt production. Humanity must confront these challenges to underpin future prosperity and maintain functioning ecosystems. Concerted action now can lead to better outcomes for people and the planet over the coming decades.

Globally, farmers produce staggering amounts of food every year. For instance, in 2016, farmers produced over a billion tonnes of maize and almost 800 million tonnes of milk (FAO 2018). Achievements such as these are the result of thousands of years of informal crop and livestock selection and the development of locally-adapted farming practices, followed by a few hundred years of formal scientific efforts to improve germplasm, optimize soil nutrient supply, control pests, and mechanize production tasks. These gains should not be taken for granted, nor should they be worshipped. Though intensified farming has led to many environmental and social challenges, the productive potential of modern agriculture will be an asset as the system's effects are brought back into better balance.

Amid unprecedented agricultural abundance, over 800 million people still experience food insecurity annually (FAO et al. 2017). This is primarily due to distributional injustice—lack of access and affordability—rather than limited supply. Poverty, armed conflict, political instability, and lack of infrastructure are the main causes of hunger. While subsistence farmers often experience food insecurity, those with disposable income in towns and cities enjoy ever more options and convenience. Moreover, the diet-related diseases of the rich world now afflict many in developing countries, as hunger gives way to a false abundance of nutrient-poor food. The food system must be restructured to ensure that all humans have equitable and secure access to sufficient quantities of nutritious, culturally-appropriate foods. Agricultural production, and hence agricultural research, has an important role to play in this transition. The development of scientific knowledge and new farming techniques can enable production of a more diverse range of crops with improved nutritional profiles, reduced environmental impacts, and increased resilience to climate change. Agriculture does not exist in a vacuum and systemic change will require enabling shifts in political and economic structures. Scientific discovery can support this social change process by creating new technical, economic, and, thereby, political possibilities. For instance, the development of no-till planting techniques and other soil conservation measures that were economically viable for farmers enabled the passage of the Conservation Compliance requirement in the 1985 Farm Bill. By the same token, research is needed now to develop production systems that could underpin an equitable and healthy food system.

These production systems must also support the conservation and regeneration of ecosystem functions that provision humanity's other life-support systems: clean water, clean air, biodiversity, and a stable climate. As currently practiced, agriculture is a threat to these indispensable functions. Land conversion, soil disturbance, irrigation water withdrawal, fertilizer application, and the use of pesticides are among the leading causes of habitat loss, biodiversity decline, soil erosion, groundwater depletion, greenhouse gas emissions, and eutrophication (Robertson and Swinton 2005, Foley et al. 2011, Hallmann et al. 2017, Haacker et al. 2015). In some cases, such as reactive nitrogen (N) pollution and genetic diversity loss, humanity has already exceeded the globe's capacity to absorb our impact, also known as a "planetary boundary" (Steffen et al. 2015). In others, such as freshwater use, human impacts are substantial but the boundary has not yet been passed, so the imperative is to ensure that impacts do not grow.

Projected changes in global population, wealth, diet, and lifestyles threaten to exacerbate many of these challenges. As the population grows toward 9.8 billion in 2050 (UN 2017) and more people adopt diets high in meat and dairy products, global food demand may increase by 26-68%, compared to 2014 (Hunter et al. 2017). This demand could be substantially reduced by reducing food waste, limiting the use of food-competitive crops for biofuels, or shifting toward less resource-intensive diets (Wise 2013, Foley et al. 2011, Kummu et al. 2017). However, food demand is likely to increase.

Increased demand, in turn, will spur both economic and political responses aimed at increasing production. High commodity prices in 2008-2012 helped drive the conversion of over 7 million acres of uncultivated U.S. land for production (Lark et al. 2015). The 2014 U.S. Farm Bill also reflected this context, as the number of acres set aside in the Conservation Reserve Program was reduced from 32 to 24 million, and new safety net programs were instituted that assumed a "new

normal" of high prices. While prices have since moderated, future increases in global demand are likely to motivate continued land conversion and intensification of agricultural inputs such as fertilizers and pesticides, risking further damage to ecosystem integrity. Moreover, given current market structures, production increases spurred by price signals in the global commodity market are unlikely to lead to the shifts in food access necessary to achieve nutritional security. Intensifying production in a way that is adapted to local conditions, both environmental and dietary, can help meet demand while preserving natural resources (Cunningham et al. 2013).

The challenge of meeting increased demand sustainably will be further complicated by the changing climate. Higher temperatures and altered precipitation patterns are projected to depress mean crop yields in many areas. Already, Lobell et al. (2011) estimate that climate change reduced global maize (*Zea mays* L.) and wheat (*Triticum aestivum* L.) yields by 3.8% and 5.5%, respectively, from 1980-2008. In the main cropping region of the United States, increased temperature and water stress are projected to reduce maize yield by up to 30-40% by the end of the 21st century under a high-emissions scenario (Jin et al. 2017). This projection accounts for the ameliorating effect of by higher atmospheric CO₂ concentration, which increases carboxylation efficiency in C3 crops and transpiration efficiency in both C3 and C4 crops (Jaggard et al. 2010, Walthall et al. 2013). The combination of higher temperature, a shift in rainfall patterns, and elevated CO₂ concentration is likely to boost yield for some crops in some regions, such as soybean (*Glycine max* L.) grown in cooler conditions (Jin et al. 2017). However, the weight of the evidence suggests that yields are likely to decline, especially in tropical regions (Challinor et al. 2014).

Some authors have suggested that genetic and agronomic adaptation can substantially reduce or even eliminate the negative yield effects of climate change (Butler and Huybers 2013, Cassman et al. 2011). For instance, shifting planting dates to earlier in the season may help avoid extreme heat and drought in mid-to-late summer (Teixeira et al. 2017), though this strategy may increase the risk of frost damage. Opportunities for double-cropping (Wu et al. 2018) may expand under climate change, enabling intensification of production on existing cropland. However, a global analysis suggests that large areas of the globe will enter a climate regime so different from that under which current cropping is practiced that substantial shifts in cropping practices will be required (Pugh et al. 2016), creating a high demand on adaptation resources. Likewise, as breeding programs shift their focus to climate adaptation, it may be more difficult to sustain long-term trend rates of yield improvement. Climate change may also depress yields by increasing atmospheric ozone concentrations, weed competitiveness, and damage from insects and pathogens (Walthall et al. 2013, Hatfield et al. 2011). We must prepare for the possibility that climate change will act as a strong yield drag. In addition to depressing mean yields, climate change is projected to increase the frequency of extreme weather events (Walsh 2014), making production more variable in time and space. A global meta-analysis (Challinor et al. 2014) found that shifts in temperature and precipitation patterns are likely to increase yield variability. However, a statistical modeling study found that the effect of increased CO₂ concentration on transpirative efficiency eliminated the increase in yield variability, though the authors note that this effect benefit may be overestimated (Urban et al. 2015). Extreme weather can affect yield in ways not typically captured in modeling studies, such as by causing flooding, anaerobic soil conditions, catastrophic erosion, and field management challenges, so uncertainty remains about the effect of climate change on yield variability. Increased variability would heighten the logistical challenge of providing food where it is needed and may lead to price swings, intensification of environmentally-risky management practices, conversion of native ecosystems, and social unrest (Bellemare 2015).

In short, new strategies are needed to develop production systems that can deliver nutritious, affordable, and accessible food; maintain high and stable yield in the face of climate change; and maintain or restore ecosystem integrity. The goal of my dissertation has been to help develop these strategies.

1.2 Clarifying Goals for Sustainable Intensification

The nexus of challenges described above is widely recognized among agricultural scientists. One commonly-discussed strategy to address it—simply put, producing more food with less pollution—is typically termed "sustainable intensification" (Garnett et al. 2013, Pretty and Bharucha 2014, Rockström et al. 2016). Though this concept implies that past intensification has not been sustainable, and therefore that farming must change, in practice the term is frequently used to justify a continuation of the status quo (e.g., Monsanto 2008, Ziegler 2017). In part, this is because the concept of sustainable intensification has been conflated with a dominant narrative that food production must double by 2050 to meet world demand. The focus on doubling food production creates an urgency around increasing production, which in turn mutes concern about resulting environmental impacts and annuls discussion of alternatives to conventional farming practices. Related calls for agriculture to become more environmentally sustainable lack urgency and specificity, rendering them weak. This imbalanced narrative, in which production is privileged over conservation, exerts a strong influence on agricultural research and policy priorities. To help reframe this narrative, I worked with colleagues to update the two most widely-cited food demand projections (Tilman et al. 2011, Alexandratos and Bruinsma 2012). Our analysis, presented here as Chapter 2 and published in *BioScience* (Hunter et al. 2017), finds that food demand will increase only 26-68% between 2014 and 2050 (rather than 100%). This lower target relieves pressure for rapid intensification. We also reviewed published goals for agricultural greenhouse gas emissions and nutrient losses to water bodies, which indicate that agricultural pollution must decrease rapidly to maintain ecosystem integrity. Together, these quantitative targets for production and environmental impacts provide a more balanced set of priorities for agricultural research and policy.

1.3 Diversification and Stability

Meeting global food demand while restoring ecosystems and adapting to climate change will require efforts at multiple scales. For instance, global trade agreements will affect the ability to balance regional shortfalls and surpluses, while also shaping the economic outlook of smallholder farmers in developing countries. Regional water stewardship will determine the potential for continued irrigation in arid regions and therefore the mix of crops that can be grown. The position of different modes of production and conservation on the landscape will influence the rates of nutrient and sediment loss, as well as habitat suitability for wildlife. At the farm level, choice of cropping system and management will affect the local biotic and abiotic conditions that interact with annual weather to determine crop yields. There are opportunities to enhance stability of food production and supply at all of these levels. This research is focused on improving yield stability at the farm level through diversification and conservation practices.

Adding biological diversity to agricultural systems has the potential to increase resistance and resilience in the face of stochastic environmental conditions. Diversification in space, such as by increasing the number of species present within a plant stand, can increase complementation and facilitation (Hooper et al. 2005). In managed agricultural systems, species can be chosen to ensure that plant mixtures contain functional traits that contribute to achieving agronomic and environmental goals. Moreover, many diversification practices, such as crop rotation, cover cropping, and perennials, have the potential to increase soil carbon and nitrogen content; enhance nutrient cycling; and improve soil structural properties that underpin water capture, storage, and drainage (McDaniel et al. 2017, Blanco-Canqui et al. 2015, Ernst et al. 2018).

Chapter 3 analyzes the effects of multi-species cover crop mixtures on the mean levels and spatiotemporal stability of cash crop yield and soil N supply. I analyze results from the first phase of the Cover Crop Cocktails project, an organically-managed three-year rotation of maize, soybean, and wheat in which a range of cover crop monocultures and mixtures were planted in two positions in the rotation (Murrell et al. 2017). This analysis is motivated by ecological literature indicating that more-diverse plant communities exhibit greater temporal stability of biomass production and other ecosystem services (Hooper et al. 2005). In general, diversifying crop rotations and adding cover crops is linked to increased yield stability (e.g., Gaudin et al. 2015). Cover crop mixtures have been shown to have a range of effects on cash crop yields, with a strong relationship between cover crop biomass carbon:nitrogen (C:N) ratio and yield of the following maize crop (Finney et al. 2016, White et al. 2017). However, the effects of cover crop mixtures on cash crop yield stability have never been tested, to the best of my knowledge. Nor has the mechanistic relationship between cover crop diversity, the stability of soil N supply, and the stability of cash crop yield. The results of this chapter illustrate the potential for cover cropping in general, and cover crop mixtures in particular, to help sustain high and stable crop yields under organic management conditions.

Chapter 4 evaluates the potential for cover crops to mitigate a specific climate change impact: increased drought stress. Cover crops have been shown to influence a range of abiotic and biotic properties that influence a crop's response to moisture deficit. First, cover crops transpire water in the spring, which may deplete soil reserves needed for cash crop growth (Ewing et al. 1991). However, cover crops also have the potential to increase water infiltration and improve soil properties that enable greater water storage (Blanco-Canqui et al. 2015; Basche 2017); reduce surface evaporation (Jones et al. 1969); enable cash crops to grow deeper roots (Chen and Weil 2010); and increase colonization of arbuscular-mycorrhizal fungi, which may enhance drought tolerance (Kabir and Koide 2002, Boomsma and Vyn 2008).

While many of these effects require years to develop, in the short term, cover crops may also affect cash crop drought physiology by influencing soil N dynamics. Availability of nitrogen and water are critical determinants of plant performance (Gonzalez-Dugo et al. 2010). Both water- and N-stress ultimately impair yield formation by reducing radiation interception (RI) and radiation use efficiency (RUE), two critical controls on photosynthesis and plant growth (Stöckle and Kemanian 2009, Wolfe et al. 1988). Water- and N-stress also both affect development of reproductive tissues, and therefore the harvest index (HI) (Earl and Davis 2003). Some have suggested that N limitation may help crops tolerate drought (Radin and Parker 1979) by reducing transpirative demand and

stimulating root growth (Bennett et al. 1986). In contrast, high N supply may reduce drought stress directly by enabling osmotic adjustment.

I tested the effects of cover crops on the drought physiology of the following maize crop with a field study embedded in the Cover Crop Cocktails project. Along with a team of collaborators, I designed and built a set of modular rainout shelters, which I then deployed in maize grown following functionally-diverse cover crops. Cover crop treatments were selected to provide a range of functional traits with respect to spring transpiration and biomass C:N ratio. The results of this chapter provide the first report of the effects of cover crops on maize yield response to experimental drought and may help farmers design cover cropping strategies that increase their drought resilience.

Chapter 5 extends this question by evaluating the drought-mitigating effects of long-term soil improvement. Since soil structural properties change slowly, it is difficult to evaluate their effects in a field study. Both anecdotal reports and long-term research studies indicate that management practices that improve soil hydraulic properties can reduce yield losses under drought. Basic soil physics suggests that improving soil structure should help soils infiltrate and retain more water, enabling crops to continue growing during droughts. However, there is little research that quantitatively assesses increased drought resilience in improved soils. As a result, it is difficult to assess the potential for soil improvement to aid drought adaptation.

I used the results of a long-term (49-year) field study of different tillage methods (Kumar et al. 2012a,b) to parameterize soils in the Cycles agroecosystem model, which shares modules with C-Farm (Kemanian and Stöckle 2010) and CropSyst (Stöckle et al. 2014). Long-term soil management strongly influenced infiltration rate (IR) and available water capacity (AWC), two critical hydraulic properties that determine precipitation capture and storage. Across a gradient of reduced soil disturbance from conventional tillage to a woodlot control, IR increased by more than 19-fold and AWC by more than 2-fold (Kumar et al. 2012b). I simulated the effects of these changes in soil properties across a range of historical and future climate conditions, with future conditions simulated based on the high-greenhouse gas emissions scenario RCP8.5. I evaluated the relative effects of AWC and IR and their interaction with residue management, which affects soil surface evaporation. Results illustrate the scope for protecting maize yield under drought by enhancing water capture and storage with soil-building practices.

1.4 Conclusion

The chapters presented here contribute in a variety of ways to the overall challenge of developing a food system that can provide nutritional security and ecosystem integrity in the face of climate change. By reshaping researchers' mental models, Chapter 2 will help ensure that the research questions asked today move agriculture in the right direction for the future. The subsequent chapters assess the potential for specific management strategies to support high and stable crop yield despite environmental stochasticity. In particular, Chapters 4 and 5 inform both short- and long-term strategies for adapting cropping systems to increased drought stress through diversification and conservation strategies such as cover crops and reduced tillage. It is my hope that these results contribute to a greater body of scientific work that helps spur practical change, which in turn opens possibilities for economic and political transformation toward a more just and environmentally sustainable food system.

1.5 References

- Alexandratos N, Bruinsma J. 2012. World Agriculture Towards 2030/2050: The 2012 Revision. Food and Agriculture Organization of the United Nations. ESA Working Paper no. 12-03.
- Bellemare, M.F. 2015. Rising food prices, food price volatility, and social unrest. Am. J. Agric. Econ. 97: 1–21. doi: 10.1093/ajae/aau038.
- Bennett, J.M., J.W. Jones, B. Zur, and L.C. Hammond. 1986. Interactive Effects of Nitrogen and Water Stresses on Water Relations of Field-Grown Corn Leaves. Agron. J. 78: 273. doi: 10.2134/agronj1986.00021962007800020012x.
- Blanco-Canqui, H., T.M. Shaver, J.L. Lindquist, C.A. Shapiro, R.W. Elmore, C.A. Francis, and G.W. Hergert. 2015. Cover Crops and Ecosystem Services: Insights from Studies in Temperate Soils. Agron. J. 107: 2449–2474. doi: 10.2134/agronj15.0086.
- Boomsma, C.R., and T.J. Vyn. 2008. Maize drought tolerance: Potential improvements through arbuscular mycorrhizal symbiosis? F. Crop. Res. 108: 14–31. doi: 10.1016/j.fcr.2008.03.002.
- Butler, E.E., and P. Huybers. 2013. Adaptation of US maize to temperature variations. Nat. Clim. Chang. 3(1): 68–72. doi: 10.1038/nclimate1585.
- Cassman, K.G., P. Grassini, and J. van Wart. 2011. Crop Yield Potential, Yield Trends, and Global Food Security in a Changing Climate. p. 37–51. *In* Rosenzweig, D.H. and C. (ed.), Handbook of

Climate Change and Agroecosystems: Impacts, Adaptation, and Mitigation. Imperial College Press, London, UK.

- Challinor, A.J., J. Watson, D.B. Lobell, S.M. Howden, D.R. Smith, and N. Chhetri. 2014. A metaanalysis of crop yield under climate change and adaptation. Nat. Clim. Chang. 4: 287–291. doi: 10.1038/nclimate2153.
- Chen, G., and R.R. Weil. 2010. Penetration of cover crop roots through compacted soils. Plant Soil 331: 31–43. doi: 10.1007/s11104-009-0223-7.
- Cunningham, S.A., S.J. Attwood, K.S. Bawa, T.G. Benton, L.M. Broadhurst, R.K. Didham, S. McIntyre, I. Perfecto, M.J. Samways, T. Tscharntke, J. Vandermeer, M.-A. Villard, A.G. Young, and D.B. Lindenmayer. 2013. To close the yield-gap while saving biodiversity will require multiple locally relevant strategies. Agric. Ecosyst. Environ. 173: 20–27. doi: 10.1016/j.agee.2013.04.007.
- Earl, H.J., and R.F. Davis. 2003. Effect of Drought Stress on Leaf and Whole Canopy Radiation Use Efficiency and Yield of Maize. Agron. J. 95: 688–696. doi: 10.2134/agronj2003.6880.
- Ernst, O.R., S. Dogliotti, M. Cadenazzi, and A.R. Kemanian. 2018. Shifting crop-pasture rotations to no-till annual cropping reduces soil quality and wheat yield. F. Crop. Res. 217: 180–187. doi: 10.1016/j.fcr.2017.11.014.
- Ewing, R.P., M.G. Wagger, and H.P. Denton. 1991. Tillage and Cover Crop Management Effects on Soil Water and Corn Yield. Soil Sci. Soc. Am. J. 55: 1081–1085.
- FAO. 2016. FAOSTAT Database. www.fao.org/faostat.
- FAO IFAD UNICEF, W.& W. 2017. The State of Food Security and Nutrition in the World 2017. Building resilience for peace and security. Rome.
- Finney, D.M., C.M. White, and J.P. Kaye. 2016. Biomass production and carbon/nitrogen ratio influence ecosystem services from cover crop mixtures. Agron. J. 108: 39–52. doi: 10.2134/agronj15.0182.
- Foley, J. a., N. Ramankutty, K. a. Brauman, E.S. Cassidy, J.S. Gerber, M. Johnston, N.D. Mueller, C. O'Connell, D.K. Ray, P.C. West, C. Balzer, E.M. Bennett, S.R. Carpenter, J. Hill, C. Monfreda, S. Polasky, J. Rockström, J. Sheehan, S. Siebert, D. Tilman, and D.P.M. Zaks. 2011. Solutions for a cultivated planet. Nature 478(7369): 337–342. doi: 10.1038/nature10452.
- Garnett, T., M.C. Appleby, A. Balmford, I.J. Bateman, T.G. Benton, P. Bloomer, B. Burlingame, M. Dawkins, L. Dolan, D. Fraser, M. Herrero, I. Hoffmann, P. Smith, P.K. Thornton, C. Toulmin, S.J. Vermeulen, and H.C.J. Godfray. 2013. Sustainable Intensification in Agriculture: Premises and Policies. Sci. Mag. 341: 33–34. doi: 10.1126/science.1234485.
- Gaudin, A.C.M., T.N. Tolhurst, A.P. Ker, K. Janovicek, C. Tortora, R.C. Martin, and W. Deen. 2015. Increasing crop diversity mitigates weather variations and improves yield stability. PLoS One 10: e0113261. doi: 10.1371/journal.pone.0113261.

- Gonzalez-Dugo, V., J.-L. Durand, and F. Gastal. 2010. Water deficit and nitrogen nutrition of crops. A review. Agron. Sustain. Dev. 30: 529–544. doi: 10.1051/agro/2009059.
- Haacker, E.M.K., A.D. Kendall, and D.W. Hyndman. 2016. Water Level Declines in the High Plains Aquifer: Predevelopment to Resource Senescence. Groundwater 54(2): 231–242. doi: 10.1111/gwat.12350.
- Hallmann, C.A., M. Sorg, E. Jongejans, H. Siepel, N. Hofland, H. Schwan, W. Stenmans, A. Müller, H. Sumser, T. Hörren, D. Goulson, and H. De Kroon. 2017. More than 75 percent decline over 27 years in total flying insect biomass in protected areas. PLoS One 12(10). doi: 10.1371/journal.pone.0185809.
- Hatfield, J.L., K.J. Boote, B. a. Kimball, L.H. Ziska, R.C. Izaurralde, D. Ort, a. M. Thomson, and D. Wolfe. 2011. Climate Impacts on Agriculture: Implications for Crop Production. Agron. J. 103: 351. doi: 10.2134/agronj2010.0303.
- Hooper, D.U., I.F.S. Chapin, J.J. Ewel, A. Hector, P. Inchausti, S. Lavorel, J.H. Lawton, D.M. Lodge, M. Loreau, S. Naeem, B. Schmid, H. Setala, A.J. Symstad, J. Vandermeer, and D.A. Wardle.
 2005. Effects of Biodiversity on Ecosystem Functioning: A Consensus of Current Knowledge. Ecol. Monogr. 75: 3–35.
- Hunter, M.C., R.G. Smith, M.E. Schipanski, L.W. Atwood, and D.A. Mortensen. 2017. Agriculture in 2050: Recalibrating targets for sustainable intensification. Bioscience 67: 386–391. doi: 10.1093/biosci/bix010.
- Jaggard, K.W., A. Qi, and E.S. Ober. 2010. Possible changes to arable crop yields by 2050. Philos. Trans. R. Soc. Lond. B. Biol. Sci. 365(1554): 2835–2851. doi: 10.1098/rstb.2010.0153.
- Jin, Z., Q. Zhuang, J. Wang, S. V. Archontoulis, Z. Zobel, and V.R. Kotamarthi. 2017. The combined and separate impacts of climate extremes on the current and future US rainfed maize and soybean production under elevated CO2. Glob. Chang. Biol. 23(7): 2687–2704. doi: 10.1111/gcb.13617.
- Johnstone, S., and J. Mazo. 2011. Global Warming and the Arab Spring. Survival (Lond). 53: 11–17. doi: 10.1080/00396338.2011.571006.
- Jones, J., J. Moody, and J. Lillard. 1969. Effects of tillage, no tillage, and mulch on soil water and plant growth. Agron. J.: 719–721.
- Kabir, Z., and R.T. Koide. 2002. Effect of autumn and winter mycorrhizal cover crops on soil properties, nutrient uptake and yield of sweet corn in Pennsylvania, USA. Plant Soil 238: 205– 215.
- Kemanian, A.R., and C.O. Stöckle. 2010. C-Farm: A simple model to evaluate the carbon balance of soil profiles. Eur. J. Agron. 32: 22–29. doi: 10.1016/j.eja.2009.08.003.

- Kummu, M., M. Fader, D. Gerten, J. Guillaume, M. Jalava, J. Jägermeyr, S. Pfister, M. Porkka, S. Siebert, and O. Varis. 2018. Bringing it all together: ways to secure nations' food supply. Curr. Opin. Environ. Sustain. 26–27: 98–117. doi: 10.1016/j.cosust.2018.01.006.
- Lark, T.J., J. Meghan Salmon, and H.K. Gibbs. 2015. Cropland expansion outpaces agricultural and biofuel policies in the United States. Environ. Res. Lett. 10(4): 044003. doi: 10.1088/1748-9326/10/4/044003.
- McDaniel, M.D., L.K. Tiemann, and A.S. Grandy. 2017. Does agricultural crop diversity enhance soil microbial biomass and organic matter dynamics? A meta-analysis. Ecol. Appl. 24: 560–570.
- Monsanto. 2008. Monsanto Will Undertake Three-Point Commitment to Double Yield in Three Major Crops, Make More Efficient Use of Natural Resources and Improve Farmer Lives Will Also Fund Public Sector Research for Wheat and Rice Breakthroughs.
- Murrell, E.G., M.E. Schipanski, D.M. Finney, M.C. Hunter, M. Burgess, J.C. Lachance, B. Baraibar, C.M. White, D.A. Mortensen, and J.P. Kaye. 2017. Achieving Diverse Cover Crop Mixtures: Effects of Planting Date and Seeding Rate. Agron. J. 109: 1–13. doi: 10.2134/agronj2016.03.0174.
- Pretty, J., and Z.P. Bharucha. 2014. Sustainable intensification in agricultural systems. Ann. Bot. 114(1911): 1571–1596. doi: 10.1093/aob/mcu205.
- Pugh, T.A.M., C. Müller, J. Elliott, D. Deryng, C. Folberth, S. Olin, E. Schmid, and A. Arneth. 2016. Climate analogues suggest limited potential for intensification of production on current croplands under climate change. Nat. Commun. 7: 12608. doi: 10.1038/ncomms12608.
- Radin, J.W., and L.L. Parker. 1979. Water Relations of Cotton Plants under Nitrogen Deficiency. Plant Physiol. 64: 499–501.
- Ray, D.K., N.D. Mueller, P.C. West, and J.A. Foley. 2013. Yield Trends Are Insufficient to Double Global Crop Production by 2050. PLoS One 8(6): e66428. doi: 10.1371/journal.pone.0066428.
- Robertson, G.P., and S.M. Swinton. 2005. Reconciling agricultural productivity and environmental integrity: a grand challenge for agriculture In a nutshell. Front. Ecol. Environ. 3(1): 38–46.
- Rockström, J., J. Williams, G. Daily, A. Noble, N. Matthews, L. Gordon, H. Wetterstrand, F. DeClerck, M. Shah, P. Steduto, C. de Fraiture, N. Hatibu, O. Unver, J. Bird, L. Sibanda, and J. Smith. 2016. Sustainable intensification of agriculture for human prosperity and global sustainability. Ambio 46: 4–17. doi: 10.1007/s13280-016-0793-6.
- Steffen, W., K. Richardson, J. Rockström, S.E. Cornell, I. Fetzer, E.M. Bennett, R. Biggs, S.R. Carpenter, W. de Vries, C.A. de Wit, C. Folke, D. Gerten, J. Heinke, G.M. Mace, L.M. Persson, V. Ramanathan, B. Reyers, and S. Sörlin. 2015. Planetary boundaries: guiding human development on a changing planet. Science (80-.). 347: 1259855. doi: 10.1126/science.1259855.

- Stöckle, C.O., and A.R. Kemanian. 2009. Crop Radiation Capture and Use Efficiency: A Framework for Crop Growth Analysis. p. 145–170. *In* Sadras, V.O., Calderini (eds.), Crop Physiology: Applications for Genetic Improvement and Agronomy. 1st ed. Academic Press, Cambridge, MA.
- Stöckle, C.O., A.R. Kemanian, R.L. Nelson, J.C. Adam, R. Sommer, and B. Carlson. 2014. CropSyst model evolution: From field to regional to global scales and from research to decision support systems. Environ. Model. Softw. 62: 361–369. doi: 10.1016/j.envsoft.2014.09.006.
- Teixeira, E.I., J. De Ruiter, A. Ausseil, A. Daigneault, P. Johnstone, A. Holmes, A. Tait, and F. Ewert. 2017. Science of the Total Environment Adapting crop rotations to climate change in regional impact modelling assessments. Sci. Total Environ. doi: 10.1016/j.scitotenv.2017.10.247.
- Tilman D, Blazer C, Hill J, Befort BL. 2011. Global food demand and the sustainable intensification of agriculture. Proceedings of the National Academy of Sciences 108: 20260-20264.
- United Nations. 2017. World Population Prospects, The 2017 Revision: Key findings and advance tables.
- Urban, D.W., J. Sheffield, and D.B. Lobell. 2015. The impacts of future climate and carbon dioxide changes on the average and variability of US maize yields under two emission scenarios. Environ. Res. Lett. 10(4): 045003. doi: 10.1088/1748-9326/10/4/045003.
- Walsh, J., D. Wuebbles, K. Hayhoe, J. Kossin, K. Kunkel, G. Stephens, P. Thorne, R. Vose, M. Wehner, J. Willis, D. Anderson, S. Doney, R. Feely, P. Hennon, V. Kharin, T. Knutson, F. Landerer, T. Lenton, J. Kennedy, and R. Somerville. 2014. Ch 2: Our Changing Climate. p. 19–67. *In* Melillo, J.M., Richmond, T. (T. C., Yohe, G.W. (eds.), Climate Change Impacts in the United States: The Third National Climate Assessment. U.S. Global Change Research Program.
- Walthall, C.L., J. Hatfield, P. Backlund, L. Lengnick, E. Marshall, M. Walsh, S. Adkins, M. Aillery, E.A. Ainsworth, C. Ammann, C.J. Anderson, I. Bartomeus, L.H. Baumgard, F. Booker, B. Bradley, D.M. Blumenthal, J. Bunce, K. Burkey, S.M. Dabney, J.A. Delgado, J. Dukes, A. Funk, K. Garrett, M. Glenn, D.A. Grantz, D. Goodrich, S. Hu, R.C. Izaurralde, R.A.C. Jones, S.-H. Kim, A.D.B. Leaky, K. Lewers, T.L. Mader, A. McClung, J. Morgan, D.J. Muth, M. Nearing, D.M. Oosterhuis, D. Ort, C. Parmesan, W.T. Pettigrew, W. Polley, R. Rader, C. Rice, M. Rivington, E. Rosskopf, W.A. Salas, L.E. Sollenberger, R. Srygley, C. Stöckle, E.S. Takle, D. Timlin, J.W. White, R. Winfree, L. Wright-Morton, and L.H. Ziska. 2013. Climate Change and Agriculture in the United States: Effects and Adaptation. USDA Technical Bulletin 1935. Washington, DC.
- White, C.M., S.T. DuPont, M. Hautau, D. Hartman, D.M. Finney, B. Bradley, J.C. LaChance, and J.P. Kaye. 2017. Managing the trade off between nitrogen supply and retention with cover crop mixtures. Agric. Ecosyst. Environ. 237: 121–133. doi: 10.1016/j.agee.2016.12.016.

Wise, T.A. 2013. Can We Feed the World in 2050? A Scoping Paper to Assess the Evidence.

- Wolfe, D.W., D.W. Henderson, T.C. Hsiao, and A. Alvino. 1988. Interactive Water and Nitrogen Effects on Senescence of Maize. I. Leaf Area Duration, Nitrogen Distribution, and Yield. Agron. J. 80: 859–864.
- Wu, W., Q. Yu, L. You, K. Chen, H. Tang, and J. Liu. 2018. Global cropping intensity gaps: Increasing food production without cropland expansion. Land use policy (February): 0–1. doi: 10.1016/j.landusepol.2018.02.032.
- Zeigler, M.M. 2017. Sustainably Doubling Agricultural Productivity: The Right Global Goal For 2050. Glob. Harvest Initiat.

Chapter 2

Agriculture in 2050: Recalibrating Targets for Sustainable Intensification

2.1 Introduction

The prevailing discourse on the future of agriculture is rife with the assertion that food production must increase dramatically—potentially doubling by 2050—to meet surging demand. Many authors also call for agriculture to become more environmentally sustainable, but with little urgency and few quantitative targets. The result: an imbalanced narrative that heavily privileges production over conservation. This imbalance persists despite calls in the growing sustainable intensification (SI) literature to treat food production and environmental protection as equal parts of agriculture's grand challenge (Robertson and Swinton 2005, Garnett et al. 2013, Pretty and Bharucha 2014, Rockström et al. 2016).

We aim to rebalance this narrative by laying out quantitative and compelling SI targets for both production and the environment. These goals will clarify the scope of the challenges that agriculture must face in the coming decades; focus research and policy on achieving specific outcomes; and ensure that SI efforts lead to measurable environmental improvements.

Our targets are based on the following standards: 1) SI production goals should aim to meet projected global food demand, while recognizing that factors beyond aggregate production also affect hunger and malnutrition (FAO et al. 2015, Schipanski et al. 2016); and 2) SI environmental goals should aim to restore and maintain ecosystem functioning in both managed and natural systems (Neufeldt et al. 2013, Rockström et al. 2016).

Many authors call for production increases of 60-100% by 2050, based on two recent food demand projections (Tilman et al. 2011, Alexandratos and Bruinsma 2012). These goals appear clear and compelling, but they exaggerate the scale of the production increase needed by 2050 because they misinterpret the underlying projections and ignore recent production gains. Moreover, the projections are often simplified into a goal of doubling yields, which serves as an urgent rallying cry for research, policy, and industry (Monsanto 2008, Foley et al. 2011, Tilman et al. 2011, Ray et al. 2013, Long et al. 2015, Buckley 2016). This, in turn, fosters a produce-at-all-costs mentality, which may exacerbate existing environmental challenges by increasing the use of fertilizers, pesticides, irrigation, and tillage.

In contrast, current SI environmental targets are unclear and unlikely to inspire action. Most authors agree that uncultivated land should not be converted for crop production (e.g., Garnett et al. 2013, Pretty and Bharucha 2014). Beyond this, however, stated goals diverge. They range from the basic—not "increasing agriculture's environmental footprint" (Buckley 2016)—to the more aggressive—"major reductions in environmental impact" (Garnett et al. 2013). Some sustainability goals would even result in increased environmental degradation, as when marginal reductions in per-unit impacts are coupled with doubled output (Monsanto 2008).

Our analysis shows that, largely due to recent production gains, an increase of ~25-70% above current production levels may be sufficient to meet 2050 demand (figure 2-1a). Calls to double food production from today's levels are not supported by existing projections. Although even a 25-70% increase will be challenging, global agricultural output is at least on the right trajectory. In contrast, agriculture's environmental performance is going in the wrong direction: aggregate impacts are increasing, and must drop sharply over the coming decades (figure 2-1b,c).

We review and update the main projections of world food demand; discuss examples of environmental improvements needed by 2050; and propose new directions for research and policy to help meet both sustainability and production goals. Our objectives are to clarify the overarching productivity and environmental goals of SI and to recalibrate the narrative on the future of agriculture. Therefore, we do not address the related social, economic, and geopolitical dimensions of SI (Loos et al. 2014, Pretty and Bharucha 2014, iPES-Food 2016); heterogeneity among regions (Alexandratos and Bruinsma 2012, Mueller et al. 2012, Cunningham et al. 2013, van Ittersum et al. 2013); or the merits of different management philosophies (Cassman 1999, IAASTD 2009, Bommarco et al. 2013, Tittonell 2014). Rectifying the prevailing SI narrative is critical because it is already shaping the future of agricultural research and policy (e.g., USDA 2015, Buckley 2016), with potentially dramatic consequences for the future of food production and the environment.

2.2 Food Demand Projections

Food demand in 2050 is projected to rise as the global population crests 9.7 billion people (UN 2015) and greater wealth drives up per-capita consumption, especially of resource-intensive animal products (Alexandratos and Bruinsma 2012). Public and scientific discourse on the subject focuses primarily on two studies (Tilman et al. 2011, Alexandratos and Bruinsma 2012). First, Alexandratos and Bruinsma of the United Nations (UN) Food and Agriculture Organization (FAO)

project a 60% increase in demand from a 2005/2007 baseline using a price-weighted index of food commodities. Second, Tilman and colleagues (2011) project that demand for calories and protein from human-edible crops will increase by 100% and 110%, respectively, from a 2005 baseline. Both of these projections account for crops used as animal feed and, to a limited extent, as biofuel feedstock.

These projections are complex and are commonly misinterpreted. First, the FAO projection of a 60% increase is frequently misquoted as a 70% increase when authors cite an earlier FAO report (Alexandratos 2006). Second, the price-weighted basis of the FAO figures implies a larger increase in crop demand than is actually projected on a mass basis: for example, FAO projects only a 46% increase in cereals demand (Alexandratos and Bruinsma 2012). Most importantly, authors often ignore the base year of the projections (Foley et al. 2011, Ray et al. 2013, Long et al. 2015, Daryanto et al. 2016), implying that the projected increase must occur from today's production levels. For both of these projections, the base year is now a decade past, and production has increased substantially in this time. This error is particularly misleading when authors explicitly graph 2050 demand as a doubling from current levels (e.g., Long et al. 2015).

We use global demand for cereals as a proxy for total crop demand to illustrate the production increase needed by 2050. Cereals are the world's dominant crops. In 2013 they were grown on 47% of global cropland and provided 63% and 56% of calories and protein, respectively, from human-edible crops (FAO 2016). Of course, ending hunger and malnutrition will require multiple crop types, including pulses, roots, vegetables, and fruits, many of which will need to be produced and marketed locally. Our focus on aggregate global cereal demand does not imply that meeting this demand would ensure global food security. Instead, our updated projections are intended to illustrate agriculture's big-picture production challenge.

We build and update approximations of the FAO and Tilman projections. FAO projects cereals demand in 2050 directly. Tilman and colleagues do not, so we approximate their projection with a simple doubling of demand from a 2005 baseline. We also linearly transform both estimates to account for differences between the original projections' assumed 2050 population and the latest United Nations analysis (UN 2015). We use the most recent FAOSTAT data (FAO 2016), from 2014, as the baseline for our projections. All data and projections are available in the supplementary materials.

Our updates to the FAO and Tilman projections indicate that production of cereals must only increase 26% and 68% from 2014 levels, respectively, to meet 2050 demand (figure 2-1a). Rapid production growth in recent years has made substantial progress toward the original projected

increases of 46% and 100%. Cereal production increased 24% from 2005 to 2014 due to both yield improvements and expansion of cropped area (FAO 2016). Production of oilcrops—which account for most of the remaining calories and protein from human-edible crops—increased even more, by 39% (FAO 2016). Projected 2050 demand for oilcrops is 46% higher than 2014 production levels based on the FAO projection and 50% higher based on a doubling from 2005.

The discrepancy between the two cereal demand projections—26% v. 68%—is largely due to differences in model assumptions. FAO assumes a lower rate of annual GDP growth than Tilman and colleagues: 2.1% as compared to 2.5%. FAO also adjusts its projection to account for potential saturation of meat consumption in the largest developing country, China, and cultural factors limiting the growth of meat consumption in the second largest, India.

The two projections have drastically different implications for the future of crop production. Under the FAO projection, the rate of average annual cereal yield growth could fall gradually over the next 35 years and still meet demand using only existing cropland. To double from a 2005 baseline, in contrast, cereal yields would have to grow continually at a compound annual rate of over 1.5%, which has not been achieved consistently since the mid 1980s (figure 2-2). Doubling yields by 2050 from a recent baseline—the increase implied when authors do not specify the base year for doubling—would require an even higher annual yield growth rate of 1.9% per year.



Figure 2-1: Food demand is projected to climb while environmental impacts must plummet. Calls to double crop production from a recent baseline imply growth rates outside of the range of empirical projections. Meanwhile, agriculture's environmental impacts need to fall rapidly to protect critical ecosystem functions. (a) Historical and projected global cereal production and demand. (b) Historical and projected direct greenhouse has (GHG) emissions from agriculture and 2050 goal. (c) Historical total phosphorous loading in the Mississippi-Atchafalaya River Basin and 2035 goal. Note: Historical data is shown in solid lines and future projections and goal trajectories are shown in dashed or dotted lines.



Figure 2-2: Decrease in world cereal yield growth rate over time. To double by 2050 from a 2005 baseline, yield growth would have to be maintained at 1.5% per year. Doubling from a 2014 baseline would require yield growth of 1.9% per year. Each point represents the compound annual growth rate of global average cereal yields over the five previous years (FAO 2016). To smooth interannual variation, growth rates were calculated using five-year moving average cereal yields.

Sustaining these rates of average annual yield growth until 2050, if it is even possible, would require widespread intensification of fertilizer, pesticide, and irrigation regimes. This level of intensification would almost certainly increase agriculture's impact on water quality, aquifers, wildlife, and the climate (Robertson and Swinton 2005, Foley et al. 2011, West et al. 2014). SI production goals should therefore be stated carefully to avoid furthering a production-at-all-costs approach to agriculture. Goals should reflect the updated projection that production must increase ~25-70% from recent levels to meet demand in 2050. Calls for doubling current production by 2050 should be avoided.

2.2 Environmental Goals

In contrast to the literature on food demand, there has been little discussion of specific environmental goals for agriculture in 2050, or of the sector's trajectory toward such goals. Instead, the prevailing discourse often focuses on increasing efficiency or improving general "sustainability," which gives the impression that marginal environmental improvements are sufficient (Petersen and Snapp 2015). To illustrate the true scope of agriculture's environmental challenges, we analyze the
sector's performance against quantitative targets that have been proposed to achieve specific environmental outcomes: mitigating climate change and limiting eutrophication in the Gulf of Mexico.

Agricultural production activities directly contribute 11-13% of the world's total anthropogenic greenhouse gas (GHG) emissions (IPCC 2014). Indirect emissions from land-use change in agriculture and forestry contribute another 12% (IPCC 2014). To avoid the worst impacts of climate change, Foley and colleagues (2011) call for an 80% reduction in agricultural GHG emissions. Since direct agricultural GHG emissions have been steadily climbing, achieving this level of reduction by 2050 would require an abrupt shift in emissions trajectory (figure 2-1b).

Losses of agricultural nutrients to waterways contribute to hypoxic "dead zones" downstream, threatening marine life and fisheries in coastal regions throughout the world. The hypoxic zone in the northern Gulf of Mexico is fed by the Mississippi-Atchafalaya River Basin system in the central US, where riverine nitrogen (N) and phosphorous (P) are primarily from agricultural sources. The second largest in the world, this dead zone reached 22,000 km² in 2002 and averages 13,650 km² per year (EPA 2016). In 2001, an intergovernmental task force set a goal to reduce the average size of the dead zone to 5,000 km² by 2015, which would require reducing annual N and P loading to a level 45% below the 1980-1996 average (MRGMWNTF 2001 and 2008). This goal was not met, and the task force recently extended the deadline to 2035 (MRGMWNTF 2015). As figure 2-1c shows, P loading has been increasing, and meeting the 45% reduction goal would require a significant shift in trajectory. We illustrate this goal using P data because the trends for total N and reactive N are diverging, and the Gulf Hypoxia Task Force goal applies only to total N. Since total N has been declining more rapidly than reactive N, using total N would indicate greater progress toward the goal than has actually been made.

These two examples show that agriculture still faces large environmental challenges, but they are not meant to imply that the sector has not made any progress. Indeed, U.S. agriculture has improved in important areas, including by cutting sheet, rill, and wind erosion by 43% between 1982 and 2007 (USDA 2011) and by beginning to reduce N losses in the Midwest (McIsaac et al. 2016). However, both U.S. and global data on concerns ranging from biodiversity loss to land conversion to irrigation water withdrawals—in addition to GHG emissions and nutrient pollution—indicate that agriculture leaves a large and growing footprint (Foley et al. 2011, West et al. 2014, Haacker et al. 2015). Clearly, environmental sustainability cannot play second fiddle to intensification; efforts to increase food production and reduce aggregate environmental impacts must go hand in hand.

2.3 Agriculture's Path to 2050

Meeting food demand while maintaining functioning ecosystems will require a recalibrated SI strategy, where up-to-date production goals are coupled with quantitative environmental targets. Research and policy should pivot to align with this strategy, both in the U.S. and globally. Here we focus on the U.S. context.

The research enterprise led by the National Science Foundation and the U.S. Department of Agriculture (USDA) should prioritize efforts to identify and meet quantitative production and environmental goals. First, research is needed to specify targets in both categories. There is a particularly urgent need to quantify the reductions in pollution and land degradation that must be achieved to sustain functioning ecosystems at multiple scales (Neufeldt et al. 2013, Rockström et al. 2016). These goals will need to be refined periodically as new information becomes available, given the uncertainty of long-term projections.

Second, applied agricultural research should focus on developing production systems that can simultaneously meet both production and environmental targets while helping farmers adapt to a range of emerging challenges, such as mounting water shortages (Falkenmark 2013; Elliott et al. 2014), pesticide resistance (Mortensen et al. 2012), yield plateaus (Grassini et al. 2013, Ray et al. 2013), and the changing climate (Challinor et al. 2014). The technical challenge of such a fundamental transformation in production systems is daunting, and meeting both sets of goals will require navigating complex tradeoffs (Robertson and Swinton 2005, Neufeldt et al. 2013, Davis et al. 2016). However, establishing clear targets will help researchers focus on these long-term challenges.

Achieving both production and environmental goals will require shifts in U.S. agricultural policy. Current policy heavily favors production, including through crop insurance and revenue- and price-based subsidy payments for commodity crops. These programs carry only minimal environmental requirements, which provide limited protection against erosion and the loss of some wetlands and grasslands, but fail to target nutrient loss, air quality, GHG emissions, and other concerns. Conservation incentive programs help producers implement many environmentally beneficial practices, but they are not structured to produce maximum benefits. Moreover, many environmental regulations currently exempt agricultural activities. To bring U.S. policy in line with future needs, producers who receive subsidies should be required to meet more stringent environmental standards, conservation programs should be reformed to tie payments to quantified outcomes (Winsten and Hunter 2011), and effective regulatory backstops should be instituted to control the most environmentally damaging practices. Quantitative targets can help guide these

policy efforts and promote effective collaborations among researchers, farmers, government agencies, and civil society groups. The Danish government's pesticide strategy, which aims to reduce pesticide loads by 40%, is one promising example of using quantitative targets to collaboratively set agro-environmental policy (DME 2013).

The goals of sustainable intensification extend beyond aggregate production and environmental performance. Additional policy efforts are needed to manage food demand by reducing food waste (West et al. 2014) and shifting diets (Davis et al. 2016). We must also halt cropland expansion (Cunningham et al. 2013); and ensure that the world's poorest people have secure access to nutritious food (FAO et al. 2015). Total land in agriculture has risen since 2005 in Africa, South America, and Asia (FAO 2016), indicating continued land conversion at the expense of native ecosystems, and conversion continues in the US as well (Lark et al. 2015). Approximately 795 million people are hungry today, despite adequate global food production, because poverty, lack of infrastructure, poor governance, natural disasters, and political unrest restrict food access (FAO et al. 2015). These problems must be addressed even as production increases and pollution plummets.

2.4 Conclusion

We call on researchers, policymakers, and farmers to embrace this recalibrated vision of sustainable intensification. Time is short: the annual cycle of planting and harvest gives farmers fewer than 35 chances to transform their production systems by mid-century. Scientists also face a limited number of opportunities to develop and test new production and conservation strategies. As a group of young agricultural scientists (and one senior scientist), this is the challenge of our careers. By the time our generation retires, agriculture's 2050 goals must be met.

2.5 References

Alexandratos N. 2006. World Agriculture: Towards 2030/2050, Interim Report. Food and Agriculture Organization of the United Nations.

Alexandratos N, Bruinsma J. 2012. World Agriculture Towards 2030/2050: The 2012 Revision. Food and Agriculture Organization of the United Nations. ESA Working Paper no. 12-03.

- Bommarco R, Kleijn D, Potts SG. 2013. Ecological intensification: Harnessing ecosystem services for food security. Trends in Ecology and Evolution 28: 230-238.
- Buckley N. 2016. Public and Private Sector Interventions for Global Food Security: A Report From the Aspen Institute Food Security Strategy Group. The Aspen Institute.
- Cassman KG. 1999. Ecological intensification of cereal production systems: Yield potential, soil quality, and precision agriculture. Proceedings of the National Academy of Sciences 96: 5952-5959.
- Challinor AJ, Watson J, Lobell DB, Howden SM, Smith DR, Chhetri N. 2014. A meta-analysis of crop yield under climate change and adaptation. Nature Climate Change 4: 287–291.
- Cunningham SA, Attwood SJ, Bawa KS, Benton TG, Broadhurst LM, Didham RK, McIntyre S, Perfecto I, Samways MJ, Tscharntke T, Vandermeer J, Villard MA, Young AG, Lindenmayer DB. To close the yield-gap while saving biodiversity will require multiple locally relevant strategies. Agriculture, Ecosystems, and Environment 173: 20-27.
- Daryanto S, Wang L, Jacinthe P-A. 2016. Global synthesis of drought effects on maize and wheat production. PLoS ONE 11 (art. e0156362).
- [DME] Danish Ministry of the Environment. 2013. Protect water, nature and human health Pesticides strategy 2013-2015.
- Davis KF, Gephart JA, Emery KA, Leach AM, Galloway JN, D'Odorico P. 2016. Meeting future food demand with current agricultural resources. Global Environmental Change 39: 125-132.
- Elliott J, Deryng D, Müller C, Frieler K, Konzmann M, Gerten D, Glotter M, Flörke M, Wada Y, Best N, Eisner S, Fekete BM, Folberth C, Foster I, Gosling SN, Haddeland I, Khabarov N, Ludwig F, Masaki Y, Olin S, Rosenzweig C, Ruane AC, Satoh Y, Schmid E, Stacke T, Tang Q, Wisser D. 2014. Constraints and potentials of future irrigation water availability on agricultural production under climate change. Proceedings of the National Academy of Sciences 111: 3239-3244.
- Falkenmark M. 2013. Growing water scarcity in agriculture: Future challenge to global water security. Philosophical Transactions of the Royal Society A 371: 20120410.
- [FAO] Food and Agriculture Organization of the United Nations. 2001. Food Balance Sheets: A Handbook.
- FAO. 2016. FAOSTAT Database. (1 December 2016; www.fao.org/faostat)
- FAO, International Fund for Agricultural Development, World Food Programme. 2015. The State of Food Insecurity in the World 2015. Meeting the 2015 international hunger targets: Taking stock of uneven progress. FAO.
- Foley JA, Ramankutty N, Brauman KA, Cassidy ES, Gerber JS, Johnston M, Mueller ND, O'Connell C, Ray DK, West PC, Balzer C, Bennett EM, Carpenter SR, Hill J, Monfreda C, Polasky S,

Rockström J, Sheehan J, Siebert S, Tilman D, Zaks DPM. 2011. Solutions for a cultivated planet. Nature 478: 337-342.

- Garnett T, Appleby MC, Balmford A, Bateman IJ, Benton TG, Bloomer P, Burlingame B, Dawkins M, Dolan L, Fraser D, Herrero M, Hoffmann I, Smith P, Thornton PK, Toulmin C, Vermeulen SJ, Godfray HCJ. 2013. Sustainable intensification in agriculture: Premises and policies. Science 341: 33-34.
- Grassini P, Eskridge KM, Cassman KG. 2013. Distinguishing between yield advances and yield plateaus in historical crop production trends. Nature Communications 4 (art. 2918).
- Haacker EM, Kendall AD, Hyndman DW. 2015. Water level declines in the high plains aquifer: Predevelopment to resource senescence. Groundwater 54: 231-242.
- [IAASTD] International assessment of agricultural knowledge, science, and technology for development. 2009. Global Report. Island Press.
- [IPCC] Intergovernmental Panel on Climate Change. 2014. Climate Change 2014: Mitigation of Climate Change. Cambridge University Press.
- [iPES-Food] International Panel of Experts on Sustainable Food Systems. 2016. From uniformity to diversity: A paradigm shift from industrial agriculture to diversified agroecological systems.
- Lark TJ, Salmon JM, Gibbs HK. 2015. Cropland expansion outpaces agricultural and biofuel policies in the United States. Environmental Research Letters 10: 044003.
- Long SP, Marshall-Colon A, Zhu X-G. 2015. Meeting the global food demand of the future by engineering crop photosynthesis and yield potential. Cell 161: 56-66.
- Loos J, Abson DJ, Chappell MJ, Hanspach J, Mikulcak F, Tichit M, Fischer J. 2014. Putting meaning back into "sustainable intensification." Frontiers in Ecology and the Environment 12: 356-361.
- McIsaac GF, David MB, Gertner GZ. 2016. Illinois river nitrate-nitrogen concentrations and loads: Long-term variation and association with watershed nitrogen inputs. Journal of Environmental Quality 45:1268-1275.
- [MRGMWNTF] Mississippi River/Gulf of Mexico Watershed Nutrient Task Force. 2001. Action Plan for Reducing, Mitigating, and Controlling Hypoxia in the Northern Gulf of Mexico.
- MRGMWNTF. 2008. Gulf Hypoxia Action Plan 2008 for Reducing, Mitigating, and Controlling Hypoxia in the Northern Gulf of Mexico and Improving Water Quality in the Mississippi River Basin.
- MRGMWNTF. 2015. Mississippi River/Gulf of Mexico Watershed Nutrient Task Force: 2015 Report to Congress.
- Monsanto. 2008. Monsanto Will Undertake Three-Point Commitment to Double Yield in Three Major Crops, Make More Efficient Use of Natural Resources and Improve Farmer Lives.

Monsanto. (2 December 2016; http://news.monsanto.com/press-release/monsanto-willundertake-three-point-commitment-double-yield-three-major-crops-make-mor)

- Mortensen DA, Egan JF, Maxwell BD, Ryan MR, Smith RG. 2012. Navigating a critical juncture for sustainable weed management. BioScience 62: 75-84.
- Mueller ND, Gerber JS, Johnston M, Ray DK, Ramankutty N, Foley JA. 2012. Closing yield gaps through nutrient and water management. Nature 490: 254-257.
- Neufeldt H, Jahn M, Campbell BM, Beddington JR, DeClerck F, De Pinto A, Gulledge J, Hellin J, Herrero M, Jarvis A, LeZaks D, Meinke H, Rosenstock T, Scholes M, Scholes R, Vermeulen S, Wollenberg E, Zougmore R. Beyond climate-smart agriculture: Toward safe operating spaces for global food systems. Agriculture & Food Security 2: 12.
- Petersen B, Snapp S. 2015. What is sustainable intensification? Views from experts. Land Use Policy 46: 1-10.
- Pretty J, Bharucha ZP. 2014. Sustainable intensification in agricultural systems. Annals of Botany 114: 1571–1596.
- Ray DK, Mueller ND, West PC, Foley JA. 2013. Yield trends are insufficient to double global crop production by 2050. PLOS One 8 (art. e66428).
- Roberston GP, Swinton SM. 2005. Reconciling agricultural productivity and environmental integrity: a grand challenge for agriculture. Frontiers in Ecology and the Environment 3: 38–46.
- Rockström J, Williams J, Daily G, Noble A, Matthews N, Gordon L, Wetterstrand H, DeClerck F, Shah M, Steduto P, de Fraiture C, Hatibu N, Unver O, Bird J, Sibanda L, Smith J. 2016. Sustainable intensification of agriculture for human prosperity and global sustainability. Ambio (doi:10.1007/s13280-016-0793-6).
- Schipanki ME, MacDonald GK, Rosenzweig S, Chappell MJ, Bennett EM, Kerr RB, Blesh J, Crews T, Drinkwater L, Lundgren JG, Schnarr C. 2016. Realizing resilient food systems. BioScience 66: 600-610.
- Tilman D, Clark M. 2014. Global diets link environmental sustainability and human health. Nature 515: 518-522.
- Tilman D, Blazer C, Hill J, Befort BL. 2011. Global food demand and the sustainable intensification of agriculture. Proceedings of the National Academy of Sciences 108: 20260-20264.
- Tittonell P. 2014. Ecological intensification of agriculture sustainable by nature. Current Opinion in Environmental Sustainability 8: 53-61.
- [UN] United Nations. 2015. World Population Prospects: The 2015 Revision, Key Findings and Advance Tables. Department of Economic and Social Affairs, Population Division. Working Paper no. ESA/P/WP.241.
- [USDA] US Department of Agriculture. 2011. RCA Appraisal 2011.

- USDA. 2015. Agriculture and Food Research Initiative Competitive Grants Program: Food Security Program 2015 Request for Applications. USDA.
- USDA. 2016. USDA National Nutrient Database for Standard Reference, Release 28. (2 December 2016; https://ndb.nal.usda.gov/ndb/)
- [USEPA] US Environmental Protection Agency. 2016. Hypoxia in the Northern Gulf of Mexico. (2 December 2016; www.gulfhypoxia.net/Overview/)
- [USGS] US Geological Survey. 2016. Annual Nutrient Flux and Concurrent Streamflow Updated Through Water Year 2015. (5 November 2016; http://toxics.usgs.gov/hypoxia/mississippi/flux_ests/delivery/index.html)
- van Ittersum MK, Cassman KG, Grassini P, Wolf J, Tittonell P, Hochman Z. 2013. Yield gap analysis with local to global relevance—A review. Field Crops Research 143: 4-17.
- West PC, Gerber JS, Engstrom PM, Mueller ND, Brauman KA, Carlson KM, Cassidy ES, Johnston M, MacDonald GK, Ray DK, Siebert S. 2014. Leverage points for improving global food security and the environment. Science 345: 325-327.
- Winsten JR, Hunter M. 2011. Using pay-for-performance conservation to address the challenges of the next farm bill. Journal of Soi and Water Conservation 66: 111A-117A.

Chapter 3

Cover Crop Mixtures: Effects on Crop Yield and Yield Stability

3.1 Introduction

Multi-species cover crop mixtures are quickly gaining popularity in the United States. Among surveyed cover crop users, half of respondents reported using mixtures in 2016, and 73% of these mixes contained more than two plant species (CTIC 2017). Two-species mixtures of a grass and a legume have long been used to combine the fast growth rate and nitrogen (N)-scavenging ability of grasses with the biological N-fixing ability of legumes, which may help optimize biomass production, N supply, and N retention (Poffenbarger et al. 2015). Farmers and agronomists are now looking to more-diverse mixtures to optimize across a wider range of services (Creamer et al. 1997), such as weed suppression, beneficial insect provisioning, and soil carbon sequestration, resulting in more "multifunctional" cover crops (Finney and Kaye 2016).

Diverse cover crop mixtures, or "cocktails", are promoted over traditional mono- and biculture cover crops for a wide range of reasons, including soil health benefits (Chu et al. 2017), grazing potential (Brown 2016), and herbicide-resistant weed management (CTIC 2017). Organic farmers collaborating on the present study ranked organic matter, biological N fixation, soil biology, and yield of the following crop, in that order, as the top services they desired from cover crop mixtures (LaChance et al. 2015). High-diversity mixtures can add cost and management complexity, which may constrain their deployment on working farms (Smith et al. 2014, CTIC/SARE 2013), yet enthusiasm remains high.

As weather variability increases and extreme temperature and moisture conditions become more common (Wolfe et al. 2017), there is an increasing need for management strategies that help maintain high and stable crop yields. At the same time, critical environmental concerns including greenhouse gas emissions and nutrient losses to waterbodies must be addressed (Hunter et al. 2017). Well-designed cover crop mixtures may be able to consistently benefit both crop yields and the environment, despite unpredictable weather, if they can harness the positive relationship between biodiversity and stability documented in the ecological literature (McCann 2000, Lin 2011). However, published reports of cash crop yields following diverse cover crop mixtures are very limited, and effects on yield stability have not been assessed.

3.1.1 Effects of Cover Crop Mixtures on Cash Crop Yields

Diversifying annual cropping systems can increase crop yields due to beneficial effects on pest cycles, nutrient dynamics, and soil quality (Varvel et al. 2000, Davis et al. 2012, Gaudin et al. 2015, St-Martin et al. 2017, Ernst et al. 2016). Cover crops—both monocultures and mixtures—are one way to gain the benefits of rotational diversity. However, evidence for the effect of cover crop mixtures on the yield of the following cash crop is limited. A recent meta-analysis (Marcillo and Miguez 2017) found that maize (*Zea mays* L.) yield increased an average of 13% following cover crop mixtures, but these were predominantly bicultures. Most studies of multi-species cover crops have found little or no effect on the yield of the following cash crop (Smith et al. 2014, Welch et al. 2016, Appelgate et al. 2017, Chu et al. 2017). Reese et al. (2014) and Wortman et al. (2012b) found yield differences relative to control plots when cover crop mixtures affected soil water availability (positively or negatively) in semi-arid environments, but no differences due to mixture composition or species diversity.

However, cover crop mixture effects on soil N availability can strongly influence the yield of the following maize crop. In a tilled system with no fertilizer added, Finney et al. (2016) found that cover crop effects on maize yield were mediated by the carbon:nitrogen (C:N) ratio of cover crop biomass. Low-C:N ratio cover crop mixtures increased soil N availability and increased maize yield by up to 47%; high-C:N ratio mixtures reduced soil N availability and decreased maize yield by up to 70%. However, the C:N ratio of individual treatments was not stable across site-years, and some mixtures switched from increasing to suppressing yield from one year to the next. This shows that yield responses are highly contingent on cover crop mixture expression, not just seeded mixture composition.

Similar effects of cover crop mixture C:N ratio on unfertilized maize yield have been confirmed in no-till systems (White et al. 2016a) and in tilled organic systems (White et al. 2017). On one farm in the latter study, maize yield was one-third higher following a low- than a high-C:N ratio cover crop mixture. White et al. (2017) also identified two additional controls on soil N supply that work in concert with cover crop biomass C:N ratio: soil organic carbon (SOC) concentration and spring cover crop biomass N content. Though N dynamics during biomass decomposition are

complex, spring cover crop biomass with a C:N ratio higher than 25 is likely to result in net immobilization, while biomass with a C:N ratio below 25 is likely to result in net mineralization (White et al. 2016a).

This link between cover crop C:N ratio and cash crop yields is consistent with findings from mono- and bi-culture cover crops (Tonitto et al. 2006, Marcillo and Miguez 2017) and is not unique to cover crop mixtures. Where this effect has been absent in cover crop mixture studies, this may have been due to low cover crop biomass (Appelgate et al. 2017), N fertilizer additions that fully met crop needs (Appelgate et al. 2017, Reese et al. 2014), or similar C:N ratios among cover crop treatments resulting from similar proportions of legumes and grasses in all mixtures (Wortman et al. 2012b). Compared to mono- and bi-culture cover crops, multi-species mixtures may enable managers to design cover crops with a mix of functional traits that results in ample biomass and a low C:N ratio, while also providing other ecosystem services (Finney et al. 2017).

3.1.2 Cash Crop Yield Stability

Multiple long-term studies in temperate agricultural systems have shown that diversifying crop rotations can increase cash crop yield stability while maintaining high yield. Diversification practices evaluated include adding cash- and noncash-crops to the rotation and applying organic fertility inputs. Many of these studies attribute reduced temporal yield variation to improved soil moisture status (Lotter et al. 2003, Mallory and Porter 2007, Gaudin et al. 2015, Ernst et al. 2018). Varvel (2000) explicitly attributed high yield stability to increased nutrient availability, while others have cited improved soil quality in general (Smith et al. 2007, Grover et al. 2009). High yield stability may also result when yield potential is very low (Wander and Aref 1998, Smith and Gross 2006), likely due to limited upside yield potential in good years. This is of course not a desirable condition.

Many diversification strategies tend to increase soil organic matter (SOM) (McDaniel et al. 2014, King and Blesh 2018), though diversification away from high-productivity crops can hinder SOM accumulation by reducing net C inputs to the system (Poffenbarger et al. 2017). High SOM has been linked to yield stability across large temporal and spatial scales in China (Pan et al. 2009) and the U.S. Corn Belt (Williams et al. 2016). Increasing SOM can mitigate crop stress in multiple ways, including by enhancing soil aeration, infiltration rate, water-holding capacity (WHC), cation-

exchange capacity, and nutrient supply (Blanco-Canqui et al. 2015). Williams et al. (2016) showed that, in the Corn Belt, increased SOM primarily improved yield stability through increased WHC.

Not all studies have found increased yield stability from diversified cropping systems. Eghball et al. (1995) did not find differences in yield stability in Nebraska maize due to long-term manure additions, which would be expected to increase SOM. This may be because their study was irrigated. St-Martin et al. (2017) found higher wheat (*Triticum aestivum*) yields but not greater yield stability in diverse rotations. This may be due to lower sensitivity to rotational diversity in wheat, as seen in Smith et al. (2008). Despite these exceptions, there is strong evidence that diversification practices that improve the crop abiotic environment, especially soil water and nutrient status, can improve both mean yield and yield stability.

3.1.3 Biodiversity Effects in Cover Crop Mixtures

Cover crop mixtures may offer another opportunity to achieve high and stable cropping system performance. Unlike in diversified annual crop rotations, in which different species are typically separated in space and time, cover crop mixtures have *in situ* diversity, with multiple species present in the same space at the same time. *In situ* species diversity has been shown to increase both the level of ecosystem functions and their stability (Hooper et al. 2005, McCann 2000) and has been proposed as a key strategy for enhancing the productivity, stability, and sustainability of cropping systems (Lithourgidis et al., Malézieux et al. 2009, Isbell et al. 2011).

Diversity increases functioning through the selection effect, complementation, and facilitation (Hooper et al. 2005). The selection effect arises probabilistically because more-diverse communities are more likely to contain high-performing species. Complementation arises when species with contrasting functional characteristics use available resources more efficiently, and facilitation when one species performs functions that benefit another.

Farm managers can exploit the mechanisms underlying these effects to develop highperforming cocktail mixes that optimize across priority functions. Since the functional traits of cover crop species and cultivars are robust and well-known (Tribouillois et al. 2015, MCCC 2018), managers can directly select species with good baseline performance in agronomically-useful traits. Cover crop mixtures can achieve complementation and facilitation by combining species with contrasting growth habits, nutrient acquisition strategies, and phenology (Creamer et al. 1997, White et al. 2016, Finney et al. 2016). This may lead to overyielding, which can be beneficial when high cover crop biomass is the top priority (Poffenbarger et al. 2015, Wortman et al. 2012a). Planned complementation also enables flexible combinations of species to achieve desired composite traits, which may be more important than maximizing biomass. For instance, Finney et al. (2016) found that mixtures designed to include complementary N functions did not produce more biomass than those without such complementarity, but the former resulted in much higher maize yield. As compared to monocultures, the wider range of functional traits available in cover crop mixtures may enable optimization across a wider range of ecosystem services (Storkey et al. 2015, Blesh et al. 2018).

Diversifying cover crops may also lead to more consistent outcomes (Tilman 1994, McCann 2000). In diverse communities of organisms, stability is enhanced when the component species exhibit both functional *response diversity*—which enables different species to thrive under different sets of environmental conditions—and functional *effect redundancy*—which enables species to substitute for each other (Lin 2011). Cover crop mixtures may be able to harness this effect to reduce spatial and temporal variability in performance. For instance, combining multiple legume species with different freezing tolerances and temperature optima for growth may help ensure a sufficient level of biological N fixation across a wide range of seasonal temperature patterns. Wortman et al. (2012b) observed that productivity losses due to hail were mitigated by the inclusion of multiple redundant brassica species in a mix.

Exploiting the benefits of biodiversity in cover crop mixtures, therefore, may increase both the mean level and spatiotemporal stability of cover crop functions. When this function is supporting cash crop yield by increasing soil N availability, the result may be higher and more stable yield.

3.1.4 Hypotheses

We examined the effect of diverse cover crop mixtures, and their component monocultures, on crop yields and yield stability in an organically-managed maize-soybean (*Glycine max* L.)-winter wheat rotation in central Pennsylvania. We hypothesized that 1) cover crop mixture biomass C:N ratio affects soil N supply and yield of the following cash crop, with low C:N-ratio cover crops increasing both N supply and yield, and low-C:N ratio cover crops decreasing both. We further hypothesized 2) that increasing cover crop mixture diversity increases the spatiotemporal stability of soil N supply and yield. Finally, we expected 3) that the spatiotemporal stability of soil N supply should be correlated with the stability of maize yield. We test a novel, rank-based indicator of

spatiotemporal stability in addition to the traditional measures based on coefficient of variation or an environmental index (Finlay and Wilkinson 1963).

3.2 Methods

3.2.1 Site Characteristics

This study was conducted from 2012-2015 at the Pennsylvania State University Russell E. Larson Agricultural Research Center, Rock Springs, PA (40°43'N, 77°56'W). Murrill channery silt loam soil (fine-loamy, mixed, semiactive, mesic Typic Hapludult) makes up approximately 80% of the study site, with the remainder consisting of Hagerstown silt loam (fine, mixed, semiactive, mesic Typic Hapludalf) and Buchanan channery loam (fine-loamy, mixed, semiactive, mesic Aquic Fragiudult). Slope is 0-3% on approximately 80% of the site and 3-8% on the remaining area (SSURGO 2017). Surface soil texture (0-20 cm depth) is predominantly clay loam with variability in sand (21.4 - 27.0%), silt (39.9 - 48.1%), and clay (29.6 - 34.3%). Average annual precipitation at the site is 1,020 mm and mean monthly temperatures range from -3 °C (January) to 22 °C (July) for 1980-2016 (Xia et al. 2012).

3.2.2 Experimental Design and Management

Treatment plots were established in a randomized, full-entry complete block design with four replications. Cash crops were planted in a three-year maize silage-soybean-winter wheat rotation, which is common for Northeast U.S. organic commodity grain farms. Organic management was instituted in July, 2012 and the site received organic certification in 2016. All cash crop seeds were conventional, untreated varieties developed without genetic modification; comparable organic varieties were not available. Cash crops, including spring barley in place of winter wheat, were planted in 2012 to establish the cropping sequence, but were not included in the analysis of results.

3.2.3 Cash Crops

Cash crops were planted using commercial-scale equipment in strips 24 m wide by 348 m long. Dairy bed pack manure from the Pennsylvania State University dairy herd was applied prior to maize and wheat planting at a rate designed to meet the phosphorus (P) requirements of the rotation. Prior to planting maize, manure was broadcast and incorporated along with cover crop residues with a moldboard plow and disc. Prior to planting soybean, cover crop residues were incorporated with a moldboard plow and disc. Soybean seeds were treated with *Bradyrhizobium japonicum* inoculum to promote nodulation (N-Dure, Verdesian Life Sciences, Cary, NC). Prior to planting wheat, manure was broadcast and incorporated along with soybean residue with a chisel plow. Following these primary tillage events, a seedbed was prepared for all crops with an s-tine field cultivator followed by a cultimulcher. Weeds were controlled in the maize and soybean with repeated passes of a tine-weeder, rotary hoe, and inter-row cultivator, as needed. Total P demand across all three years of the rotation was projected to be 225 kg P₂O₅ ha⁻¹ and, due to variability in manure composition, 184 kg ha⁻¹ was ultimately applied (Table 3-1).

Planting and harvest dates, manure rates, and manure analysis are summarized in Table 3-1.

Manure was applied on a wet-weight basis at a target rate of 45 Mg ha⁻¹ before maize and 34 Mg ha⁻¹ before wheat; application rates were not adjusted for moisture- or N-content of the manure. Manure was incorporated by primary tillage within a day of application. Maize and soybean seeding rates were consistent among years, while wheat planting rates were increased in 2014 to compensate for late planting after soybean harvest (Table 3-1).

Table 3-1: Field management det	ails.
---------------------------------	-------

		Timing of Field Operations and Sampling									
Crop ^a	Vear	Seed Cover	Cove Sampli	r Crop ng Dates	Apply Manure	Plant	Harvest	Crop Seeding Rate	Dry Manure Rate	Manure Plant- Available N ^b	Manure Phosphate
0100	I Cal	Clop	Fall	Spring				seeds ha ⁻¹	Mg ha ⁻¹	kg N ha ⁻¹	kg P ₂ O ₅ ha ⁻¹
	2012	8/25	11/9	1 0					U	0	0
м [.]	2013	8/8	10/29	5/13	5/15	5/31	9/10	82,000	15.7	85.3	75.0
Maize	2014	8/15	11/5	5/5	5/8	6/2	9/15-16	82,000	20.7	141	76.6
	2015			5/4	5/11	5/28	9/14-15	82,000	17.7	158	131
	2012	10/10	11/19								
Sauhaan	2013	9/20	11/5	5/21		6/5	10/02	444,600			
Soybean	2014	9/30	11/12	5/13		6/3	10/14	444,600			
	2015			5/13		6/10	10/14	444,600			
	2012				10/23	10/25		4,500,000	12.3	65.4	88.8
Wheat	2013				10/3	10/16	7/15-16	4,500,000	12.1	54.7	66.0
	2014				10/21	10/24	7/21	5,700,000	12.0	49.5	114
	2015						7/22				

^a Maize variety: Master's Choice MC4050 maize in all years; soybean variety: Growmark FS HS 22C10 in 2013 and 2014 and HS 21C40 in 2015; wheat variety: cv. Malabar; W.I. Miller and Sons, Farmdale, OH.
^b Manure plant-available nitrogen (N) is calculated assuming 40% availability following White et al. (2017).

3.2.4 Cover Crops

Cover crop treatments were planted in 24 m x 29 m split plots within the cash crop strips. Cover crops planted after wheat and prior to maize (PM) were established in August (for dates see Table 3-1). Cover crops planted after maize and prior to soybean (PS) were established in late September or early October. Due to wheat's position in the rotation, cover crop legacy effects on wheat plots were minimal until the final year.

Legume seed was inoculated with N-Dure dry inoculant containing the appropriate *Rhizobia* species prior to seeding. The preceding wheat or maize stubble was chisel plowed, disked, S-tined and cultimulched before cover crop planting. Cover crops were planted with an Almaco (Nevada, IA) Cone Plot Planter mounted on a seed drill with 19 cm spacing (Murrell et al. 2017). Fallow plots were tilled as needed to eliminate weeds in fall and spring, at most once per season.

Cover crops were terminated by flail mowing within a day of the spring biomass sampling (for dates see Table 3-1). All treatments were terminated on the same day, which resulted in suboptimal termination timing for some species due to phenological and functional differences among species. In 2013, cover crops were allowed to grow until roughly two weeks before the beginning of the cash crop planting window, by which time the cereal rye was headed out (Feekes 10.5). This maximized growth of the slower-growing legumes and allowed canola to bloom, providing pollinator resources, but also resulted in very high cereal rye biomass with a high C:N ratio, and subsequent nutrient immobilization (see Results). As a result, in 2014 and 2015 the cover crops were terminated 8-9 days earlier, when the rye was in the early (PM) or late (PS) boot stage (Feekes 10.0) (Table 3-1).

Cover crop treatments were designed to include both functional and species diversity while meeting specific management objectives. Six monocultures were selected with contrasting functional traits: two legumes (*Fabaceae*), medium red clover (*Trifolium pratense* L.) and Austrian winter pea (*Pisum sativum* L.); two brassicas (*Brassicaceae*), canola (*Brassica napus* L. cv. Wichita) and forage radish (*Raphanus sativus* L. cv. Tillage Radish); and two grasses (*Poaceae*), cereal rye (*Secale cereale* L. cv. Aroostook) and spring oat (*Avena sativa* L. cv. Jerry). One species from each family is known to be winter-hardy in central Pennsylvania (clover, canola, and rye), while the other is known to be susceptible to winter kill (pea, radish, and oat). Each of these species was grown in monoculture at recommended seeding rates (Table 3-2).

These component species were combined into 5 functional mixtures of increasing species

diversity (Table 3-2). A three-species mixture designed to help manage weeds (3SppW) contained cereal rye, oat, and red clover. A three-species mixture designed to optimize N management (3SppN) differed between planting windows. Prior to maize, clover and pea were combined with a low rate of rye to increase N supply to the maize while minimizing N leaching. Prior to soybean, the 3SppN treatment included three N scavengers—rye, oat, and radish—to avoid losses of residual N. A 4Spp mix with greater potential to provision beneficial insects was created by modifying each of these 3SppN mixes by adding canola, which may produce flowers before cover crop termination. Finally, a 6Spp mix combined each component monoculture into an "insurance mix" with greater functional response diversity and functional effect redundancy. Cereal rye was included in all mixtures due to its reliability, but the rye seeding rate was reduced at higher mix diversity levels. Further details of cover crop establishment, seeding rates, and mixture design are available in Murrell et al. (2017).

				Clover	Pea	Rye	Oat	Canola	Radish
Treatment	Abbreviation	Next Crop ^a	No. Spp.		I	oure liv	e seed	s m ⁻² —	
Fallow control	Fallow		0						
Medium red clover	Clover		1	600					
Austrian winter pea	Pea		1		60				
Cereal rye	Rye		1			500			
Oat	Oat		1				300		
Canola	Canola		1					400	
Forage radish	Radish		1						60
3 species weed	3SppW		3	300		250	150		
3 species nitrogen	3SppN	Maize	3	300	30	100			
3 species nitrogen	3SppN	Soybean	3			250	150		50
4 species	4Spp	Maize	4	300	30	100		200	
4 species	4Spp	Soybean	4		30	100	150	200	50
6 species	6Spp		6	150	15	100	75	100	20

Table 3-2: Cover crop treatment species diversity and seeding rates.

^a Where not specified, seeding rates were the same for both cover crop planting windows.

Cover crops were terminated by flail mowing within a day of the spring biomass sampling (for dates see Table 3-1). All treatments were terminated on the same day, which resulted in suboptimal termination timing for some species due to phenological and functional differences among species. In 2013, cover crops were allowed to grow until roughly two weeks before the beginning of the cash crop planting window, by which time the cereal rye was headed out (Feekes 10.5). This maximized growth of the slower-growing legumes and allowed canola to bloom, providing pollinator resources, but also resulted in very high cereal rye biomass with a high C:N ratio, and subsequent

nutrient immobilization (see Results). As a result, in 2014 and 2015 the cover crops were terminated 8-9 days earlier, when the rye was in the early (PM) or late (PS) boot stage (Feekes 10.0) (Table 3-1).

3.2.5 Data Collection

Daily temperature, precipitation, and solar radiation based on satellite observations was obtained from Phase 2 of the North American Land Data Assimilation System (NLDAS; Xia et al. 2012). Comparison to locally-measured weather data showed good agreement and the satellite-based data was more complete. Growing degree days (GDD) were calculated with a base of 10 °C and a maximum of 30 °C. Seasonal insolation was calculated by summing daily values from one week after planting until harvest.

Cover crop biomass was sampled as reported in Murrell et al. (2017). Briefly, aboveground biomass taller than ~2 cm was sampled in the fall and spring in three 0.25 m² subplots per plot. Radish roots often protruded more than 2 cm above the soil surface, so radishes were cut at the root-shoot interface to avoid sampling root biomass in only one species. Biomass was sorted to species, dried, weighed, and analyzed for C and N concentrations by the combustion method as described in Finney et al. (2016). A mean value for weed C:N ratio was applied to all weed biomass and included in the calculation of overall C:N for each cover crop treatment. Due to mechanical cultivation, fallow plots were relatively weed-free and biomass was assumed to be zero, except in experimental weedy subplots as reported by Baraibar et al. (2017). In all other plots, weed biomass was analyzed along with cover crop biomass since it also affects soil N dynamics.

Soil nitrate (NO₃⁻) and ammonium (NH₄⁺) were measured with a composite of six 20-cm depth soil samples per plot extracted with 2M KCl and analyzed using a microplate colorimetric technique (Finney et al. 2016). Sampling was conducted biweekly in maize and monthly in soybean from April through the end of July. Nitrogen in NO₃⁻ and NH₄⁺ was summed to calculate total soil inorganic nitrogen (SIN). To represent cover crop effects on SIN during maize growth, the area under the curve of SIN (SIN_{auc}) for the readings between early June and late July was calculated using the auc function in the MESS package in R (Ekstrøm 2017). Due to inconsistency in sampling dates among years in soybean, SIN_{auc} was not calculated for soybean. Potential for NO₃⁻ leaching below 30 cm depth was measured with anion resin exchange bags and reported in Finney et al. (2017).

Maize was harvested for silage at 60-70% moisture from two subsamples of crop row at least 5.3 m in length. Samples were taken with at least a 3m buffer from all sides of the plot. Total wet

weight was recorded in the field and a subsample was weighed, dried at 55 °C, and weighed again to determine the moisture content. Subsamples were averaged to represent the entire plot. Soybean and wheat were harvested at physiological maturity with a small-plot combine pass along the full length of the plot. For soybean, a subsample of the seeds was weighed, dried at 65 °C, and weighed again to determine the moisture content. For wheat, moisture content was determined with a DICKEY-john (Auburn, IL) GAC 2100 moisture meter. Crops remaining following biomass sampling were harvested with commercial-scale harvesting equipment. Yield of maize silage, soybean, and wheat is reported at moisture contents of zero, 13, and 13.5 percent, respectively.

3.2.6 Stability Metrics

Effects of cover crop treatment on spatiotemporal stability of maize and soybean yield and SIN_{auc} in maize was measured with three different methods. In each case, the four blocks in each of the three years were treated as a group of twelve different environments. No stability metrics were calculated for wheat yield due to the limited cover crop legacy.

First, we calculated the coefficient of variation (CV) across all 12 environments. The CV is a commonly-used metric for assessing stability, with a low CV indicating high stability (Tilman 1996, McCann 2000, Smith et al. 2007, Gaudin et al. 2015). Second, a stability analysis (Finlay and Wilkinson 1963, Tollenaar and Lee 2002, Williams et al. 2016) was performed by regressing values by treatment on an environmental index (EI) calculated as the grand mean value (yield or SIN_{auc}) within each environment. Environments were ordered by EI and the slope of treatment values over EI served as the temporal stability metric; a low slope indicates high stability. Due to the low number of observations (12 environments) and the need to correct for multiple comparisons among 11 cover crop treatment levels, this analysis was underpowered. As a result, plots of the results were visually inspected for evidence of patterns that corresponded to known cover crop treatment characteristics, such as biomass production, C:N ratio, plant family, N acquisition strategy, phenology, and mixture diversity.

Neither CV nor the EI-based stability analysis accounts for mean performance level in addition to stability. This is problematic since, in agronomic settings, the goal is to achieve consistent high performance in desired services, such as yield, and consistent low performance in disservices, such as N leaching.

A novel, rank-based metric of spatiotemporal stability was developed to address this

shortcoming. Treatment outcomes (SIN_{auc} and yield) were assigned a rank score, with a score of 11 for the highest value and a score of 1 for the lowest value. Rank scores were assigned within years and blocks, yielding twelve values per treatment. A consistent-performance index (CPI) was calculated from these rank scores for each factor of interest (f; SIN_{auc} or yield) as:

 $CPI_f = \sum (rank(f)_{i,i}) / (i * j)$

for i years and j blocks. The CPI is essentially the mean rank by CC treatment across all years and blocks. Rank scores serve as a measure of relative performance within each year-by-block environment. Taking the mean of these scores accounts for the consistency of relative performance. This method shares features with a quantile-based approach used in plant breeding (Fox et al. 1990, Temesgen et al. 2015) and threshold-based metrics of ecosystem multifunctionality (e.g. Byrnes et al. 2014). However, this rank-based CPI is novel in the context of assessing agronomic treatment effects and the relationship between the stability of two ecosystem functions.

To evaluate the relative importance of spatial and temporal variability, we calculated spatial CV across blocks within years (mean of all three years) and temporal CV across annual mean values.

3.2.7 Statistical Analyses

All statistical analyses were performed in R (R Core Team 2013). Cover crop biomass and C:N ratio, SIN_{auc} in maize, SIN in soybean, and cash crop yield were analyzed separately for each planting window (PM v. PS) and year. Sub-samples were averaged prior to analysis. Mixed-effect linear models fit to a Gaussian distribution were specified with the lmer function of the lme4 package (Bates et al. 2015). Pairwise comparisons among cover crop treatment means were evaluated with the emmeans function of the emmeans package (Lenth 2018) with a Tukey adjustment for multiple comparisons. Models were evaluated to ensure they met the assumptions of independence and normality of residuals and random effects (Pinheiro and Bates 2000, SSCC 2016). Explanatory power of fixed effects in mixed models was assessed with marginal R² (R²_m) calculated with the r.squaredGLMM function in the MuMIn package (Bartoń 2016) following Nakagawa and Schielzeth (2013). An alpha value of 0.05 was used to assess statistical significance.

Differences among cover crop treatments within years and, for cash crop yield, among years, were assessed with mixed models with a random intercept for block. Analyses assessing affects

across years, such as cover crop effect on SIN_{auc} and the relationship between SIN_{auc} and maize yield, employed a mixed model with random intercepts for year and block. Differences among EI slopes and CPI scores were assessed with the emtrends function in the emmeans package (Lenth 2018). Ordinary least squares regression with the lm function of R (R Core Team 2013) was used to assess the relationship between pairs of stability metrics and between stability metrics and species diversity of cover crop treatments. The latter test was performed to reveal any patterns in the relationship between species diversity and stability. Due to the limited number of cover crop treatments at diversity levels above 1, this is not a highly robust test, but results could inform future work.

3.3 Results

3.3.1 Weather Conditions

Precipitation and temperature varied substantially among the study years (Fig. 3-1). In both 2013 and 2015, precipitation was below average prior to planting of summer crops and in late summer, but high during June and July. Water stress symptoms were observed in the maize in the fall of 2013 and 2015. In 2014, precipitation was consistently above average throughout most of the growing season. Precipitation deficit rarely affected cover crop growth, though dry conditions in August of 2013 reduced PM cover crop establishment, which may have contributed to increased weed competition (Baraibar et al. 2017). Severe winter temperatures in 2013-2014 and 2014-2015, in conjunction with low snow cover, challenged cover crop overwinter survival. Growing-season temperatures did not deviate substantially from long-term normals in any year (Fig. 3-1b), but growing degree day accumulation was higher in 2015 (1,290 GDD) than in 2013 (1,190 GDD) and 2014 (1,150 GDD). Seasonal insolation was also lower in 2013 and 2014 than in 2015 (2,010, 2,020, and 2,200 MJ m⁻², respectively).



Figure **3-1**: Monthly a) precipitation and b) mean temperature for 2013, 2014, and 2015, in comparison to monthly averages for 1980 to 2016 (horizontal black bars). Data is from NLDAS (Xia et al. 2012).

3.3.2 Cover Crop Performance

Cover crop biomass production differed strongly by cover crop treatment, season, planting window, and year (Fig. 3-2; Murrell et al. 2017). In the PM window, cover crop mixtures produced more biomass than monocultures on average, though not more than the most productive monocultures (Table 3-3). In the fall (Fig. 3-2A), oat and Austrian winter pea were generally the most productive monocultures; mixtures containing either or both of these species (3SppW and 6Spp) almost always produced equivalent biomass. In the spring, cereal rye was always the most productive monoculture,

though it was not statistically different from canola and clover in 2015. Rye biomass exceeded 6Spp in 2013 and 3SppW and 6Spp in 2014; otherwise spring mixtures produced equivalent biomass.

Component species were relatively evenly represented in fall PM mixtures, with the exception of red clover, which did not establish well in the late-summer planting window. Spring mixtures (Fig. 3-2C) were dominated by cereal rye. This shift reflects the phenology of the component species, with both oat and radish reliably winterkilling and rye exhibiting very high spring growth rates following vernalization. Winter survival of Austrian winter pea was highly variable, with strong overwintering in the relatively mild 2012-2013 winter but near-total winterkill in the following years. Pea survival was better in mixtures than in monocultures, likely due to suppressed fall growth rate, which delayed flowering, and to over-winter protection by other species' biomass (Murrell et al. 2017).

In the PS window (Fig. 3-2, Table 3-4), late planting resulted in minimal fall biomass production (Fig. 3-2B). Only cereal rye reliably overwintered, which reduced the effective treatments in the PS window to two: those with rye and those without (Fig. 3-2D). In general, spring rye biomass did not differ among rye-containing treatments (Table 3-4), despite seeding rate being reduced by 80% in the 4Spp and 6Spp mixes. The only exception was in 2013, when 4Spp and 6Spp produced less biomass than the rye monoculture. Rye planted in the PS window produced equivalent spring biomass to that planted roughly two months earlier in the PM window. This was in part due to it being terminated 8-9 days later, but also shows rye's excellent adaptation as a late-planted cover crop.

Table **3-3**: Aboveground biomass (kg ha⁻¹ dry matter) and carbon-to-nitrogen (C:N) ratio by year of cover crops grown prior to maize (PM). Biomass and C:N values both include weeds. C:N ratio mean is weighted by the biomass of each replicate. Means within years that share a letter are not significantly different at the alpha = 0.05 level with a Tukey correction for multiple comparisons. Cover crop biomass values were previously reported in Murrell et al. (2017) and Baraibar et al. (2018).

			Cover Crop Treatment										
		Year	Fallow	Clover	Pea	Radish	Canola	Oat	Rye	3SppW	3SppN	4Spp	6Spp
		2012	-	647 a	2440 bc	2120 bc	2350 bc	3340 d	1810 b	2470 bc	2240 bc	2260 bc	2670 cd
	Biomass	2013	-	1960 a	4470 c	2230 a	2140 a	3890 bc	1770 a	3490 bc	2690 ab	2850 ab	3710 bc
Fall		2014	-	1270 a	3120 cd	2060 abc	2040 abc	3450 d	1360 ab	2470 bcd	2720 cd	2120 abc	2660 cd
C:N		2012	-	14.1 b	9.46 a	15.3 b	15.5 bc	25.3 e	18.9 d	23.4 e	12.7 ab	15.5 b	18.7 cd
	C:N	2013	-	16.7 abc	13.0 a	19.6 cd	22.1 d	33.3 e	18.4 bcd	31.2 e	14.3 ab	14.8 ab	21.6 d
		2014	-	14.5 ab	11.3 a	18.4 bcd	23.1 e	40.2 g	22.0 de	33.8 f	13.7 ab	16.2 abc	23.8 e
		2013	-	2330 b	1900 b	97.2 a	4010 c	33.8 a	5850 de	4280 cd	6050 e	5850 de	3360 bc
	Biomass	2014	-	1350 bc	13.2 a	41.6 a	562 ab	18.7 a	2390 d	1210 bc	1700 cd	1930 cd	1340 bc
Spring — C:1		2015	-	1690 cd	142 a	243 ab	1770 cd	25.4 a	2230 cd	1640 cd	2530 d	2370 d	1240 bc
		2013	-	11.6 a	9.85 a	19.8 b	28.3 c	19.8 b	41.0 d	39.4 d	28.2 c	26.6 c	27.9 c
	C:N	2014	-	11.1 a	19.8 c	19.8 c	14.6 b	19.8 c	26.8 f	23.4 de	20.8 cd	21.5 cde	23.7 e
		2015	-	11.2 a	17.8 b	19.8 b	17.6 b	19.8 b	30.5 c	26.7 c	21.9 b	19.2 b	20.1 b

Table 3-4: Aboveground biomass (kg ha⁻¹ dry matter) and carbon-to-nitrogen (C:N) ratio by year of cover crops grown prior to soybean (PS). Biomass and C:N values both include weeds. C:N ratio mean is weighted by the biomass of each replicate. Means within years that share a letter are not significantly different at the alpha = 0.05 level with a Tukey correction for multiple comparisons. Fall biomass and C:N ratio are not reported for the fallow treatment due to missing data.

			Cover Crop Treatment										
		Year	Fallow	Clover	Pea	Radish	Canola	Oat	Rye	3SppW	3SppN	4Spp	6Spp
		2012	-	0.767 a	42.7 abc	42.8 abc	29.1 ab	84.9 bcd	112 de	105 de	151 e	140 de	95.7 cde
	Biomass	2013	-	14.0 a	122 b	158 bc	76.6 ab	236 cd	171 bcd	256 cd	263 d	237 cd	233 cd
Fall C:N		2014	-	8.26 a	94.2 b	131 bc	104 b	205 de	249 e	197 cde	239 de	216 de	179 cd
		2012	-	16.8 de	12.1 abc	9.90 a	11.6 abc	14.5 cd	13.5 bc	14.0 cd	12.6 abc	10.7 ab	12.4 abc
	C:N	2013	-	15.1 e	11.7 bc	9.38 a	10.7 b	14.5 e	13.5 de	13.9 e	12.7 cd	11.0 b	12.5 cd
		2014	-	13.7 d	10.9 ab	9.40 a	10.7 ab	14.5 d	13.6 cd	12.8 cd	13.4 cd	11.8 bc	12.0 bc
		2013	227 a	235 а	747 a	303 a	291 a	443 a	6010 c	4890 bc	5510 bc	3930 b	3540 b
	Biomass	2014	3.50 a	39.1 a	9.68 a	5.97 a	1.95 a	13.5 a	2190 b	2050 b	1720 b	1960 b	1670 b
Spring — C		2015	92.5 a	101 a	692 b	72.2 a	301 ab	146 a	1850 c	1850 c	1780 c	2280 c	1800 c
		2013	22.1 a	19.0 a	12.5 a	21.3 a	20.1 a	20.2 a	40.3 c	40.7 c	34.5 bc	30.7 b	33.9 bc
	C:N	2014	20.2 a	19.9 a	20.2 a	20.2 a	20.2 a	20.2 a	32.3 c	32.3 c	29.3 bc	28.7 b	30.8 bc
		2015	20.2 b	19.9 b	10.9 a	20.2 b	13.4 a	20.2 b	31.8 de	31.1 de	33.8 e	26.4 c	28.8 cd



Figure **3-2**: Cover crop biomass production in fall (A, C) and spring (B, D) in the planting windows prior to maize (A, B) and prior to soybean (C, D). Clusters of bars represent results from the 2012-2013, 2013-2014, and 2014-2015 cover cropping seasons, respectively. Note the different scale in the expanded portion of C. Adapted from Murrell et al. (2017).

Cover crop C:N ratio also differed by cover crop treatment, season, planting window, and year. Prior to maize (Fig. 3-3, Table 3), C:N ratios changed dramatically between the fall and spring in most treatments. In the fall, the oats and the 3SppW mixture, which was dominated by oat, had the highest C:N ratio (~23-40). C:N ratios were low in the pea, clover, 3SppN, and 4Spp (~9-16). The remaining treatments were not different and were clustered around a C:N ratio of 20. In the spring, rye biomass always had the highest C:N ratio (~27-41). The difference with other species was most extreme in 2013, when later termination allowed rye to head out. The mixtures generally had lower C:N ratios than the rye monoculture, except 3SppW in 2013 and 2015, due to inclusion of non-grass cover crop species. Spring C:N was lowest in the clover in all years, and in pea in 2013, when it overwintered. The invariant C:N ratio of 20.0 in fall for fallow and 19.8 in spring for fallow, oat, radish, and 2014 pea reflects the mean C:N ratio of weeds.

Prior to soybean, fall cover crop C:N ratios differed among treatments, but the effect on soil nutrient dynamics was likely minor due to very limited growth (Table 3-4). Spring C:N ratios corresponded strongly to the presence or absence of rye (Fig. 3-4, Table 3-4). As with biomass, C:N

ratio was very similar between the PM and PS planting windows in the rye-containing treatments, though it was typically higher in the PS mixtures since there was much less, if any, non-rye biomass.



Figure **3-3**: Cover crop biomass carbon:nitrogen ratio in the fall (A) and spring (B) prior to maize (mean and standard deviation). C:N ratio is not reported for the fallow treatment since weeds were controlled with tillage.



Figure **3-4**: Cover crop biomass carbon:nitrogen ratio in the spring prior to soybean (mean and standard deviation).

3.3.3 Soil Inorganic Nitrogen – Prior to Maize

In the PM window, SIN varied by cover crop treatment and year (Fig. 3-5). In general, SIN increased sharply following cover crop termination and manure application (indicated with downward arrows in Fig. 3-5). However, SIN was elevated prior to cover crop termination in pea, fallow, and 2013 radish, due to the lack of cover crop N uptake in these treatments in spring. This result was not seen in oat treatments, despite the lack of a growing cover crop. This was likely due to either slower N release from or N immobilization due to the high-C:N ratio oat biomass. By mid-June, maize N uptake began reducing SIN and treatment differences were eventually eliminated.



Figure 3-5: Soil inorganic nitrogen in nitrate (NO_3^-) and ammonium (NH_4^+) in the top 20 cm of soil in plots planted to maize in 2013, 2014, and 2015. Downward arrows indicate the dates of cover crop termination, which were closely followed by manure application and tillage. Upward arrows indicate the dates of maize planting.

Cover crops drove strong differences in the integrated measure of SIN across the maize growing season, SIN_{auc}, with cover crop treatment explaining 51.5% (R^2_m) of the variation in SIN_{auc} across all three years (Fig. 3-6, Table 3-5). Pea and clover had among the highest SIN_{auc} levels each year, suggesting that they increased net N mineralization, but were only different from fallow in 2013. SIN_{auc} was also high in radish in 2013, reflecting high biomass and low C:N ratio the previous fall. Rye, oat and 3SppW had among the lowest SIN_{auc} each year, but the only statistical evidence for net immobilization relative to fallow was in rye and 3SppW in 2013. Difficulty in resolving on net mineralization and immobilization following termination of cover crops with spring biomass C:N ratios well below and above 25 is likely due to the effects of manure on soil N dynamics and site spatial heterogeneity.

Table **3-5**: Area-under-the-curve of soil inorganic nitrogen (SIN_{auc}) in nitrate (NO₃⁻) and ammonium (NH₄⁺) in the top 20 cm of soil in plots planted to maize between early June and late July. Means within years that share a letter are not significantly different at the alpha = 0.05 level with a Tukey correction for multiple comparisons.

Cover Crop Treatment	2013	2014	2015
Fallow	589 bc	572 ab	659 abc
Clover	896 d	606 ab	969 bc
Pea	988 d	808 b	997 с
Radish	764 cd	586 ab	635 abc
Canola	559 bc	591 ab	605 ab
Oat	580 bc	481 a	472 a
Rye	314 a	438 a	482 a
3SppW	313 a	489 a	559 a
3SppN	563 bc	568 ab	689 abc
4Spp	542 abc	674 ab	704 abc
6Spp	487 ab	474 a	630 ab



Figure **3-6**: Area-under-the-curve of soil inorganic nitrogen (SIN_{auc}) in nitrate (NO₃⁻) and ammonium (NH₄⁺) in the top 20 cm of soil in plots planted to maize between early June and late July pooled across 2013, 2014, and 2015 (mean and standard deviation).

Differences in SIN among years are attributable to manure rates and weather patterns. Manure was applied on a wet-weight basis, but varied substantially in moisture content and N concentration. As a result, manure plant-available N was 65.3% and 85.2% higher in 2014 and 2015, respectively, than in 2013 (Table 3-1). Despite the lower manure N content in 2013, the later termination date allowed pea and clover to accumulate ample biomass N and maintain high SIN during early maize growth. However, late termination led to very low SIN following rye and 3SppW. Soil inorganic N was lower in 2014 than in 2015 despite similar manure plant-available N and cover crop biomass and C:N ratios in the two years. This is likely due to leaching caused by high rainfall in May of 2014 (Fig. 3-1a). Above-average temperatures in May of 2015 (Fig. 3-1b) may have also increased N mineralization from cover crop biomass, manure, and soil organic matter.

Spatiotemporal stability of SIN_{auc} did not differ by cover crop according to the traditional EIbased stability analysis (Table 3-6, Fig. 3-7). There was also no relationship between cover crop species diversity and any of the stability metrics.

However, there were strong differences in the consistent performance index for SIN_{auc} (CPI_{sin}), with low-C:N ratio cover crops consistently having the highest scores (Table 3-6). This finding aligns with a visual inspection of the EI-based stability analysis plot (Fig. 3-7), which shows that SIN_{auc} following pea and clover was variable but consistently high, while SIN_{auc} following radish and 4Spp was lower but more stable. The cover crop treatments dominated by high-C:N ratio grass biomass, such as rye, 3SppW, and oat, resulted in consistently low SIN_{auc}.

For the most part, the rank order of mean SIN_{auc} is identical to that for CPI_{sin}, but there are instructive exceptions. The fallow treatment is ranked higher (5th) by CPI_{sin} than by mean SIN_{auc} (6th). This is likely because this treatment had lower variability than 3SppN, the treatment that it moved ahead of in the CPI_{sin} ranking, so its average rank was higher even if the overall mean was not. Indeed, CV of SIN_{auc} was lower following fallow than following 3SppN. The same pattern holds for the other pair of treatments that switched rank: oat and 6Spp. Mean SIN_{auc} was lower following oat, but oat had a lower CV and ranked higher than 6Spp according to CPI_{sin}. The 3SppN and 4Spp mixtures had higher mean SIN_{auc} and CPI_{sin} scores than rye.

The CV does not reveal patterns of stability in SIN_{auc} based on any known cover crop characteristics. While the two legume monoculture cover crops resulted in relatively high CV of SIN_{auc} , the grass-dominated 3SppW had the highest CV. Likewise, the mixtures had CV's spanning the full range of monoculture CV's.

Table **3-6**: Mean area-under-the-curve of soil inorganic nitrogen (SIN_{auc}) and spatiotemporal stability metrics of SIN_{auc} (consistent performance index (CPI_{sin}), coefficient of variation (CV), and slope of the environmental index (EI)), by cover crop treatment. Values represent all three years of the study. Means within columns that share a letter are not significantly different at the alpha = 0.05 level with a Tukey correction for multiple comparisons. An EI slope of one indicates mean stability for this set of treatments, lower slope indicates greater stability, and higher slope indicates lower stability. There were no statistical differences among EI slopes.

Cover Crop	SINauc	CPIsin	CV	EI
Treatment				slope
Pea	931 e	10.2 f	24.7	2.29
Clover	824 de	9.08 ef	26.9	1.28
Radish	662 cd	7.50 def	18.6	0.182
4Spp	640 c	6.92 cde	16.8	0.699
3SppN	607 bc	6.25 cde	24.3	1.29
Fallow	607 bc	6.50 cde	22.6	1.26
Canola	585 abc	6.08 bcd	21.9	0.808
6Spp	531 abc	4.08 abc	23.2	1.22
Oat	511 abc	4.17 abc	21.6	0.71
3SppW	453 ab	3.25 ab	31.4	0.645
Rye	411 a	2.00 a	24.1	0.606



Figure 3-7: Spatiotemporal stability of the area under the curve of soil inorganic nitrogen (SIN_{auc}) in nitrate (NO₃⁻) and ammonium (NH₄⁺) in the top 20 cm of soil in plots planted to maize. Environmental index is the mean SIN_{auc} of all treatments in each block of four blocks in three years. A slope of one indicates mean stability for this set of treatments, lower slope indicates greater stability, and higher slope indicates lower stability.

3.3.4 Soil Inorganic Nitrogen – Prior to Soybean

In the PS plots, SIN primarily varied among years and between cover crops treatments that included rye and those that did not (Fig. 3-8). Limited sampling dates in 2013 make comparisons with other years challenging. In both 2014 and 2015, cover crops that did not include rye resulted in higher SIN than those that did. Immediately after cover crop termination, SIN was 3-4 times higher following non-rye cover crops, but this difference declined as the season progressed. As in the PM window, SIN levels were higher in 2015 than in 2014, despite similar cover crop performance between years. Again, this may be due to leaching in May of 2014 and elevated temperature increasing mineralization in May of 2015. Mid-June SIN was lower in rye than in radish and pea in 2014 (6/11/2014) and higher in pea than in rye, canola, 3SppW, 3SppN, and 4Spp in 2015 (6/24/2015; Fig. 3-9, Table 3-7). Cover crop treatment explained 25.1% (R^2_m , p < 0.0001) of the variation in mid-June SIN in soybean across 2014 and 2015.



Figure **3-8**: Soil inorganic nitrogen (SIN) in nitrate (NO_3^-) and ammonium (NH_4^+) in the top 20 cm of soil in plots planted to soybean in 2013, 2014, and 2015. Downward arrows indicate the dates of cover crop termination, which were closely followed by tillage. Upward arrows indicate the dates dates of soybean planting. Note that SIN was sampled on only two dates in 2013.

Table 3-7: Soil inorganic nitrogen (SIN) in nitrate (NO ₃ ⁻) and ammonium (NH ₄ ⁺) in the top 20 cm of
soil in plots planted to soybean in mid-June. Means within years that share a letter are not
significantly different at the alpha = 0.05 level with a Tukey correction for multiple comparisons.

Cover Crop Treatment	2014	2015
Fallow	8.43 ab	14.8 ab
Clover	9.03 ab	12.3 ab
Pea	10.5 b	18.3 b
Radish	10.4 b	13.9 ab
Canola	9.22 ab	12.1 a
Oat	8.34 ab	14.2 ab
Rye	5.15 a	10.1 a
3SppW	7.78 ab	10.3 a
3SppN	7.04 ab	11 a
4Spp	6.36 ab	11 a
6Spp	6.97 ab	12.4 ab



Figure **3-9**: Soil inorganic nitrogen (SIN) in nitrate (NO₃⁻) and ammonium (NH₄⁺) in the top 20 cm of soil in plots planted to soybean in mid-June of 2014 and 2015 (6/11/2014 and 6/24/2015; mean and standard deviation).

3.3.5 Maize Silage Yield

Maize silage yield was highest in 2015, intermediate in 2013, and lowest in 2014 (Fig. 3-10, Table 3-8). Yield was below the county average in every year following every cover crop (Table 3-8). This may be because the maize was planted roughly one month later than conventional practice. This was done to ensure rapid germination and avoid pest and pathogen damage to the seeds and seedlings, which cannot be managed with chemical controls under organic management. Nutrient availability may have also been limited due to the reliance on manure and cover crop residues for fertility.

Maize silage yield differed strongly by cover crop (Fig. 3-10, Table 3-8). Cover crop treatment explained 21.7% of the variability in annual maize yield across all three years (R^{2}_{m} , p < 0.0001). Pea resulted in among the highest maize yield in every year and surpassed all other cover crop treatments in 2014. Maize yield following clover, radish, canola, 3SppN, 4Spp, and 6Spp were not different from that following pea in 2013 or 2015. Yield following fallow matched yield following pea in 2013 and 2014, but not in 2015. Yield following rye was always among the lowest, but generally was not different from most other treatments, except pea, clover and radish in 2013 and pea and 3SppN in 2014. Maize yield was positively correlated with both SIN_{auc} (Fig. 3-11) and spring cover crop C:N ratio, which explained 23.0% and 15.4% of the variability in maize yield,

respectively (R^{2}_{m} ; p < 0.0001 for both). The response of maize yield to SIN_{auc} was less robust in 2015, perhaps because additional N mineralization following depletion of SIN stocks by maize uptake met the N requirements of maize grown in treatments with low SIN_{auc}.



Figure **3-10**: Maize silage yield (Mg ha⁻¹ dry matter) following cover crop monocultures and mixtures (mean and standard deviation).



Figure **3-11**: Relationship between maize silage yield (Mg ha⁻¹ dry matter) and the area-under-thecurve of soil inorganic nitrogen (SIN_{auc}) in nitrate (NO₃⁻) and ammonium (NH₄⁺) in the top 20 cm of soil under maize between early June and late July.

As with SIN_{auc}, spatiotemporal stability of maize silage yield did not differ by cover crop treatment when analyzed based on the slope of the EI analysis (Table 3-9, Fig. 3-12). There was also no relationship between cover crop species diversity and any of the stability metrics.

However, the CPI for maize silage yield (CPI_{*Zm*}) strongly differentiated among cover crop treatments, with the highest scores following cover crops with low biomass C:N ratios. Again, this result is confirmed by visual inspection of the EI analysis plot (Fig. 3-12), which shows that maize yield was high and quite stable following pea. While yield was substantially less stable following clover, radish, and 3SppN, illustrated by high slopes against the EI, these treatments also out-yielded all others except pea in moderate-to-favorable environments. In contrast, rye and 3SppW were consistent poor-performers. The fallow treatment appears to be the most stable. However, compared to clover, radish, and 3SppN, the yield increase following fallow in bad years is much smaller than the yield loss in good years, so on balance this type of stability may not be beneficial.

The CPI_{Zm} captures both the mean level and the relatively stability of the treatments. Mean yield determines CPI scores more strongly than variability, but shifts in the rank order of treatments between mean maize silage yield and CPI_{Zm} confirm that the index also rewards low variability. For instance, radish is ranked above clover in the CPI_{Zm} , despite a lower mean yield, and also has a lower CV. Likewise, fallow increases in rank over oat and 6Spp and has lower CV than both of them. Importantly, there was a strong relationship between CPI_{sin} and CPI_{Zm}, with the former explaining 84.9% of the variation in the latter (Fig. 3-13). The CPI_{Zm} score for all mixtures except 3SppW was higher than for rye.

The CV does little to further illuminate spatiotemporal yield stability. Pea produced the lowest CV, while clover produced the second-highest. 4Spp produced the second-lowest, while 3SppW produced the highest. Radish and canola resulted in moderate and nearly identical CV's, potentially suggesting greater yield stability following brassica cover crops, which could be due to their low-to-moderate biomass C:N ratios. However, it is difficult to draw this conclusion from two data points.
Table 3-8: Maize silage, soybean, and wheat yields by cover crop and year. Means within or across years that share a letter are not significantly different at the alpha = 0.05 level with a Tukey correction for multiple comparisons. There are no pairwise differences among cover crop treatments for soybean or wheat yield.

Cover Crop Treatment												County		
Crop	Year	Fallow	Clover	Pea	Radish	Canola	Oat	Rye	3SppW	3SppN	4Spp	6Spp	Mean	Mean ^a
M.:	2013	14.1 bc	15.7 c	16.3 c	15.3 c	13.5 abc	12.5 abc	9.17 a	10.0 ab	13.2 abc	13.4 abc	13.7 abc	13.4 B	17.7
Silago	2014	11.1 abc	10.1 ab	14.2 c	10.2 ab	10.0 ab	9.60 ab	8.40 a	9.84 ab	11.6 bc	10.8 ab	9.65 ab	10.5 A	18.1
Shage	2015	12.4 a	16.3 ab	16.5 b	15.9 ab	14.3 ab	15.5 ab	12.5 ab	13.8 ab	15.9 ab	14.9 ab	14.3 ab	14.8 C	18.9
	2013	3.00	3.06	2.74	2.71	2.78	2.68	2.88	2.92	3.26	2.67	2.85	2.87 A	3.44
Soybean	2014	3.64	3.48	3.45	3.61	3.41	3.82	3.65	3.45	3.35	3.58	3.42	3.53 C	3.56
	2015	2.95	2.97	3.04	3.05	3.12	3.14	3.00	3.14	3.05	3.10	2.86	3.04 B	3.26
	2013	2.85	2.55	2.89	2.94	2.94	3.02	2.99	2.47	2.66	3.14	2.75	2.84 C	4.64
Wheat	2014	2.37	2.59	2.71	2.16	2.29	2.52	2.42	2.56	2.42	2.17	2.14	2.40 B	4.74
	2015	1.93	1.85	1.90	2.13	2.03	1.98	2.07	1.87	1.84	1.96	2.20	1.98 A	4.88

Units: maize silage, Mg ha⁻¹ dry matter; soybean, Mg ha⁻¹ at 13% moisture; wheat, Mg ha⁻¹ at 13.5% moisture. ^a Data from NASS QuickStats (2018).

Table **3-9**: Mean maize silage yield and spatiotemporal stability metrics of yield (consistent performance index (CPI_{Zm}), coefficient of variation (CV), and slope of the environmental index (EI)), by cover crop treatment. Values represent all three years of the study. Means within columns that share a letter are not significantly different at the alpha = 0.05 level with a Tukey correction for multiple comparisons. An EI slope of one indicates mean stability for this set of treatments, lower slope indicates greater stability, and higher slope indicates lower stability. There were no statistical differences among EI slopes.

Cover Crop	Maize			FI
Ture ture unt		CPI_{Zm}	CV	-1
Treatment	silage yield			slope
	Mg ha ⁻¹			
Pea	15.6 d	10.2 d	13.0	0.744
Clover	14.1 cd	7.42 cd	25.7	1.33
Radish	13.8 cd	8.00 cd	21.9	1.25
3SppN	13.5 bcd	7.08 bcd	22.5	1.18
4Spp	13.0 bcd	6.00 bc	17.0	0.840
Canola	12.6 bc	5.58 bc	22.2	0.945
6Spp	12.5 bc	5.42 bc	22.7	1.12
Oat	12.5 bc	5.25 bc	24.5	1.17
Fallow	12.5 bc	5.58 bc	19.8	0.642
3SppW	11.2 ab	3.92 ab	26.8	0.974
Rye	10.0 a	1.58 a	22.1	0.811



Figure **3-12**: Spatiotemporal stability of maize silage yield. Environmental index is the mean yield of all treatments in each block of four blocks in three years.



Figure 3-13: Relationship between spatiotemporal consistent-performance index of SIN_{auc} (CPI_{sin}) and maize silage yield (CPI_{Zm}). Each point represents one cover crop treatment. CPI score for a given value (yield or SIN_{auc}) corresponds to the mean rank for that value across three years and four blocks.

3.3.6 Soybean Yield

Soybean yield was highest in 2014, intermediate in 2015, and lowest in 2013 (Fig. 3-14, Table 3-8). Yield was higher than the county average in 2014 and below it in the other years. Differences among years were likely due to precipitation patterns, with consistent rains in 2014 promoting high yield and late-season drought depressing yield in 2013 and 2015.

There were no cover crop effects on soybean yield, either by treatment or between the ryecontaining and no-rye treatment groups (Fig. 3-14, Table 3-8). Soybean yield could not be explained by SIN measured at any time during soybean growth or by spring cover crop C:N ratio.



Figure **3-14**: Soybean yield (13% moisture) following cover crop monocultures and mixtures (mean and standard deviation).

There were no indications of differences in spatiotemporal stability of soybean yield based on any of the metrics used (Table 3-10, Fig. 3-15), nor was there a relationship between treatment diversity and any of the stability metrics. Neither EI slope nor CPI of soybean yield (CPI_{Gm}) differed by cover crop treatment. While EI slope was relatively high for oat and rye, suggesting that grasses may result in low soybean yield stability, two mixtures that were essentially entirely composed of cereal rye (3SppN and 3SppW) had the lowest EI slopes. Likewise, CV did not differ consistently by cover crop characteristics, with the rye-containing and no-rye treatments distributed across the full range of CV values.

Table **3-10**: Mean soybean yield and spatiotemporal stability metrics of yield (consistent performance index (CPI_{Gm}), coefficient of variation (CV), and slope of the environmental index (EI)), by cover crop treatment. Values represent all three years of the study. There were no statistical differences among values in any of the columns. An EI slope of one indicates mean stability for this set of treatments, lower slope indicates greater stability, and higher slope indicates lower stability.

Cover Crop Treatment	Soybean vield	CPI _{Gm}	CV	EI slope
	Mg ha ⁻¹			brope
3SppN	3.22	6.58	12.3	0.336
Oat	3.22	6.67	16.3	1.41
Fallow	3.2	7.00	15.3	0.978
Rye	3.17	5.25	17.6	1.33
3SppW	3.17	6.58	9.88	0.738
Clover	3.17	6.42	14.4	0.999
Radish	3.12	5.50	14.2	1.11
4Spp	3.12	5.92	15.0	1.2
Canola	3.11	5.83	10.0	0.761
Pea	3.08	5.33	16.6	1.12
6Spp	3.05	4.92	14.0	1.02



Figure **3-15**: Spatiotemporal stability of soybean yield. Environmental index is the mean yield of all treatments in each block of four blocks in three years. A slope of one indicates mean stability for this set of treatments, lower slope indicates greater stability, and higher slope indicates lower stability.

3.3.7 Wheat Yield

Wheat yield was highest in 2013, intermediate in 2014, and lowest in 2015 (Fig. 3-16, Table 3-8), despite an increase in the seeding rate in the final year. This trend tracks a decline in plant-available N in applied manure (Table 3-1), which was caused by variability in manure moisture and N content. Lower yield in 2014 and 2015 may have also been due to low winter temperatures and lack of snow cover. Wheat yield was far below the county average in every year, likely due to late planting and slow mineralization of manure N in cold conditions.

Wheat yield did not differ by cover crop (Fig. 3-16, Table 3-8). Cover crop treatment effects were tested separately for 2015 wheat, since this is the only year in which the wheat plots had a legacy of cover crops from both the PM and PS planting windows. Despite this more substantial cover crop legacy, there were also no cover crop effects on 2015 wheat yield, either by cover crop treatment or when the rye-containing and no-rye groups were pooled.



Figure **3-16**: Wheat yield (13.5% moisture) following cover crop monocultures and mixtures (mean and standard deviation).

3.4 Discussion

3.4.1 Cover Crop Effects on Crop Yields

Cover crops exerted a strong influence on the yield of the following maize crop but did not affect yield of soybean or wheat. The strong positive relationship between SIN_{auc} and maize yield (Fig. 3-10) indicates that cover crops affected yield by modifying soil N availability. Compared to fallow, both SIN_{auc} and maize yield tended to increase following cover crops with low-C:N ratio biomass and decreased following those with high-C:N ratio biomass (Figs. 3-6 and 3-9).

In soybean, high-C:N ratio cover crops—essentially, treatments that included rye—had a similar effect on SIN, but no effect on yield. Though soybeans have been shown to respond to applications of N fertilizer, despite their ability to fix atmospheric N, this response is most common in environments with higher yield potential than that assessed here (Salvagiotti et al. 2008). Lack of an effect on wheat yield, even in 2015 with the legacy of two prior cover crop plantings, is likely due to the temporal separation between cover crop and wheat growth. The manure applied before wheat planting also likely diluted any cover crop effects on soil N.

Mean maize yield was consistently highest following pea, which produced a large amount of low-C:N ratio biomass in the fall of each year and in the spring of 2013. The yield advantage following pea was greatest in 2014, when SIN was low in the top 20 cm across all cover crops, including pea, likely due to heavy spring rains following cover crop termination. This indicates that either SIN retained below 20 cm or newly-mineralized N from decomposing pea residue was sufficient to support high yield. It is unclear why yield was higher following pea in 2014 than following clover, which had higher SIN than pea at cover crop termination. This discrepancy may be due to spatial variability across our heterogeneous site. Regardless, the legacy of legume monocultures clearly resulted in the highest yields.

However, previously-reported results from this experiment show that N leaching potential during the fall and spring cover crop growth period was much higher under pea and clover than any other treatment except fallow (Finney et al. 2017). Elevated SIN following pea and clover during the brief period between cover crop termination and maize planting further increases the risk of heavy N losses. This indicates a management tradeoff that could be better optimized by cover crop treatments that combine low-C:N ratio biomass and low leaching potential.

Mixtures dominated by grasses, which uniformly had high-C:N ratio biomass, produced the lowest maize yield. Yield was numerically lowest following rye in every year except 2015, when yield was lower in fallow. The 3SppW mix, which was dominated by oat in the fall and rye in the spring, also produced low maize yield. However, yield was higher following mixtures that contained substantial biomass from legumes and brassicas in addition to rye and oat. For example, yield following 3SppN was not different from that following pea in any year, and nor was yield following 4Spp and 6Spp in 2013 and 2015. Nitrogen leaching potential under 3SppN, 4Spp, and 6Spp was very low (Finney et al. 2017), indicating that a balanced mixture of species with complementary N-functional traits can optimize N supply and retention services in diverse mixtures. The brassica cover crop species—canola and radish—resulted in moderate yield when grown in monoculture and helped mitigate the yield drag from rye when included in mixtures (4Spp and 6Spp).

Over-winter survival exerted strong effects on cover crop mixture composition and resulting maize yield. Mixture evenness declined greatly from fall to spring (Murrell et al. 2017) as radish and oat winterkilled; pea was set back or killed; and rye began to grow rapidly following vernalization. Rye rarely made up more than 35% of PM mixture biomass in the fall but was regularly over 75% in the spring. In the 3SppW mix, phenological complementarity allowed both oat and rye to thrive in their respective windows of maximum growth, leading to large amounts of high-C:N ratio biomass in both fall and spring and ultimately to low maize yield. However, phenological complementarity also allowed pea and canola to produce substantial biomass in the 3SppN and 4Spp mixes in the fall, which moderated their composite C:N ratio and reduced maize yield drag. This indicates that phenological complementarity is a powerful tool for shaping cover crop performance and that careful mixture design can help achieve specific services.

Winter phenology may also affect the relationship between biomass C:N ratio, SIN_{auc}, and maize yield. Despite the oat monoculture exhibiting among the highest C:N ratios in the fall, SIN_{auc} was not depressed following oat in 2013 and 2014. This is likely because it died in the winter and subsequent decomposition reduced residue C:N ratio prior to maize growth (White et al. 2016). However, winter survival did not seem to affect the performance of Austrian winter pea, which resulted in similar SIN_{auc} and maize yield in 2013 and 2015 and similar yields across all years, despite only overwintering in 2013.

In general, our results confirm previous findings (Finney et al. 2016, White et al. 2016, White et al. 2017) that cover crop C:N ratio can have a large effect on the yield of the following crop, particularly N-scavengers such as maize, when the cover crops are allowed to produce substantial biomass. The yield benefit following N-mineralizing cover crops suggests that combining cover cropping with a P-based manure fertility program may enable adequate N fertility while avoiding overapplication of P, which is common when manure is used to meet plant N requirements. Over the course of a single crop rotation, we do not see evidence that cover crop C:N ratio affects leguminous cash crops or those separated temporally from the cover crop growth window. However, longer-term cover cropping may result in changes to soil structural and chemical properties that would affect the growth of all crops in the rotation (Blanco-Canqui et al. 2015).

These results seem likely to be broadly applicable to annual cropping systems in humid, temperate regions, especially since they align with past findings for less-diverse cover crops (Tonitto et al. 2006, Marcillo and Miguez 2017). However, maize produced under different soil and management conditions is likely to respond differently to equivalent cover crop performance. Our site was relatively N-limited compared to most commercial farms, since manure applications were targeted to meet P requirements. Higher levels of manure or other N inputs may mitigate the negative yield effects of high-C:N ratio cover crops, or diminish the benefits of low-C:N ratio cover crops. Likewise, as White et al. (2017) found, SOC levels interact with cover crop N supply to affect maize yield. Soils with higher N-mineralization capacity may be able to support high maize yield following higher-C:N ratio cover crops, which could present an opportunity for reducing N losses without affecting productivity (White et al. 2017). However, given that many system components—e.g., cover crop growth, soil N mineralization, rainfall, drainage, and crop N uptake—are highly variable in response to soil, weather, and management conditions, further research is needed to determine the effects of multi-species cover crops on maize yield and N loss dynamics.

3.4.2 Cover Crop Effects on Crop Yield Stability

Traditional methods of quantifying stability—coefficient of variation and stability analysis using an environmental index—did not illuminate any differences among cover crop treatments, or relationships between cover crop performance and cash crop response. However, visual inspection of the EI plots of SIN_{auc} (Fig. 3-7) and maize yield (Fig. 3-12) suggests substantially different performance among treatments. This points to a fundamental challenge of analyzing stability in agronomic systems: traditional stability metrics are blind to the level of the function measured. In agronomic systems, the level of the function matters, whether it is yield, N mineralization, weed suppression, or one of many other management targets. For desirable functions, the goal is to achieve performance that is both high and stable; for undesirable functions, low and stable performance is preferred. However, a low CV or a low slope in an EI analysis may coincide with either high or low mean performance. Moreover, for biological functions that asymptote at the low and high end of the driving variable, such as the response of maize yield to N additions, both high and low levels of that variable are likely to result in a stable outcome.

A new stability metric is needed that accounts for both mean performance level and consistency across time and/or space. The rank-based consistent-performance index (CPI) evaluated here meets this criterion, as shown by an evaluation of differences in the rank order of cover crop treatments between mean performance level and CPI. For both SIN_{auc} and maize yield, CPI treatment rank increased relative to mean performance rank only when a treatment was more stable (as measured by CV) than the treatment(s) it moved above in rank. The CPI scores were able to numerically represent the patterns of relative mean performance and stability that were only evident from the EI analysis upon visual inspection of the plots (Fig. 3-12).

The CPI proved useful despite the relatively low level of spatiotemporal variability present in the dataset, which covered only three years at a contiguous site. The CPI may be even more useful when applied across highly variable environments, where large outliers could skew mean service levels, but would have little effect on CPI. Overall, the ability of CPI to provide information about both the level and consistency of a function suggests that it may be a useful tool for assessing agronomic management strategies. It is equally applicable to both desired services and disservices.

The CPI was also the only metric that showed a relationship between the stability of soil N supply and maize yield (Fig. 3-13). Such relationships are critical if cover cropping is to affect the stability of cash crop performance. Notably, the relationship between CPI_{sin} and CPI_{Zm} , was much stronger than that between SIN_{auc} and maize yield, with more than four times as much of the variation explained.

Contrary to our hypothesis, none of the stability metrics were correlated with species diversity. However, the mixtures assessed here all contained cereal rye, and many were rye-dominated, especially in the spring. As a result, the mixtures were limited in functional diversity and species diversity was confounded with species identity. Nevertheless, our results show that diversifying the rye monoculture tended to increase both CPI_{Zm} and CPI_{sin} , especially when the added species had complementary N functions. Adding oat and clover to rye in the 3SppW treatment did not increase either CPI metric, since oat co-dominated and was not different from rye in N function. However, strong performance from pea in 3SppN and from pea and canola in 4Spp resulted in much higher CPI_{Zm} and CPI_{sin} than the rye monoculture. This finding is an example of the phenomenon

reported in Finney et al. (2017), based on the same experiment, in which mixtures increase multifunctionality by mitigating disservices.

3.5 Conclusions

Selecting cover crop species is an exercise in optimizing across multiple objectives in an uncertain environment subject to variable weather and management. Millennia of selection and breeding have produced cover crop species with known environmental tolerances, clear functional traits, and relatively robust performance from year to year. These species can be combined to provide a desired set of functions, assuming relative stability in the soil-climate-management environment. Though cover crop performance was fairly consistent across three seasons at our site, others have found widely divergent outcomes from the same cover crop mixture planted in different site-years (Finney et al. 2016, White et al. 2017).

Our analysis confirms that cover crop mixtures have the potential to strongly affect the yield of the following cash crop, especially a crop with a high N demand such as maize. As in previous studies (Finney et al. 2016, White et al. 2016, White et al. 2017), cover crop biomass C:N ratio was a key determinant of yield. However, all of the studies that have shown this result have been conducted in low-input systems in Pennsylvania. Further research is critically needed to determine the yield effects of cover crop mixtures in other contexts, to aid farmers in designing mixtures that support high yield while also providing other desired services.

Our results indicate that cover crop mixtures can aid in optimization across multiple functions. For instance, diversifying a rye monoculture with pea and canola both increased maize yield and reduced N leaching potential during cover crop growth (Finney et al. 2017). This same strategy also increased the spatiotemporal stability of both soil N supply and maize yield.

The strong relationship between CPI_{sin} and CPI_{Zm} suggests that, at least in low-input environments, soil nutrient supply may be a key determinant of crop yield stability. This finding contrasts with much of the literature on yield stability, which focuses on factors that affect soil water status (Lotter et al. 2003, Mallory and Porter 2007, Gaudin et al. 2015, Ernst et al. 2018) and soil quality in general (Smith et al. 2007, Grover et al. 2009). However, there are likely to be co-benefits for nutrient supply from many of the management interventions that improve soil water supply and quality, such as adding organic inputs and diversifying rotations with legumes. Future studies of yield stability should investigate both water and nutrient effects and their interaction. Evaluating spatiotemporal stability proved challenging. The traditional metrics—coefficient of variation and environmental index—failed to verify a relationship between N supply stability and maize yield stability, despite the strong mechanistic linkage. However, the rank-based consistent-performance index (CPI) developed here clearly showed that consistently high performance in cover crop N supply (SIN_{auc}) resulted in consistently high performance in maize silage yield. Rank-based indices such as this show promise for future analyses of spatiotemporal stability of agronomic production and other ecosystem services.

Overall, these results suggest that strategic diversification of cover crop treatments could result in increased spatiotemporal stability of high performance across multiple services. However, it still remains to be seen whether increasing mixture diversity *per se* can help harness the insurance effect to provide stable functioning in the face of environmental variability. There was no indication of this in our study, but our conclusions are limited due to the low number of high-diversity treatments, the dominance of rye in the mixtures, and the short duration of the study. The benefits of cover crop mixture diversity for yield stability may accrue slowly, as in the case of increased SOM, and may become more apparent across the wider range of environmental conditions experienced with numerous site-years. Ideally, studies testing this hypothesis would include the following features: cover crop treatments designed to include a range of functional response diversity and functional effect redundancy; a wide range of soil-climate conditions; and long duration. Further research will help resolve whether mixture diversity can help provide insurance against environmental variability while also optimizing crop production and environmental outcomes.

3.6 References

- Appelgate, S.R., A.W. Lenssen, M.H. Wiedenhoeft, and T.C. Kaspar. 2017. Cover crop options and mixes for upper midwest corn–soybean systems. Agron. J. 109: 968–984. doi: 10.2134/agronj2016.08.0453.
- Baraibar, B., M.C. Hunter, M.E. Schipanski, A. Hamilton, and D.A. Mortensen. 2018. Weed Suppression in Cover Crop Monocultures and Mixtures. Weed Sci. 66: 121–133. doi: 10.1017/wsc.2017.59.
- Bartoń, K. 2016. MuMIn: Multi-Model Inference.
- Bates, D., M. Mächler, B. Bolker, and S. Walker. 2015. Fitting Linear Mixed-Effects Models Using lme4. J. Stat. Softw. 67: 1–48. doi: 10.18637/jss.v067.i01.

- Blanco-Canqui, H., T.M. Shaver, J.L. Lindquist, C.A. Shapiro, R.W. Elmore, C.A. Francis, and G.W. Hergert. 2015. Cover Crops and Ecosystem Services: Insights from Studies in Temperate Soils. Agron. J. 107: 2449–2474. doi: 10.2134/agronj15.0086.
- Blesh, J. 2018. Functional traits in cover crop mixtures: Biological nitrogen fixation and multifunctionality. J. Appl. Ecol. 55: 38–48. doi: 10.1111/1365-2664.13011.
- Brown, G. 2016. Cover Crops for Grazing. In Grassfed Exchange. Perry, GA.
- Byrnes, J.E.K., L. Gamfeldt, F. Isbell, J.S. Lefcheck, J.N. Griffin, A. Hector, B.J. Cardinale, D.U. Hooper, L.E. Dee, and J. Emmett Duffy. 2014. Investigating the relationship between biodiversity and ecosystem multifunctionality: Challenges and solutions (R Freckleton, Ed.). Methods Ecol. Evol. 5: 111–124. doi: 10.1111/2041-210X.12143.
- Chu, M., S. Jagadamma, F.R. Walker, N.S. Eash, M.J. Buschermohle, and L.A. Duncan. 2017. Effect of Multispecies Cover Crop Mixture on Soil Properties and Crop Yield. Agric. Environ. Lett. 2: 170030. doi: 10.2134/ael2017.09.0030.
- Claus Thorn Ekstrøm. 2017. MESS: Miscellaneous Esoteric Statistical Scripts.
- Creamer, N.G., M.A. Bennett, and B.R. Stinner. 1997. Evaluation of cover crop mixtures for use in vegetable production systems. HortScience 32: 866–870.
- CTIC. 2017. Report of the 2016-17 National Cover Crop Survey. West Lafayette, IN.

CTIC/SARE. 2013. 2012 – 2013 Cover Crop Survey. West Lafayette, IN.

- Davis, A.S., J.D. Hill, C.A. Chase, A.M. Johanns, and M. Liebman. 2012. Increasing Cropping System Diversity Balances Productivity, Profitability and Environmental Health. PLoS One 7: e47149. doi: 10.1371/journal.pone.0047149.
- Eghball, B., G.D. Binford, J.F. Power, D.D. Baltensperger, and F.N. Anderson. 1995. Maize Temporal Yield Variability under Long-Term Manure and Fertilizer Application: Fractal Analysis. Soil Sci. Soc. Am. J. 59: 1360–1364.
- Ernst, O.R., A.R. Kemanian, S.R. Mazzilli, M. Cadenazzi, and S. Dogliotti. 2016. Depressed attainable wheat yields under continuous annual no-till agriculture suggest declining soil productivity. F. Crop. Res. 186: 107–116. doi: 10.1016/j.fcr.2015.11.005.
- Ernst, O.R., S. Dogliotti, M. Cadenazzi, and A.R. Kemanian. 2018. Shifting crop-pasture rotations to no-till annual cropping reduces soil quality and wheat yield. F. Crop. Res. 217: 180–187. doi: 10.1016/j.fcr.2017.11.014.
- Finlay, K.W., and G.N. Wilkinson. 1963. The Analysis of Adaptation in a Plant-Breeding Program. Aust. J. Agric. Res. 14: 742–54.

- Finney, D.M., C.M. White, and J.P. Kaye. 2016. Biomass production and carbon/nitrogen ratio influence ecosystem services from cover crop mixtures. Agron. J. 108: 39–52. doi: 10.2134/agronj15.0182.
- Finney, D.M., and J.P. Kaye. 2016. Functional diversity in cover crop polycultures increases multifunctionality of an agricultural system. J. Appl. Ecol. doi: 10.1111/1365-2664.12765.
- Finney, D.M., E.G. Murrell, C.M. White, B. Baraibar, M.E. Barbercheck, B.A. Bradley, S. Cornelisse, M.C. Hunter, J.P. Kaye, D.A. Mortensen, C.A. Mullen, and M.E. Schipanski. 2017. Ecosystem Services and Disservices Are Bundled in Simple and Diverse Cover Cropping Systems. Agric. Environ. Lett. 2: 170033. doi: 10.2134/ael2017.09.0033.
- Fox, P.N., R. Cormierl, and A. Canada. 1990. Yield and adaptation of hexaploid spring triticale. Euphytica 47: 57–64.
- Gaudin, A.C.M., T.N. Tolhurst, A.P. Ker, K. Janovicek, C. Tortora, R.C. Martin, and W. Deen. 2015. Increasing crop diversity mitigates weather variations and improves yield stability. PLoS One 10: e0113261. doi: 10.1371/journal.pone.0113261.
- Grover, K.K., H.D. Karsten, and G.W. Roth. 2009. Corn grain yields and yield stability in four long-term cropping systems. Agron. J. 101: 940–946. doi: 10.2134/agronj2008.0221x.
- Hooper, D.U., I. F. S. Chapin, J.J. Ewel, A. Hector, P. Inchausti, S. Lavorel, J.H. Lawton, D.M. Lodge, M. Loreau, S. Naeem, B. Schmid, H. Setala, A.J. Symstad, J. Vandermeer, And D.A. Wardle. 2005. Effects of Biodiversity on Ecosystem Functioning: A Consensus of Current Knowledge. Ecol. Monogr. 75: 3–35.
- Hunter, M.C., R.G. Smith, M.E. Schipanski, L.W. Atwood, and D.A. Mortensen. 2017. Agriculture in 2050: Recalibrating targets for sustainable intensification. Bioscience 67: 386–391. doi: 10.1093/biosci/bix010.
- Isbell, F., P. Adler, N. Eisenhauer, D. Fornara, K. Kimmel, C. Kremen, D. Letourneau, M. Liebman, H. Polley, S. Quijas, and M. Scherer-Lorenzen. 2017. Benefits of increasing plant diversity in sustainable agroecosystems. J. Ecol.: 871–879. doi: 10.1111/1365-2745.12789.
- King, A.E., and J. Blesh. 2018. Crop rotations for increased soil carbon: Perenniality as a guiding principle: Perenniality. Ecol. Appl. 28: 249–261. doi: 10.1002/eap.1648.
- Lachance, J., M. Hunter, and D. Finney. 2015. Post-Its and Priorities: A Participatory Exercise for Understanding Perspectives of Diverse Stakeholders. J. Ext. 53: 5TOT2.
- Lenth, R. 2018. emmeans: Estimated Marginal Means, aka Least-Squares Means.
- Lin, B.B. 2011. Resilience in Agriculture through Crop Diversification: Adaptive Management for Environmental Change. Bioscience 61: 183–193. doi: 10.1525/bio.2011.61.3.4.
- Lithourgidis, A.S., C.A. Dordas, C.A. Damalas, and D.N. Vlachostergios. 2011. Annual intercrops: an alternative pathway for sustainable agriculture. Aust. J. Crop Sci. 5: 396–410.

- Lotter, D.W., R. Seidel, and W. Liebhardt. 2003. The performance of organic and conventional cropping systems in an extreme climate year. Am. J. Altern. Agric. 18: 146.
- Malézieux, E., Y. Crozat, C. Dupraz, M. Laurans, D. Makowski, H. Ozier-Lafontaine, B. Rapidel, S. de Tourdonnet, and M. Valantin-Morison. 2009. Mixing plant species in cropping systems: concepts, tools and models. A review. Agron. Sustain. Dev. 29: 43–62. doi: 10.1051/agro.
- Mallory, E.B., and G.A. Porter. 2007. Potato yield stability under contrasting soil management strategies. Agron. J. 99: 501–510. doi: 10.2134/agronj2006.0105.
- Marcillo, G.S., and F.E. Miguez. 2017. Corn yield response to winter cover crops: An updated metaanalysis. J. Soil Water Conserv. 72: 226–239. doi: 10.2489/jswc.72.3.226.
- Mccann, K.S. 2000. The diversity-stability debate. Nature 405: 228-233.
- MCCC. 2018. Selector Tools. Midwest Cover Crop. Counc. http://mccc.msu.edu/selector-tool/.
- Mcdaniel, M.D., L.K. Tiemann, and A.S. Grandy. 2017. Does agricultural crop diversity enhance soil microbial biomass and organic matter dynamics? A meta-analysis. Ecol. Appl. 24: 560–570.
- Murrell, E.G., M.E. Schipanski, D.M. Finney, M.C. Hunter, M. Burgess, J.C. Lachance, B. Baraibar, C.M. White, D.A. Mortensen, and J.P. Kaye. 2017. Achieving Diverse Cover Crop Mixtures: Effects of Planting Date and Seeding Rate. Agron. J. 109: 1–13. doi: 10.2134/agronj2016.03.0174.
- Nakagawa, S., and H. Schielzeth. 2013. A general and simple method for obtaining R2 from generalized linear mixed-effects models. Methods Ecol. Evol. 4: 133–142.
- NASS. 2018. Quick Stats. USDA. Washington, DC.
- Pan, G., P. Smith, and W. Pan. 2009. The role of soil organic matter in maintaining the productivity and yield stability of cereals in China. Agric. Ecosyst. Environ. 129: 344–348. doi: 10.1016/j.agee.2008.10.008.
- Pinheiro, J.C., and D. Bates. 2000. Mixed-effects models in S and S-PLUS. Springer-Verlag, New York, NY.
- Poffenbarger, H.J., S.B. Mirsky, R.R. Weil, J.E. Maul, M. Kramer, J.T. Spargo, and M.A. Cavigelli. 2015. Biomass and nitrogen content of hairy vetch-cereal rye cover crop mixtures as influenced by species proportions. Agron. J. 107: 2069–2082. doi: 10.2134/agronj14.0462.
- Poffenbarger, H.J., D.W. Barker, M.J. Helmers, F.E. Miguez, D.C. Olk, J.E. Sawyer, J. Six, and M.J. Castellano. 2017. Maximum soil organic carbon storage in Midwest U.S. cropping systems when crops are optimally nitrogen-fertilized. PLoS One 12(3): 1–17. doi: 10.1371/journal.pone.0172293.
- Reese, C.L., D.E. Clay, S. a. Clay, A.D. Bich, A.C. Kennedy, S. a. Hansen, and J. Moriles. 2014. Winter Cover Crops Impact on Corn Production in Semiarid Regions. Agron. J. 106: 1479.

- Salvagiotti, F., K.G. Cassman, J.E. Specht, D.T. Walters, A. Weiss, and A. Dobermann. 2008. Nitrogen uptake, fixation and response to fertilizer N in soybeans: A review. F. Crop. Res. 108: 1–13. doi: 10.1016/j.fcr.2008.03.001.
- Smith, R.G., L.W. Atwood, and N.D. Warren. 2014. Increased productivity of a cover crop mixture is not associated with enhanced agroecosystem services. PLoS One 9: e97351.
- Smith, R.G., and K.L. Gross. 2006. Weed community and corn yield variability in diverse management systems. Weed Sci. 54: 106–113. doi: 10.1614/WS-05-108R.1.
- Smith, R.G., K.L. Gross, and G.P. Robertson. 2008. Effects of crop diversity on agroecosystem function: Crop yield response. Ecosystems 11: 355–366. doi: 10.1007/s10021-008-9124-5.
- Smith, R.G., F.D. Menalled, and G.P. Robertson. 2007. Temporal yield variability under conventional and alternative management systems. Agron. J. 99: 1629–1634. doi: 10.2134/agronj2007.0096.
- SSCC. 2016. Mixed Models: Diagnostics and Inference.
- St-fartin, A., G. Vico, G. Bergkvist, and R. Bommarco. 2017. Diverse cropping systems enhanced yield but did not improve yield stability in a 52-year long experiment. Agric. Ecosyst. Environ. 247: 337–342. doi: 10.1016/j.agee.2017.07.013.
- Storkey, J., T.D. Ring, J. Baddeley, R. Collins, S. Roderick, H. Jones, and C. Watson. 2015. Engineering a plant community to deliver multiple ecosystem services. Ecol. Appl. 25: 1034– 1043. doi: 10.1890/14-1605.1.
- Temesgen, T., G. Keneni, T. Sefera, and M. Jarso. 2015. Yield stability and relationships among stability parameters in faba bean (Vicia faba L.) genotypes. Crop J. 3: 258–268. doi: 10.1016/j.cj.2015.03.004.
- Tilman, D., and J.A. Downing. 1994. Biodiversity and stability in grasslands. Nature 367: 363–365.
- Tollenaar, M., and E.A. Lee. 2002. Yield potential, yield stability and stress tolerance in maize. F. Crop. Res. 75: 161–169.
- Tonitto, C., M.B. David, and L.E. Drinkwater. 2006. Replacing bare fallows with cover crops in fertilizer-intensive cropping systems: A meta-analysis of crop yield and N dynamics. Agric. Ecosyst. Environ. 112: 58–72. doi: 10.1016/j.agee.2005.07.003.
- Tribouillois, H., F. Fort, P. Cruz, R. Charles, O. Flores, E. Garnier, and E. Justes. 2015. A Functional Characterisation of a Wide Range of Cover Crop Species: Growth and Nitrogen Acquisition Rates, Leaf Traits and Ecological Strategies. PLoS One: e0122156.
- Varvel, G.E. 2000. Crop Rotation and Nitrogen Effects on Normalized Grain Yields in a Long-Term Study Crop Rotation and Nitrogen Effects on Normalized Grain Yields in a Long-Term Study. Agron. J. 92: 938–941.

- Wander, M., and S. Aref. 1998. Long-term trends of corn yield and soil organic matter in different crop sequences and soil fertility treatments of the Morrow Plots. p. 153–198. *In* Advances in Agronomy. Academic Press, Cambridge, MA.
- Welch, R.Y., G.D. Behnke, A.S. Davis, J. Masiunas, and M.B. Villamil. 2016. Using cover crops in headlands of organic grain farms: Effects on soil properties, weeds and crop yields. Agric. Ecosyst. Environ. 216: 322–332. doi: 10.1016/j.agee.2015.10.014.
- White, C.M., S.T. DuPont, M. Hautau, D. Hartman, D.M. Finney, B. Bradley, J.C. LaChance, and J.P. Kaye. 2017. Managing the trade off between nitrogen supply and retention with cover crop mixtures. Agric. Ecosyst. Environ. 237: 121–133. doi: 10.1016/j.agee.2016.12.016.
- White, C.M., D.M. Finney, A.R. Kemanian, and J.P. Kaye. 2016. A Model–Data Fusion Approach for Predicting Cover Crop Nitrogen Supply to Corn. Agron. J. 108: 2527–2540. doi: 10.2134/agronj2016.05.0288.
- White, C., M. Barbercheck, T. DuPont, D. Finney, A. Hamilton, D. Hartman, M. Hautau, J. Hinds, M. Hunter, J. Kaye, and J. La Chance. 2016. Making the Most of Mixtures: Considerations for Winter Cover Crops in Temperate Climates.
- Williams, A., M.C. Hunter, M. Kammerer, D.A. Kane, N.R. Jordan, D.A. Mortensen, R.G. Smith, S. Snapp, and A.S. Davis. 2016. Soil water holding capacity mitigates downside risk and volatility in US rainfed maize: Time to invest in soil organic matter? PLoS One 11: 1–11. doi: 10.1371/journal.pone.0160974.
- Wolfe, D.W., A.T. Degaetano, G.M. Peck, M. Carey, L.H. Ziska, J. Lea-cox, and A.R. Kemanian. 2018. Unique challenges and opportunities for northeastern US crop production in a changing climate. Clim. Change 146: 231–245.
- Wood, S.A., D.S. Karp, F. Declerck, C. Kremen, S. Naeem, and C.A. Palm. 2015. Functional traits in agriculture: agrobiodiversity and ecosystem services. Trends Ecol. Evol. 30: 531–539.
- Wortman, S.E., C. a. Francis, and J.L. Lindquist. 2012a. Cover Crop Mixtures for the Western Corn Belt: Opportunities for Increased Productivity and Stability. Agron. J. 104: 699. doi: 10.2134/agronj2011.0422.
- Wortman, S.E., C. a. Francis, M.L. Bernards, R. a. Drijber, and J.L. Lindquist. 2012b. Optimizing Cover Crop Benefits with Diverse Mixtures and an Alternative Termination Method. Agron. J. 104: 1425–1435. doi: 10.2134/agronj2012.0185.
- Xia, Y., K. Mitchell, M. Ek, J. Sheffield, B. Cosgrove, E. Wood, L. Luo, C. Alonge, H. Wei, J. Meng, B. Livneh, D. Lettenmaier, V. Koren, Q. Duan, K. Mo, Y. Fan, and D. Mocko. 2012.
 Continental-scale water and energy flux analysis and validation for the North American Land Data Assimilation System project phase 2 (NLDAS-2): 1. Intercomparison and application of model products. J. Geophys. Res. Atmos. 117: D03109. doi: 10.1029/2011JD016048.

Chapter 4

Cover Crop Effects on Maize Physiology Under Experimental Drought Conditions

4.1 Introduction

Cover crops may be a critical tool for adapting agriculture to climate change while also contributing to sustainable intensification by helping meet food demand and reducing environmental impacts (Hunter et al. 2017). Cover crops can limit soil loss caused by extreme rainfall events (Wolfe et al. 2018), mitigate climate forcing (Kaye and Quemada 2017), help maintain or increase crop yield (Marcillo and Miguez 2017), and reduce losses of nutrients and sediment to waterways (Tonitto et al. 2006). However, given projections of increased drought stress in many agricultural regions, a key question remains unanswered: How do cover crops impact the drought physiology of the following cash crop?

Increased agricultural drought is among the most concerning projected effects of climate change. Short-term droughts can lead to substantial yield losses and prolonged drought stress may cause total crop failure (Denmead and Shaw 1960, Campos et al. 2004). Climate projections indicate that higher temperatures and a reduction in summer precipitation will increase drought frequency and severity across much of the United States, including the Northeast (Hayhoe et al. 2007, Walthall et al. 2013, Wolfe et al. 2018). While it has been argued that elevated atmospheric carbon dioxide (CO₂) concentrations will buffer against drought stress by reducing transpirative water losses (Leakey et al. 2006, Manderscheid et al. 2014, van der Kooi et al. 2016), higher canopy temperature may counteract these water savings and exacerbate heat stress (Gray et al. 2016, Wang et al. 2012).

In the absence of irrigation, drought is one of the most challenging stresses for farmers to manage. An ideal drought-resistant system would both maximize soil water supply and optimize crop water use for the local ecohydrological regime. Soil water supply can be enhanced by improving soils to increase infiltration rate and storage capacity (Basche 2017) and by reducing evaporative water losses (Wang et al. 2018). Crop water use is influenced by crop species, cultivar, relative maturity, planting date, stand density, and fertility (Bodner et al. 2015). Due to the tight physiological coupling of transpirative water loss and CO₂ uptake (Jones et al. 1986), strategies that

reduce crop water demand often reduce yield potential. In temperate climates that rely on in-season rainfall, such as the Midwest and Northeast US, it is usually optimal to maximize canopy photosynthesis to ensure that all available soil water is used for plant growth (Blum 2009). However, if terminal drought (i.e., drought that occurs at the end of the growing season) becomes more common under climate change, a shift toward water-saving tactics such as earlier seeding or shorter-season cultivars may be adaptive (Bodner et al. 2015).

Given the unpredictability of seasonal precipitation, farmers will be best served by cropping systems with built-in drought adaptation strategies. Survey evidence suggests that cover crops may fit this bill: farmers reported 10-15% higher yields in cover-cropped fields of maize (*Zea mays*) and soybean (*Glycine max*) in U.S. Midwest states affected by drought in 2012 (CTIC/SARE 2013). This reported yield increase was larger than in other states in 2012 and in the same states in other years of the survey. Advocacy organizations have also argued that cover cropping, and other soil-improving practices, can help reduce drought risk (NRDC 2015, Basche 2017). However, there is little research evaluating these claims. This study aims to help fill this gap by investigating the effects of cover crops on drought stress in the following maize crop.

4.1.1 Cover Crop Effects on Crop Water Balance

Cover cropping may have either negative or positive effects on crop water balance under drought. The primary negative effect occurs when cover crop transpiration depletes soil water (Ewing et al. 1991, Campbell et al. 1984, Wortman et al. 2012). This risk limits cover crop adoption in dry climates, though early termination during dry conditions can mitigate moisture losses (Munawar et al. 1990, Baker and Griffis 2009, Krueger et al. 2011). High-rainfall environments rarely experience negative effects of cover crop transpirative water losses (Blanco-Canqui et al. 2015).

Cover crops and their residues can also positively affect water infiltration and storage; reduce surface evaporation; and enhance cash crop water access and drought tolerance. Cover crops can increase infiltration and storage in the short term by slowing overland water flow and in the long term by increasing macroporosity, aggregation, and field capacity (Blanco-Canqui et al. 2015; Basche 2017, Basche and DeLonge 2017). Retaining residues as a mulch can substantially reduce evaporation from the soil surface (Jones et al. 1969, Frye et al. 1988, Wang et al. 2018). Likewise, cover crops may reduce evaporative losses if they disrupt weed life cycles (Baraibar et al. 2018) and

thereby reduce the need for tillage to control weeds. Cash crop roots have been shown to follow cover crop root channels into deeper soil layers, improving subsoil water access (Chen and Weil 2010). Cover crops that host arbuscular-mycorrhizal fungi can enhance colonization of the following maize (Kabir and Koide 2002), which may improve drought tolerance (Boomsma and Vyn 2008). With proper management, cover crops have the potential to help maximize soil water supply to crops.

4.1.2 Water and Nitrogen Stress

In the short term, cover crops may also affect cash crop drought physiology by influencing soil nitrogen (N) dynamics. Decomposing cover crops with a carbon:nitrogen (C:N) ratio below 25 tend to increase soil inorganic nitrogen (SIN) availability due to net mineralization of N, while cover crops with a high C:N ratio tend to reduce soil SIN availability due to net N immobilization (White et al. 2016). Cover crop biomass C:N ratio can have profound effects on cash crop N nutrition and ultimately yield, especially in low-input and organic systems. Maize yield has been shown to increase or decrease by over 50% following low- and high-C:N ratio cover crops, respectively (Finney et al. 2016, White et al. 2017).

In drought conditions, cover crop effects on maize N status may interact strongly with water stress to influence plant performance (Gonzalez-Dugo et al. 2010). Though the physiological processes involved are complex, both water- and N-stress ultimately impair yield formation by reducing radiation interception (RI) and radiation use efficiency (RUE), two critical controls on photosynthesis and plant growth (Stöckle and Kemanian 2009, Wolfe et al. 1988a). Water- and N-stress also both affect development of reproductive tissues, and therefore the harvest index (HI) (Earl and Davis 2003). By contrast, intrinsic water-use efficiency is not strongly affected by plant N status (Jones et al. 1986).

Both water- and N-stress directly reduce radiation capture (Bennett et al. 1989). Plants experiencing either dry soil conditions or N limitation initiate feed-forward responses that preemptively reduce leaf cell elongation before water and N become critically limited (Lambers et al. 2008). This reduces the rate of leaf expansion and therefore canopy size. Water stress can also reduce radiation capture by inducing leaf wilting or rolling. Both water- and N-stress also stimulate root growth (Gonzalez-Dugo et al. 2010, Lambers et al. 2008), which diverts photosynthates from aboveground biomass, thus limiting the substrate available for canopy expansion. Canopy area limitation is then compounded as reduced radiation capture further limits photosynthate production (Bennett et al. 1989).

Radiation use efficiency is also affected by both water- and N-stresses. Deficiencies of either N or water can reduce leaf chlorophyll concentration, which directly reduces photosynthetic capacity (Huber et al. 1989, Sanchez et al. 1983, Wolfe et al. 1988b). Water stress also reduces stomatal conductance as stomata close in response to both chemical signaling and low turgor pressure. This minimizes transpirative water loss, but also limits carbon dioxide uptake and carbon fixation (Jones et al. 1986, Stone et al. 2001).

Harvest index declines when stress retards reproductive growth processes. Both pollination and kernel set can be reduced by hot and dry conditions (Hatfield et al. 2011), and drought stress may exacerbate the effects of high temperature by reducing transpirative cooling. Likewise, low N status can limit the number, size and growth rate of maize kernels (Melchiori and Caviglia 2008, Uhart and Andrade 1995). Drought and N deficiency can also reduce pollination by increasing the anthesissilking interval (ASI), the length of time from tasseling to silking, which reduces pollen loads (Connor et al. 2011, Bänziger et al. 2000). Following flowering, grain filling may be reduced if photosynthates or N supplies are limited by any of the following: stomatal closure; low soil N availability; low radiation interception due to reduced vegetative growth or early senescence; or low vegetative reserves of carbohydrates or N resulting from deficiencies in early growth stages (NeSmith and Ritchie 1992, Tollenaar and Dwyer 1998, Connor et al. 2011).

Analyzing HI and the size, number, and N concentration of seed yield can provide insight into both the timing and severity of reproductive stresses. While any reproductive stress reduces HI, stress prior to and immediately following kernel set reduces the number of kernels (KN), and stress during later reproductive growth inhibits grain fill and reduces kernel mass (KM) and N concentration. Therefore, partitioning stress effects between KN and KM can provide insight into stress conditions during reproductive growth.

While direct effects of water- and N-stress on maize performance are similar, their interaction may be more complex. Some have suggested that N limitation may help crops tolerate drought (Radin and Parker 1979) by reducing transpirative demand and stimulating root growth (Bennett et al. 1986), though lower transpiration may also exacerbate N limitation by limiting root uptake. By the same token, water stress could help avoid N limitation by stimulating root growth and reducing N demand. However, field studies of interacting N- and water-stress show that N stress generally compounds water stress, and vice versa (Bennett et al. 1989, Markelz et al. 2011), even in terminal drought situations (Wolfe et al. 1988a). Low N is only likely to improve agronomic performance

under drought when it results in early-season water conservation that enables survival of terminal drought. In most other cases, high N supply will promote maximum yield under drought by enabling effective use of available water resources (Blum 2009).

High N supply may also directly limit drought stress by enabling osmotic adjustment. Sufficient N nutrition promotes production of N-containing compatible solutes such as proline and glycine betaine, which enable osmoregulation and may help delay stomatal closure (Ashraf and Foolad 2007, Taiz and Zieger 2010). In one study of field-grown maize, the higher N fertilizer rate resulted in lower (more negative) mid-day leaf water potential, higher turgor pressure, and higher stomatal conductance under water stress (Bennett et al. 1986).

The goal of this study is to determine the short-term mechanisms by which cover crops affect the drought physiology of the following maize crop. Previous studies of the interaction between Nand water-stress have typically been conducted with synthetic fertilizer N sources. To the best of our knowledge, interactions between cover crop-driven nutrient dynamics and water availability have not been investigated to date.

We tested the following hypotheses:

- H1: Spring cover crop transpiration reduces soil moisture and increases maize drought stress.
- H2: Cover crop N provisioning increases maize N status, radiation capture, and radiation use efficiency under drought.
- H3: High N status enables greater osmotic adjustment in response to water stress.
- H4: Cover crop N provisioning increases maize yield, yield components, and yield stability under drought.

4.2 Methods

This study was conducted from 2013-2015 at the Pennsylvania State University Russell E. Larson Agricultural Research Center, Rock Springs, PA (40°43'N, 77°56'W). The dominant soil series (comprising approximately 80% of total land area) is Murrill channery silt loam (fine-loamy, mixed, semiactive, mesic Typic Hapludult). Other soil series present at the site are Hagerstown silt loam (fine, mixed, semiactive, mesic Typic Hapludalf) and Buchanan channery loam (fine-loamy, mixed, semiactive, mesic Aquic Fragiudult). Approximately 80% of the site area has a 0-3% slope, with 3-8% slopes in the remaining area (SSURGO 2017). Soil texture measured in the top 20 cm is predominantly clay loam with variability in sand (21.4 - 27.0%), silt (39.9 - 48.1%), and clay (29.6 - 34.3%). Long-term (1980-2016) average annual precipitation at the site is 1,020 mm and mean monthly temperatures range from -3 °C (January) to 22 °C (July) (Xia et al. 2012).

4.2.1 Experimental Design and Management

The study was embedded in a large systems experiment (Murrell et al. 2017; Finney et al. 2017) investigating a 3-year crop rotation under organic management. The rotational sequence was maize (*Zea mays* L.) silage—soybean (*Glycine max* L.)—winter wheat (*Triticum aestivum* L.), which is typical of many Northeast U.S. organic cash grain farms.

The field site was laid out in a randomized, full-entry complete block design with four replications. Cover crop treatments were planted in 24 m x 29 m split plots within the cash crop strips. Cover crops were planted following both maize silage and winter wheat. This study focused on the cover crops planted after wheat and their effects on the subsequent maize crop.

The site was transitioned to organic management in July, 2012 and received certification in 2016. Maize was planted in late May or early June (Master's Choice MC4050, 82,000 seeds ha⁻¹). Dairy bed pack manure from the Pennsylvania State University dairy herd was broadcast and plowed in along with cover crop residues prior to maize establishment. Manure application rates were designed to meet the phosphorus (P) requirements of the rotation, rather than the nitrogen (N) requirements, creating a baseline N fertility level characterized by moderate N deficit. Weeds were controlled through primary tillage and seedbed preparation prior to planting, as well as by repeated passes of a tine-weeder, rotary hoe, and inter-row cultivator. Maize silage management information is summarized in Table 4-1.

	Seed Cover	Sample Cover Crop		Apply	Plant Maiza	Install Rainout	Harvest	Dry Manure	Manure Plant- Available N
Year	Crop	Bio	mass	Manure	Maize	Shelters	Maize	Rate	
		Fall	Spring					Mg ha ⁻¹	kg N ha ⁻¹
2013-14	8/8	10/29	5/5	5/8	6/2	7/8	9/17	20.7	141
2014-15	8/15	11/5	5/4	5/11	5/28	7/10	9/21-22	17.7	158

Table 4-1: Management dates, manure rate, and manure plant-available N.

Note: Manure plant-available N is calculated assuming 40% availability following White et al. (2017).

4.2.2 Cover Crop Treatments

Five cover crop treatments were selected with contrasting functional traits related to spring transpiration, biomass production, and N supply. Treatments included a tilled fallow control; medium red clover (*Trifolium pratense* L.); cereal rye (*Secale cereale* L. cv. Aroostook); forage radish (*Raphanus sativus* L. cv. Tillage Radish); and a 3-species mixture of red clover, rye, and Austrian winter pea (*Pisum sativum* L.). The latter treatment, known as 3SppN, was designed to both minimize N leaching and provide N to the following corn crop (Murrell et al. 2017). Expected functional traits and target plant populations for the cover crop treatments are reported in Table 4-2. Seeding rates were adjusted based on annual germination tests.

			Spe	cies		Functional Trait			
-	No.	Clover	Rye	Radish	Pea	Spring	Biomass	Nitrogen	
Treatment	Spp.	p	ure live	seed m ⁻² –		Transpiration	Production	Supply	
Fallow control	0					-	-	~	
Medium red clover	1	600				~	~	+	
Cereal rye	1		500			+	+	-	
Forage radish	1			60		-	~	~	
3 species nitrogen	3	300	100		30	+	+	~	

Table **4-2**: Cover crop treatments, treatment abbreviations, number of species per treatment, target plant populations, and expected level of functional traits.

Level of functional trait expected: +, high; ~, moderate; -, low.

Cover crops were established in August and terminated in May of the following year. The preceding wheat stubble was chisel plowed, disked, S-tined and cultimulched. Cover crops were planted with an Almaco (Nevada, IA) Cone Plot Planter mounted on a seed drill with 19 cm spacing

(Murrell et al. 2017). Legume seed was inoculated with dry inoculant prior to seeding. Fallow plots were tilled to eliminate weeds. Cover crops were terminated by flail mowing and moldboard plowing. Cover crop planting and termination dates are listed in Table 4-1.

4.2.3 Rainout Shelters

Modular rainout shelters were installed during maize growth to simulate drought. Due to the organic management system, field operations for mechanical weed control continued until early July, so the shelters were installed on 7/8/14 and 7/10/15.

A preliminary year of the study was conducted in 2013 to develop and refine methods. Results from this year indicated that the shelter roofs must be permanently and tightly affixed, rather than removable, to prevent water from pooling on them. Data from 2013 was not used in the analysis due to methodological differences with the subsequent years.

Rainout shelter frames were constructed of 1.9 cm-diameter electrical metal tube conduit that was joined at the corners with aluminum fittings (Shade King, Thorndale, TX) to produce a gable roof shape. Shelters were covered with 6 mil poly film rated for 92% light transmission (Sun Master, Growers Supply, Dyersville, IA), which was secured to the shelter legs with wiggle wire (Envirotech Greenhouse Solutions, Richmond, CA) and plastic clips. Pipe insulation was applied around the horizontal frame bars to reduce abrasion on the roof plastic. Aluminum gutters were attached below the roof plastic and angled toward a downspout and flexible pipe that carried the captured precipitation away from the plots. For stability, the middle leg on each side was installed over rebar that had been pounded vertically into the soil. In addition, two guy wires were attached from each gable roof end to rebar installed outside the shelters. Parts lists and design specifications are available from the authors upon request. Fig. 4-1 shows a rainout shelter installed in the field.



Figure 4-1: Rainout shelter shortly after installation during early maize growth.

The shelter footprint was 2.7 x 3.0 m. Leg height was initially 1.5 m and was increased to 3.0 m when required to accommodate maize growth. Raising the shelters as the maize plants grew, rather than starting at full height, helped ensure that neighboring maize plants were present to block precipitation that otherwise may have blown in on the open sides of the shelter. Shelters were oriented with the open ends to the north and south. This allowed the west wall of the shelter to block precipitation from the prevailing wind direction (Dauer et al. 2007) and increased light penetration from the south. Berms were dug around the base of the shelter to control overland water flow. Subsurface and capillary flow from soil adjacent to the shelters was not controlled. One plot in each year was removed from the analysis due to persistent flooding that nullified the drought treatment.

Drought plots were paired with ambient plots that generally were not manipulated, except for a single irrigation event on September 4, 2015 to compensate for lack of precipitation (~2.5 cm of water applied directly to the soil surface with buckets). Drought and ambient plots were located in close proximity, usually 5-10 m apart, to minimize spatial variation in soil properties, cover crop performance, and maize stands (plant populations and heights). Weeds were removed by hand to eliminate uncontrolled competition for water, nutrients, and light. To avoid edge effects, all samples were taken within a sampling zone at the center of the plots that spanned the middle two rows of maize and measured $1.22 \times 1.52 \text{ m}$.

4.2.4 Ambient Weather and Shelter Microclimate

Daily temperature, precipitation, and solar radiation data based on satellite observations were obtained from Phase 2 of the North American Land Data Assimilation System (NLDAS; Xia et al.

2012). Growing degree days (GDD) were calculated with a base of 10 °C and a maximum of 30 °C. Seasonal insolation was calculated by summing daily values from one week after planting until harvest.

Soil volumetric moisture content (θ_v) was measured regularly using time-domain reflectometry (TDR; Jackson et al. 2000) with a TDR100 (Campbell Scientific, Logan, UT) and handbuilt TDR probes equipped with three 10 cm-long stainless-steel waveguides. TDR probes were tested prior to deployment and installed horizontally at 10, 20, and 40 cm depths. Two sets of probes were installed in each experimental plot, in both ambient and drought conditions. Installation holes were dug between the two middle rows of maize, with one located adjacent to each row, and waveguides were inserted toward the nearest row. Therefore, the TDR readings represent the moisture content in the rooting zone on the margin of the row and inter-row areas. TDR probes were installed following rainout shelter installation and readings were taken roughly every week until harvest (Fig. 4-2, Table 4-3).

Total centimeters of water in the top 50 cm of soil (SW₅₀) was estimated for each TDR reading by assuming that the TDR probes at 10, 20, and 40 cm depths represented soil in the depth ranges of 0-15cm, 15-30cm, and 30-50 cm, respectively, and summing the value for each depth interval. This value was then used to estimate the cm of water extracted from the top 50 cm of soil over the course of the measurement period by subtracting the final value from the initial value. This was only done for the drought plots, which generally exhibited monotonic declines in θ_v (Fig. 4-4).

Mid-canopy air temperature was recorded every 30 minutes using iButton Thermochron temperature loggers (iButtonLink, Whitewater, WI). Loggers were suspended 1 m above the ground in a fine mesh bag inside of an upside-down reflective plastic cup affixed to a stake, which was placed in a gap in a row of maize in the inner sampling zone. Loggers were installed in the ambient and drought plots following rainout shelter installation in the fallow, rye, and clover treatments and maintained until the end of the season (2014: 7/10 to 9/9; 2015: 7/17 to 9/24). Thirty-minute data was used to calculate daily mean, minimum, and maximum temperature values as well as mean daytime (06:00 to 20:00) and nighttime (20:00 to 06:00) temperatures.

Predawn leaf temperature was measured on September 16, 2015, when the maize was beginning to senesce, using an infrared thermometer (Raytek MX 4BT-NI). Four upper leaves per experimental plot were read in both the ambient and drought conditions in all cover crop treatments.

Attenuation of photosynthetically active radiation (PAR) under the rainout shelters was measured at various times. Day-long attenuation was measured on two separate days (June 22 and 24, 2015) from 8:30 to 17:30. A shelter was installed in low turf grass next to the field site in the

same orientation as used in the field. One LICOR LI-190 Quantum Sensor (LICOR Biosciences, Lincoln, NE) was placed in the center of the shelter and another was placed in an unobstructed location adjacent to the shelter; both were leveled. Readings were taken every 30 seconds from 9 am to 5:30 pm.

Additional PAR attenuation measurements were made in two blocks on the afternoon of August 17, 2015, when the plastic roofs had been subject to dust deposition and UV weathering for over 5 weeks. Simultaneous readings were taken with two LI-190 Quantum Sensors affixed to the top of steel conduit, one within and one outside each shelter. Finally, data from measuring leaf area index (LAI; see method in section 4.2.6, below) on September 18, 2015 was analyzed to assess shelter roof effects on the fraction of beam v. diffuse radiation, since photosynthetic efficiency is higher with diffuse than with beam radiation (Stöckle and Kemanian 2009).

4.2.5 Cover Crop and Soil Measurements

Cover crop aboveground biomass was measured in the fall and spring at three sub-sampling locations in each large (24 x 29 m) plot. Sub-sampling locations were randomly selected to account for variation in the large (24 x 29 m) plots and were not placed in a buffer zone 3m in from the edge of each plot. Fall biomass was collected prior to the first killing frost in late October or November (Table 4-2). All biomass taller than \sim 2 cm within a 0.25 m² frame was cut, sorted to species, dried at 60 °C, and weighed. Spring sub-sampling locations were located 1 m from fall locations in similar cover crop and weed conditions. Spring biomass was collected in mid-May (Table 4-2) in the same manner as in the fall. Since the drought and ambient subplots were sited in part based on maize populations, their location was not known at the time of cover crop sampling, so cover crops could not be sampled from the subplot locations.

Cover crop biomass was analyzed by species for total carbon and nitrogen concentrations by the combustion method (Pella 1990, Horneck and Miller 1998) using an Elementar Vario Max (Elementar, Langenselbold, Germany). Tissue was ground to 1 mm with a Cyclone Sample Mill (Udy Corporation, Fort Collins, Colorado) and submitted to the Penn State Agricultural Analytical Services Lab for analysis. Total C and N in all species were summed and the latter divided by the former to calculate the C:N ratio. Weeds were included in this calculation using mean C and N concentrations for fall or spring weed biomass. Therefore, spring C:N ratio is the same for both the fallow and radish treatments, since neither contained any living cover crop biomass.

Spring cover crop water use was measured with the same TDR system described above. Two TDR probes per cover crop treatment were installed at 20 cm depth beneath the cover crop row in early-to-mid April and read weekly until cover crop termination in early May.

Soil nitrate (NO₃⁻) and ammonium (NH₄⁺) were measured every two weeks from late March or early April through late July, and monthly thereafter. Six soil cores per cover crop treatment plot were taken to 20 cm depth, homogenized, extracted with 2M KCl, and analyzed using a microplate colorimetric technique for NO₃⁻ and NH₄⁺ concentration as reported in Finney et al. (2016). Total soil inorganic N (SIN) was calculated as the sum of N in NO₃⁻ and NH₄⁺. The area under the curve of SIN (SIN_{auc}) was calculated for the readings between maize planting (6/4 in both years) and the end of August (8/27/14 and 8/25/15). This measure is used as an indicator of overall soil N availability during maize growth.

4.2.6 Maize Ecophysiology

Maize pre-dawn leaf xylem water potential, nitrogen status, canopy development, and stomatal conductance were measured regularly to document maize physiological responses to the cover crop and drought stress treatments. Measurement dates are presented in Fig. 4-2 and Table 4-3. Root pits were dug following maize harvest in 2015 to assess rooting depth and density. Results are not reported here since this measure was not replicated in time, but see Appendix.



Figure 4-2: Timeline of ecophysiological measurements (θ_v , soil volumetric water content; Ψ_L , leaf xylem water potential; SPAD, SPAD meter; SIN, soil inorganic nitrogen; LAI, leaf area index; g_s , stomatal conductance).

Year	$\theta_{\rm v}$	$\Psi_{\rm L}$	SPAD	LAI	gs	Height
-	7/22	8/6	7/10	7/10	7/10	7/4
	7/31	8/19	7/15	7/18	7/17	7/31
	8/5	8/29	7/24	7/25	7/18	8/5
	8/11		8/1	8/7	7/24	8/8
2014	8/18		8/8	8/15	8/7	8/11
	8/25		8/14	9/4	8/14	
	9/3		8/26		8/26	
	9/9		9/3			
	9/14					
	7/21	7/29	7/15	7/16	8/4	7/12
	7/29	8/14	7/20	7/20	8/14	7/20
	8/5		7/29	7/24	9/11	7/24
	8/10		8/4	7/31		7/28
2015	8/12		8/12	8/4		8/10
2013	8/21		8/17	8/13		
	8/27		8/24	8/21		
	9/3		9/11	8/28		
	9/9			9/18		
	9/20					

Table 4-3: Dates of ecophysiological measurements.

 θ_v , soil volumetric water content; Ψ_L , leaf xylem water potential; SPAD, SPAD meter; LAI, leaf area index; g_s , stomatal conductance.

Maize water stress was assessed by measuring pre-dawn leaf xylem water potential (Ψ_L ; MPa) using a pressure chamber (PMS Instruments, Albany, OR; Jackson et al. 2000). Four samples per plot were collected before dawn by removing the distal 15 cm of the newest fully-expanded leaf. Later in the season, when newly expanded leaves were not available, healthy leaves at or above the ear leaf were chosen. Leaves were placed in a humidified plastic bag to avoid sample desiccation and the bags were placed in a cooler to maintain dark and cool conditions, then transported to the lab for reading. To prepare the leaves for reading, a cut was made with a razor blade along each side of the midrib and a clean cut was made across the end of the midrib. The midrib was inserted into the pressure chamber collar and the chamber was pressurized. The pressure (MPa) was recorded when xylem fluid was extruded from the cut end of the xylem.

Maize N status was assessed by measuring leaf chlorophyll content with a SPAD meter (SPAD 500, Konica Minolta, Tokyo, Japan; Earl and Tollenaar 1997, Casa et al. 2015). Measurements began prior to shelter installation and continued weekly until harvest. The sensor head was placed on a clean, intact portion of a fully-expanded upper leaf at a distance of ~20 cm from the leaf tip. One leaf on each plant within the sampling area was measured and all readings were

averaged.

Maize canopy development was assessed by measuring hemispherical LAI with a Decagon AccuPar LP-80 ceptometer (Meter, Pullman, WA) with an Apogee QSO-S PAR Photon Flux ambient sensor (Apogee Instruments, Logan, UT). The ceptometer was placed on the ground beneath the maize canopy, arranged diagonally to span the row and inter-row space equally, and leveled. The ambient sensor was affixed to vertical metal conduit resting on the ground and extending above the canopy. Three randomly-chosen locations within the inner sampling area of each subplot were measured three times each and all readings were averaged. When taking readings under the rainout shelters, the ambient sensor was placed under the shelter as well, so that the roof plastic was impacting both sensors equally. Readings were taken within 2 hours of solar noon under clear sky conditions.

Leaf area index was measured weekly under full sun from mid-July through canopy closure in late August and once after senescence had begun in September. These LAI readings were used to calculate fractional interception (FI) of total daily solar radiation (R_d) across the growing season. Starting and ending dates with an LAI value of zero were added to the sequence of LAI readings. The start date was one week after planting, representing the time of emergence, and the final date was October 15th, an estimated date of full senescence, had the maize not been harvested for silage. A cubic polynomial was fit through the subplot-level LAI readings. Inflection of the fitted curve below zero in the first two weeks was removed by extrapolating linearly from a value of 0.1 on day one of the time series to the fitted value for day 14. Daily fractional interception (FI_d) of total solar radiation was calculated for each fitted LAI value using an extinction coefficient for diffuse radiation that integrates across the range of daily solar zenith angles (Campbell and Norman 1998; Fuchs et al. 1976; Kemanian 2017, *personal communication*). Daily radiation interception (RI_d) was calculated as

 $RI_d = FI_d * R_d$

and season-long radiation interception (RI_s) was calculated for each year as the sum of all RI_d values up until the harvest date. Season-long radiation use efficiency (RUE_s) was calculated by dividing total maize biomass by RI_s .

The ability of the maize plants to sustain transpiration was assessed by measuring stomatal conductance (g_s ; mmol H₂O m⁻² s⁻¹) using a Decagon SC-1 Leaf Porometer. The porometer cuvette was placed on a clean, undamaged area of the leaf blade that was unshaded and oriented toward the sun (Reicosky et al. 1975). This reduced variation due to irradiance and angle of incidence. At the

end of the growing season, some highly-stressed plots contained few healthy leaves that were not curled, making it difficult to find leaf blades oriented toward the sun. In these cases, the best sun-lit, healthy leaf areas were chosen. Four leaves were read per plot, two in each row. Porometry readings began in mid-late July and continued periodically throughout the season. Readings were taken on cloud-free days to ensure that leaves were acclimated to full-sun conditions and care was taken not to shade the leaves prior to measurement. Readings were taken between 11 am and 4 pm, when transpirative demand and water stress are greatest. Measurements on a block were completed within a single day to avoid weather confounds.

4.2.7 Maize Height, Yield, Yield Components, and Tissue Nitrogen

Following plot establishment and prior to shelter installation, the maize plants within the inner sampling area of each plot were counted and initial heights of all plants were measured. The height of all plants in each plot was summed to produce a measure of total initial heights (Hts₀), which was used in statistical models to represent initial plant population and vigor. Height was then measured repeatedly on the same two representative plants per plot until tassels were mature; the heights of these plants were averaged to represent the whole plot. Time of tasseling and silking was also recorded to calculate anthesis-silking interval (ASI). Plants were deemed to be tasseled when the tassel was fully expanded, and to be silking when silks were visible.

Maize was harvested at silage maturity (roughly 65% biomass moisture content) to align with the larger field experiment. Maize plants were cut by hand 15 cm above the soil surface and the ears were separated with husks attached, including immature ears in axils above the main ear. Stalks and leaves were weighed in the field, coarsely ground using a small brush chipper, and a sub-sample was collected for subsequent analysis. Sub-samples were weighed, dried at 60 °C, and weighed again. Moisture content of sub-samples was used to calculate total shoot dry matter. Ears were weighed, dried at 60 °C, and weighed again. Husks were then removed and kernels were shelled using a mechanical sheller. To determine mean kernel mass (KM), 25.0 g of kernels from each plot were counted. Due to large variation in kernel development, any kernel with yellow pericarp was included in this analysis. Mean kernel mass was then used to determine kernel number per ear (KN). Harvest index (HI) was calculated as the ratio of kernel biomass to total biomass multiplied by 100.

Relative drought stress effects were calculated for a range of yield factors (YF; final height, total biomass, kernel biomass, KM, KN, and HI) as:

$$DS_{rel} = (YF_d - YF_a) / YF_a$$

where YF_d is the yield factor for the drought plot and YF_a is the same yield factor for the paired ambient plot within the same cover crop treatment.

Maize kernels and vegetative tissue were analyzed for total nitrogen concentration by the combustion method (Horneck and Miller 1998) using an Elementar Vario Max (Elementar, Langenselbold, Germany). Tissue was ground to 1 mm and submitted to the Penn State Agricultural Analytical Services Lab for analysis. Kernels were ground with a Cyclone Sample Mill (Udy Corporation, Fort Collins, Colorado) and stalks and leaves were ground with a Wiley Mill (Thomas Scientific, Swedesboro, NJ).

4.2.8 Statistical Analysis

All statistical analysis was performed in R (R Core Team 2013). Sub-samples were averaged by subplot prior to analysis. Mixed-effect linear models fit to a Gaussian distribution were specified with the lmer function of the lme4 package (Bates et al. 2015). The significance of individual predictors, including both main effects and interactions, was determined by comparing the model with and without that predictor using the anova function (R core team 2017; Kniss 2017). Pairwise comparisons among CC treatments were evaluated with the emmeans function of the emmeans package (Lenth 2018) with a Tukey adjustment for multiple comparisons. Explanatory power of fixed effects in mixed models was assessed with marginal R^2 (R^2_m) calculated with the r.squaredGLMM function in the MuMIn package (Bartoń 2016) following Nakagawa and Schielzeth (2013). Area under the curve of SIN was calculated with the auc function in the MESS package (Ekstrøm 2017). An alpha value of 0.05 was used to assess statistical significance.

Final models were evaluated to ensure they met the assumptions of independence and normality of residuals and random effects (Pinheiro and Bates 2000, SSCC 2016). Leaf water potential and stomatal conductance data were transformed to meet the assumption of normality following Box-Cox analysis using the boxcox function in the MASS package (Venables and Ripley 2002).

Random intercepts for year and block were included in models assessing effects across years; for comparisons within a single year, only a random intercept for block was included. Comparisons

between years were made by including year in the model as a fixed effect, with a random intercept for block. When comparing between drought (DRT) treatments, cover crop (CC) was included in the model if it was significant, and vice versa for comparing among CC treatments. To compare treatment means across the season with repeated measures, random intercepts and slopes were included for each subplot to account for temporal dependence among readings.

A yield stability analysis (Finlay and Wilkinson 1963) was performed for maize kernel yield to assess adaptability across multiple environments. The drought and control treatments in each year were considered to be separate environments. An environmental index (EI) was calculated for each environment as the mean yield of all treatments in that environment. Years were ordered by EI and the slope of the regression of CC treatment mean yields against the EI was used as the indicator of yield stability (Tollenaar and Lee 2002). Estimated marginal means accounting for the interaction between CC and EI were used to compare mean kernel yield in the stability analysis.

The hypothesis that high maize N status enables greater osmotic adjustment was evaluated by testing whether the relationship between N status and g_s differed by DRT. The final SPAD meter reading (SPAD_{last}) was used as the indicator of maize N status because it integrates across the growing season. The mid-August value of g_s was used, since this is when the drought stress was strongest. A positive interaction between SPAD_{last} and the drought treatment, indicating higher g_s at higher SPAD_{last} values under drought, was taken as evidence that high maize N status counteracted drought stress.

The relative importance of RI, RUE, and osmotic adjustment for maize yield formation under drought was tested with a regression model. Kernel biomass was modeled as a function of RI_s, SPAD_{last}, and g_s . Total initial heights (Hts₀) was included as a covariate to account for plant population and early-season vigor. Non-significant predictors were removed and the explanatory power (R^2_m) of the fixed effects in the reduced model was evaluated. To determine whether the model based on ecophysiological measures captures the DRT and CC effects, these terms and their interaction were tested against the reduced model.

4.3 Results and Discussion

4.3.1 Cover Crops

Aboveground biomass, C:N ratio, and winter phenology varied substantially among cover crops (Table 4-4; Murrell et al. 2017). There were no differences by CC in 2013 fall biomass (including weeds), but the 3SppN mixture produced more biomass than the clover or rye monocultures in fall of 2014, largely due to substantial Austrian winter pea growth late in the season. The pea entirely winterkilled in 2014 and was nearly eliminated in 2015. Red clover was highly suppressed in both fall and spring in the 3SppN mixture. Radish produced substantial fall biomass but winterkilled and had the lowest spring biomass. Rye produced more spring biomass than clover but was not different from 3SppN, which was dominated by rye in the spring. The red clover monoculture overwintered well and produced substantial biomass in the spring (> 1 Mg ha⁻¹, not including weeds). Weed biomass in the fallow was negligible due to mechanical control in fall and spring, so this treatment was not included in the pairwise comparisons reported above. Fallow plot biomass values reported by Baraibar et al. (2018) for the same experiment reflect a subplot in which weeds were not controlled.

Cover crop biomass C:N ratios varied as expected according to plant family (Table 4-4). In fall, the pea-dominated 3SppN and clover treatments had low C:N ratios and the radish and rye had moderate ratios. In spring, clover had a very low C:N ratio; 3SppN and the weeds in the radish plots had a moderate ratio; and rye had a high ratio. In spring of 2015, 3SppN biomass had a much lower C:N ratio than the rye monoculture despite containing similar amounts of rye biomass.

Table 4-4: Cover crop dry matter (kg ha-1) and C:N ratio in the fall and spring of the 2013-2014 and 2014-2015 cover crop growing seasons. Means within columns and years that share a letter are not significantly different at the alpha = 0.05 level with a Tukey correction for multiple comparisons.

					Fal	1		Spring							
				Dry]	Matter				Dry Matter						
Year	Cover	Clover	Rye	Radish	Pea	Weeds	Total	-	Clover	Rye	Radish	Pea	Weeds	Total	C:N
	Crop†			—— kg	ha-1 —			C:N		kg ha-1					
	Clover	561				1400	1960 a	16.7 ab	1040				308	1350 b	11.2 a
2013-	Rye		1320			450	1770 a	18.4 bc		2360			29.6	2390 c	26.8 c
2014	Radish			1640		590	2230 a	19.8 c					41.6	41.6 a	19.8 b
	3SppN	67.2	587		1530	503	2690 a	14.3 a	77.3	1590		0	26.8	1700 bc	20.9 b
	Clover	614				653	1270 a	14.2 a	1370				329	1690 b	11.2 a
2014-	Rye		1310			47.2	1360 a	21.5 c		2190			31.4	2230 b	30.9 c
2015	Radish			1860		202	2060 ab	18.5 b					243	243 a	19.8 b
	3SppN	168	930		1530	84.8	2720 b	13.6 a	209	2200		113	6.56	2530 b	21.3 b

[†] Clover, medium red clover; Rye, cereal rye; Radish, forage radish; 3SppN, cereal rye, Austrian winter pea, and medium red clover.
4.3.2 Ambient Weather Conditions in the Maize Growing Season

Ambient weather conditions were similar to long-term averages, but there were important differences between the years. Precipitation during the growing season (May to September) was above average and consistent in 2014 (Fig. 4-3a). In 2015, June and early July were very wet, but precipitation declined in August and early September, leading to dry surface soil conditions in the ambient treatment.

Average temperatures during the growing season followed long-term trends in 2014 but were above average throughout most of the 2015 growing season (Fig. 4-3b). As a result, fewer growing degree days accumulated during the growing season in 2014 (1,160 GDD) than in 2015 (1,350 GDD). Seasonal insolation was also lower in 2014 than in 2015 (2,050 v. 2,330 MJ m⁻², respectively). Both the 2014 and 2015 growing seasons followed unusually cold winters, which contributed to poor overwinter survival of pea.

4.3.3 Shelter Microclimate

The rainout shelters reduced soil moisture content with minimal effects on canopy temperature and PAR irradiance.

Soil volumetric water content (θ_v) across the season was lower in the drought treatment at 10, 20, and 40 cm depths (Fig. 4-4; Table 4-5; p < 0.0001 for all depths in both years). There were no differences in θ_v by CC at any depth in either year. Due to the heavy precipitation in June and early July in 2015, soils initially held more water in the top 50 cm than in 2014 (p < 0.0001). It is likely this early season moisture delayed the onset of drought stress in 2015.

Maize grown in drought conditions extracted little water from the top 50 cm of soil during the growing season: the difference in SW₅₀ between the first and last readings was only \sim 1 cm in 2014 and \sim 2-8 cm in 2015. This amount of water is insufficient to support the observed maize growth during the period the shelters were in place. The remainder was either supplied by lateral soil recharge through subsurface or capillary flow, or else extracted from below 50 cm depth. Drought has been shown to increase the depth of soil water extraction (Stone et al. 2001).



Figure 4-3: Monthly precipitation (A) and mean temperature (B) for the growing season (May to September) in 2014 and 2015, in comparison to monthly averages for 1980 to 2016 (horizontal black bars). Data is from NLDAS (Xia et al. 2012).

Despite this evidence that the water limitation was not absolute, the drought treatment reduced pre-dawn leaf water potential (Ψ_L) relative to ambient conditions. Pre-dawn Ψ_L was lower under drought conditions across both years (p < 0.0001), indicating that soil water availability was meaningfully lower in the drought treatment. However, Ψ_L did not differ by CC either across the season (p = 0.955) or at the height of the drought stress in mid-August (Fig. 4-5, Table 4-5). This suggests that the cover crops did not differentially affect the degree of moisture stress experienced by the following maize crop.



Figure 4-4: Volumetric water content in ambient (blue) and drought (red) maize plots at 10, 20 and 40 cm depth in 2014 and 2015.



Figure 4-5: Pre-dawn leaf xylem water potential by cover crop, drought treatment, and year (readings taken on 8/19/14 and 8/14/15; mean and standard deviation).

95

Table 4-5: Shelter microclimate measurements. Soil volumetric water content was measured with time domain reflectometry probes installed horizontally at 10, 20, and 40 cm depths. Air temperature was measured with temperature loggers suspended 1 m above the ground in the maize canopy. Minimum, maximum, and mean temperatures reflect the entire 24-hour cycle. Day and night temperatures are the means for 06:00 to 20:00 and 20:00 to 06:00, respectively. Pre-dawn leaf temperature was measured with an infrared radiometer. Overall means within columns and years are significantly different at the alpha = 0.05 level when they do not share a letter. There were no differences by cover crop treatment for any of the measurements reported here. There were also no significant differences in air temperature between the ambient and drought conditions.

Year	Cover Crop †	Ambient/	Soil Volumetric Water Content			A	Pre-Dawn Leaf				
		Drought	10 cm	20 cm	40 cm	Min	Max	Mean	Day	Night	Temperature
			cm ³ H ₂ O cm ⁻³ soil $$					°C			°C
2014	Fallow	А	0.264	0.272	0.303	14.3	30.3	20.7	22.3	18.5	
		D	0.175	0.202	0.232	14.5	30.1	20.9	22.5	18.6	
	Clover	А	0.278	0.279	0.259						
		D	0.173	0.224	0.266						
	Rye	А	0.262	0.274	0.306	14.3	30.7	21.0	22.3	19.2	
	-	D	0.175	0.216	0.252	14.4	30.1	20.9	22.2	19.1	
	Radish	А	0.294	0.298	0.309						
		D	0.196	0.231	0.261						
	3SppN	А	0.280	0.300	0.290						
		D	0.175	0.214	0.241						
	Overall	А	0.276 a	0.285 a	0.293 a	14.3	30.5	20.8	22.3	18.8	
	Mean	D	0.179 b	0.217 b	0.250 b	14.5	30.1	20.9	22.3	18.9	
2015	Fallow	А	0.260	0.268	0.326	13.7	31.5	21.2	24.5	16.5	7.55
		D	0.170	0.183	0.233	13.8	31.2	21.3	24.6	16.6	8.48
	Clover	А	0.255	0.266	0.290						7.53
		D	0.178	0.198	0.237						8.44
	Rye	А	0.245	0.283	0.326	13.7	31.9	21.3	24.7	16.5	7.78
		D	0.178	0.196	0.248	13.7	31.2	21.3	24.7	16.6	8.53
	Radish	А	0.240	0.260	0.304						7.63
		D	0.173	0.179	0.244						8.55
	3SppN	А	0.256	0.271	0.314						7.66
		D	0.184	0.212	0.246						8.59
	Overall	А	0.251 A	0.270 A	0.311 A	13.7	31.7	21.2	24.6	16.5	7.63 B
	Mean	D	0.177 B	0.194 B	0.242 B	13.7	31.2	21.3	24.6	16.6	8.52 A

† Fallow, no cover crop; Clover, medium red clover; Rye, cereal rye; Radish, forage radish; 3SppN, cereal rye, Austrian winter pea, and medium red clover.

No differences were detected by DRT in any aspect of mid-canopy air temperature, including daily minimum, maximum, mean, and daytime and nighttime means (Table 4-5; p > 0.05 in all cases). Likewise, no CC differences were detected. This suggests that, in general, the effect of the shelters on the temperature environment of the droughted maize was negligible.

Mean predawn leaf temperature at the end of the season (September 16, 2015) was 0.90 °C higher in the drought than in the ambient subplots (Table 4-5; p < 0.0001). This may be due to reduced evaporative cooling of water-stressed plants. It may also be due to the shelter roofs restricting the downward flow of cool nighttime air, but the lack of difference in mid-canopy nighttime temperatures suggests that air was well-mixed under the shelters. Regardless of the cause, higher nighttime leaf temperatures likely increased nighttime respiration rates, reducing C accumulation. There was no CC effect on predawn leaf temperature (p = 0.976).

Rainout shelters with new roof plastic reduced PAR irradiance by an average of 11.5% and 15.0% over the course of two separate days (6/22/15 and 6/24/15). After two months of dust deposition and exposure to ultraviolet radiation, PAR was reduced by 20.3% on August 17, 2015. This ~20% reduction in irradiance would not result in a commensurate reduction in photosynthesis or growth, because maize photosynthetic response to radiation begins to saturate at ~1,000 µmol PAR m⁻² s⁻¹ (Leakey et al. 2006). PAR consistently exceeded 1,000 µmol m⁻² s⁻¹ between 9:00 and 17:30 on all measurement days, except under cloud cover, and ranged up to over 1,700 µmol m⁻² s⁻¹ in the shelters. The roofs reduced the beam fraction of the incident radiation by 1.3% (p = 0.0433) on September 18, 2015. The increase in photosynthetic efficiency (Stöckle and Kemanian 2009) that this would be expected to cause, though minor, may have partially offset the reduction in PAR levels.

4.3.4 Cover Crop Effects on Spring Soil Water Content

Due to consistent spring rains, cover crop transpiration did not reduce spring soil moisture at cover crop termination (p = .660; Fig. 4-6). Precipitation during the spring cover crop growth window was ample and consistent in both 2014 and 2015. April precipitation was 86.1 and 90.0 mm, respectively; the long-term average is 85.5 mm.

Trends toward drier soil under the cover crops relative to the fallow developed during the measurement period, but were erased as rains sufficiently recharged the soil profile (data not shown). In years with an abnormally dry spring, cover crop transpiration may threaten maize water availability. However, spring precipitation is fairly reliable in Pennsylvania and is predicted to

increase under climate change (Hayhoe et al. 2007, Wolfe et al. 2018). Areas with less-consistent spring rains or and those facing drying trends may need to adaptively manage spring cover crops to avoid excessive transpirative losses (Blanco-Canqui et al. 2015).



Figure 4-6: Soil volumetric water content just prior to cover crop termination (5/2/2014 and 4/29/2015; 20 cm depth; mean and standard deviation).

4.3.5 Cover Crop N Provisioning

Cover crop treatments caused large differences in SIN_{auc} (p < 0.0001; Fig. 4-7). Across both years of the study, SIN_{auc} was higher in clover than in rye and fallow due to N mineralized from the low-C:N ratio clover biomass. These differences resulted despite all plots receiving a manure application at cover crop termination, reflecting the strong effects of cover crop biomass decomposition on SIN levels. SIN_{auc} was higher in 2015 than 2014 (p = 0.0287), likely because ample spring rains in 2014 leached NO₃⁻ from the soil profile, and high spring temperatures in 2015 drove rapid microbial N mineralization.



Figure 4-7: Soil inorganic nitrogen in nitrate (NO_3^-) and ammonium (NH_4^+) in the top 20 cm of soil under maize in 2014 and 2015. Downward arrows indicate the dates of cover crop termination, which were closely followed by manure application and tillage. Upward arrows indicate the dates of maize planting.

4.3.6 Maize Nitrogen Status

Cover crop effects on soil N levels drove differences in maize leaf greenness and biomass N concentration.

Maize leaf SPAD meter readings indicate that rye had an early and persistent effect on leaf chlorophyll content (Fig. 4-8A). SPAD readings were lower following rye than following all other cover crops, starting with the first reading and continuing throughout the season. SPAD readings following all other cover crop treatments were equivalent. Water stress from the drought treatment also reduced leaf greenness, but not until later in the season (Fig. 4-8A). Initial SPAD readings showed no differences by DRT in 2014 or 2015 (p = 0.115 and 0.658, respectively). Differences due to drought developed on July 24th, 2014 (p = 0.00292) and on September 11th, 2015 (p = 0.000224), six weeks later than in 2014. The delayed onset of drought stress effects on SPAD readings in 2015 is likely due to the greater soil water content upon shelter installation (Fig. 4-4). The limitation of chlorophyll content due to the rye and drought treatments likely reduced radiation use efficiency (Huber et al. 1989).



Figure **4-8**: Maize SPAD meter reading (A), leaf area index (B), stomatal conductance (C), and height (D) by cover crop, drought treatment, and year.

The final SPAD reading (SPAD_{last}) is used as an integrative measure of N status across the growing season. The final SPAD reading differed by CC and DRT but there was no interaction (Fig. 4-9, Table 4-5). Rye had a stronger effect on SPAD_{last} than the drought treatment. The final SPAD reading was reduced following rye, relative to all other cover crop treatments, by 26.3% in 2014 and 34.6% in 2015 (p = 0.00166 and 0.0020, respectively). In contrast, drought reduced SPAD_{last} by 15.3% in 2014 and by 23.7% in 2015, relative to ambient conditions (p = 0.00573 and 0.00804, respectively). Though there was not a significant interaction between CC and DRT (p = 0.952), rye caused a larger average numerical reduction in SPAD_{last} in drought than in ambient conditions. As compared to the average of all the other cover crops, in 2014 rye reduced SPAD_{last} by 31.2% in drought and by 28.8% in ambient conditions. This suggests that rye-induced N limitation was compounded, rather than offset, by the drought treatment.



Figure **4-9**: Final SPAD readings by cover crop, drought treatment, and year (sampling dates: 9/3/14 and 9/11/15; mean and standard deviation).

Table 4-6: Select ecophysiological measures of maize grown following cover crops under either ambient conditions or in rainout shelters. Across both years, means within a column are significantly different at the alpha = 0.05 level when they do not share a letter. Capital letters distinguish between ambient and drought conditions. Lower-case letters distinguish among cover crops, with a Tukey correction for multiple comparisons.

Year	Cover	Ambient/	Hts ₀ §	SPAD ¶	LAI #	RIs ††	RUE _s ‡‡	gs §§	$\Psi_L\P\!\!\P$
	Стор	Sheller 4	cm	SPAD	m ³ m ⁻³	MJ m ⁻²	g MJ ⁻¹	mmol	MPa
				reading				$m^{-2} s^{-1}$	
	Fallow	A	72.8	46.7	4.12	1310	1.06	292	-0.51
	1 4110 11	D	69.9	42.7	2.87	1170	0.886	193	-0.83
	Clover	A	78.6	47.2	3.94	1380	0.984	300	-0.30
	Clover	D	74.9	40	3.28	1220	0.967	250	-0.87
	Drvo	А	73.2	35.1	3.46	1270	0.796	300	-0.57
2014	Куе	D	72.5	26.7	2.39	1050	0.743	170	-0.77
2014	D 1' 1	А	75.1	43.2	4	1350	1	302	-0.57
	Radish	D	72.4	36.3	2.51	1040	0.952	238	-0.84
	2 See N	А	75.5	43.1	3.84	1320	1.06	340	-0.43
	3SppN	D	74.2	36	2.73	1110	0.722	187	-0.78
	Overall	А	75.1	43.5	3.89	1330	0.991	307	-0.47
	Mean	D	72.8	36.8	2.77	1120	0.86	209	-0.82
	Fallerr	А	121	35.3	4.29	1770	0.947	388	-0.0083
	Fallow	D	122	24.6	3.52	1660	0.877	215	-0.18
	Clover	А	131	33.9	4.73	1820	0.999	480	-0.019
2015		D	136	28.2	3.56	1690	0.897	191	-0.27
	Drug	А	125	23.6	3.81	1670	0.709	315	-0.047
	Кус	D	125	15.1	2.76	1530	0.661	176	-0.23
2013	Radish	А	121	29.8	4.55	1770	0.883	356	-0.0063
		D	120	25.4	3.36	1600	0.842	191	-0.18
	2 See NI	А	142	33.8	4.39	1790	1.05	363	-0.019
	SSppin	D	141	25.4	3.73	1670	0.938	189	-0.21
	Overall	А	128	31.1	4.36	1760	0.927	380	-0.020
	Mean	D	129	23.7	3.38	1630	0.851	191	-0.21
	CC ##								
	Fallow		92.9 ab	38.4 b	3.67 b	1440 bc	0.947 b	268 a	-0.42 a
	Clover		105 c	37.4 b	3.88 b	1530 c	0.962 b	305 a	-0.36 a
2014	Rye		103 a	24.3 a	3.13 a	1410 a	0.727 a	241 a	-0.36 a
2014-	Radish		97.1 bc	33.7 b	3.61 ab	1440 ab	0.920 b	272 a	-0.39 a
2015	3SppN		108 bc	34.6 b	3.67 b	1470 bc	0.942 b	270 a	-0.35 a
	DPT +++	А	102 B	37.3 B	4.12 B	1540 B	0.960 B	344 B	-0.24 B
		D	101 A	30.3 A	3.08 A	1380 A	0.856 A	200 A	-0.51 A
	CC*DRT ‡ ‡‡		ns §§§	ns	ns	ns	ns	ns	ns

[†] Fallow, no cover crop; Clover, medium red clover; Rye, cereal rye; Radish, forage radish; 3SppN, cereal rye, Austrian winter pea, and medium red clover.

‡ A, data from ambient plots; D, data from drought plots.

§ Htso, total initial heights measured on 7/4/14 and 7/12/15.

¶ SPAD, final SPAD meter reading, measured on 9/3/2014 and 9/11/2015.

LAI, leaf area index, measured on 8/15/2014 and 8/13/2015.

*††*RI_s, seasonal solar radiation interception.

‡: RUE_s, seasonal solar radiation use efficiency.

§§ gs, stomatal conductance, measured on 8/14/2014 and 8/14/2015.

¶¶ Ψ_L , leaf xylem water potential, measured on 8/19/2014 and 8/14/2015.

CC, cover crop.

††† DRT, drought treatment (ambient or drought).

‡‡‡ CC*DRT, interaction between drought treatment and cover crop.

\$ ns, not significantly different at the alpha = 0.05 level with a Tukey correction for multiple comparisons.

Nitrogen concentration (%N) in maize vegetative tissue (stem and leaves) followed the same pattern of N limitation shown by SPAD_{last}. Vegetative %N varied by CC and DRT but there was no interaction (Table 4-6). The rye treatment reduced vegetative tissue %N relative to all other cover crops, and the drought treatment reduced it relative to ambient conditions. These results support the conclusion that both drought stress and rye-induced N limitation reduced maize N status. Furthermore, they suggest that the decline in chlorophyll content reported above was at least in part due to reduced N availability, and not simply a reflection of reduced chlorophyll stability caused by water stress (Sanchez et al. 1983).

4.3.7 Radiation Capture and Use Efficiency

Cover crop N-provisioning increased maize radiation capture under drought by supporting greater canopy development. Both cover crop N-limitation and the drought treatment resulted in lower LAI and radiation capture, but there was no interaction between CC and DRT for LAI, RI_s, or RUE (Table 4-6).

Leaf area index was lower in drought conditions by 7/18/14 and 7/24/15 (p < 0.0001 and p = 0.000131, respectively; Fig. 4-8B). Rye reduced LAI relative to all other cover crops. The rye effect first became apparent on the same day as the drought effect in 2015, 7/24 (p = 0.0234), but 30 days later than the drought effect in 2014, on 8/7 (p = 0.00845). This suggests that N stress in the rye treatment was stronger in 2015, likely because wetter soils and warmer temperatures increased plant demand for N.

In mid-August of both years, at the peak of the growing season, DRT reduced LAI by 1.05 units (p < 0.0001). LAI was lower following rye than following clover, 3SppN, and fallow by a margin of 0.537-0.745 units, but was not different than radish (Fig. 4-10; Table 4-6). Both N- and drought-induced reductions in LAI were lower than those reported in Wolfe et al. (1988a), likely due to more moderate stress levels. Leaf rolling was infrequent, even during strong stress events, and therefore had little effect on LAI readings. Limited leaf rolling may be due to cultivar characteristics.



Figure **4-10**: Hemispherical leaf area index by cover crop, drought treatment, and year (measured on 8/15/14 and 8/13/15; mean and standard deviation).

These LAI differences, when integrated across the growing season, resulted in substantial differences in RI_s (total seasonal radiation interception) (Fig. 4-11). Values for RI_s were lower in 2014 than in 2015 because of both lower LAI values and lower seasonal insolation. Drought reduced RI_s by 15.4% in 2014 and 7.46% in 2015. Seasonal radiation interception was also lower following rye than following clover, 3SppN, and fallow, but was not different than radish; clover resulted in higher RI_s than radish. The rye treatment reduced RI_s by 6.19% relative to the average of the other cover crop treatments in 2014, and by 7.09% 2015. Drought therefore had a larger effect on RI_s than the rye treatment in 2014, but a similar effect in 2015.



Figure 4-11: Seasonal solar radiation interception by cover crop, drought treatment, and year (mean and standard deviation).

Seasonal radiation use efficiency, measured as total biomass divided by RI_s, was enhanced by cover crop N provisioning under both ambient and drought conditions (Fig. 4-12, Table 4-6). Rye reduced RUE_s relative to all other treatments by 19.4% in 2014 and 26.3% in 2015. The reduction in RUE_s following rye was substantially larger than the reduction in RI_s. Moreover, SPAD_{last} explains 53.1% of the variation in RUE_s (R^2_m) across both years. These results reflect the direct mechanistic relationship between leaf chlorophyll concentration, photosynthetic capacity, and RUE_s.

In contrast, drought reduced RUE_s by 13.3% in 2014 and 8.15% in 2015, which are nearly equivalent to the drought-induced reductions in RI_s in each year. This suggests that, at the level and developmental trajectory of drought imposed in this study, water stress had similar effects on leaf expansion and photosynthetic capacity. Stone et al. (2001) found a similar magnitude of reduction in RUE and RI in sweet corn in New Zealand, though RUE was more sensitive than RI to drought stress in most of their drought treatments, including a terminal drought of moderate severity similar to that imposed here.



Figure 4-12: Maize radiation use efficiency by cover crop, drought treatment, and year (mean and standard deviation).

4.3.8 Osmotic Adjustment

There is limited evidence that high maize N status may have enabled osmotic adjustment and thereby reduced the effect of drought stress on g_s .

Drought reduced stomatal conductance across the season in both years (p < 0.0001) but there was no effect of cover crop (p = 0.359; Fig. 4-8C). Drought stress strongly affected g_s in mid-August, causing a 41.7% drop (Fig. 4-13, Table 4-6). Notably, in a model predicting g_s in mid-August, there was a positive interaction between SPAD_{last} and DRT (p = 0.0277). This suggests that higher maize N status enhanced stomatal conductance under water stress (Fig. 4-14). It is important to note that this relationship is driven entirely by the 2014 data.



Figure **4-13**: Mid-August leaf stomatal conductance by cover crop, drought treatment, and year (readings taken on 8/14/14 and 8/14/15; mean and standard deviation).



Figure 4-14: Relationship between final SPAD reading and stomatal conductance in mid-August by drought treatment and year (readings taken on 8/14/14 and 8/14/15 between 11:00 and 16:00).

4.3.9 Maize Development and Yield

Maize development and yield, as measured by height, yield, and yield components, reflects the interaction between drought stress and cover crop effects on soil N supply.

Initial conditions differed by year but not by experimental treatment. Maize population in the sampling area did not differ by CC or DRT (p > 0.05 for all comparisons) but was higher in 2015 than in 2014 (15.3 v. 13.2 plants per plot, p < 0.0001). Initial height of the maize plants was also greater in 2015 than in 2014 (p < 0.0001; Table 4-6), due in part to the later sampling date in 2015 (7/12/15 v. 7/4/14). Given both larger populations and greater height, the composite measure of total initial heights (Hts₀) was also higher in 2015 than in 2014 (p < 0.0001).

Final height (Ht_{last}) differed by both CC and DRT but there was no interaction (Table 4-7, Fig. 4-8D). Maize grown following rye was significantly shorter than that following clover, 3SppN, and radish. Maize was also shorter following fallow than clover. Drought conditions reduced mean maize height in 2014 (p < 0.0001) but not in 2015 (p = 0.753), suggesting that drought stress was

limited during vegetative growth in 2015. However, drought did reduce final vegetative biomass in 2015 (p = 0.000240). This may be due to either lower accumulation of vegetative stores or greater demands on these stores during grain filling.

Across both years, ASI did not differ by DRT (p = 0.453) and there were no pairwise differences by CC, suggesting that the water- and N-stresses may not have been very intense by the beginning of reproductive growth. However, ASI sensitivity has decreased in modern cultivars (Campos et al. 2006).

As with final height, both total and kernel biomass differed by both CC and DRT but there was no interaction (Table 4-7). Maize following rye produced less total and kernel biomass than that following all other cover crops and fallow (Fig. 4-15). Kernel biomass was higher in 2015 than in 2014 under both drought and well-watered conditions (p < 0.0001), likely because soil N availability, GDD, and insolation were all higher in 2015.



Figure 4-15: Maize kernel biomass by cover crop, drought treatment, and year (mean and standard deviation).

Table 4-7: Height, yield and yield components of maize grown following various cover crop treatments under either ambient or imposed drought conditions. Results are reported for 2014, 2015, and the two years pooled. Across both years, means within a column are significantly different at the alpha = 0.05 level when they do not share a letter. Capital letters distinguish between ambient and drought conditions. Lower-case letters distinguish among cover crops, with a Tukey correction for multiple comparisons.

Year	Cover Crop	Ambient/	Final	Total	Kernel	Kernel	Kernel	Harvest	Kernel	Vegetative	Total N
	Ť	Drought	Height	Biomass	Biomass	Number	Mass	Index	Nitrogen	Nitrogen	
			cm	—— kg	ha ⁻¹ ——	No. per	g per			%	·····
						ear	kernel				
	Fallow	A	256	13.8	6.57	477	0.189	47.6	1.13	0.925	1.04
	1 4110 11	D	236	10.4	4.49	430	0.166	42.9	1.20	0.768	0.987
	Clover	A	275	13.6	6.56	492	0.205	47.9	1.10	0.923	1.02
	Clover	D	254	11.7	5.12	406	0.187	43.7	1.06	0.731	0.905
	D	А	242	10.1	4.46	374	0.186	44.1	1.03	0.808	0.920
2014	куе	D	218	7.79	3.13	320	0.166	40.2	0.967	0.557	0.749
2014	D 1' 1	А	276	13.5	6.24	473	0.201	46.1	1.04	0.883	0.969
	Radish	D	241	9.85	4.18	359	0.178	42.4	1.04	0.682	0.856
	20 11	А	268	14.1	6.34	457	0.203	44.4	1.05	0.892	0.978
	3SppN	D	229	8.05	3.66	376	0.169	45.0	1.07	0.690	0.891
	Overall	А	264	13.2	6.12	459	0.198	46.1	1.07	0.890	0.989
	Mean	D	237	9.67	4.17	381	0.174	43.0	1.07	0.692	0.884
	Fallow	А	286	16.8	8.92	439	0.271	53.1	1.02	0.665	0.883
		D	282	14.6	7.38	385	0.233	50.9	1.09	0.548	0.858
	Classer	А	290	18.1	9.68	441	0.266	53.3	1.05	0.603	0.879
	Clover	D	298	15.3	8.11	459	0.233	52.8	1.19	0.541	0.931
	D	А	263	12.1	5.65	295	0.233	50.9	0.897	0.480	0.709
2015	Куе	D	254	10.4	4.55	293	0.200	49.0	0.940	0.414	0.683
2013	Dadiah	А	286	15.7	8.07	454	0.230	51.4	0.982	0.575	0.814
	Kauisii	D	280	13.6	6.79	397	0.218	50.2	1.11	0.540	0.865
	2 Sun M	А	294	18.7	9.84	456	0.271	52.4	1.02	0.614	0.860
	Soppin	D	296	15.8	8.16	442	0.234	51.6	1.15	0.547	0.899
	Overall	А	284	16.5	8.41	416	0.253	52.2	0.995	0.583	0.826
	Mean	D	282	14.1	6.98	396	0.223	51.0	1.09	0.522	0.856
2014	CC ‡										
2014-	Fallow		262 ab	13.6 b	6.65 b	436 b	0.209 ab	48.2 ab	1.12 b	0.744 b	0.951 b
2013	Clover		279 с	14.7 b	7.37 b	450 b	0.223 b	49.4 b	1.10 b	0.699 b	0.934 b
	Rye		246 a	10.1 a	4.54 a	317 a	0.199 a	46.0 a	0.952 a	0.558 a	0.761 a
	Radish		271 bc	13.2 b	6.32 b	421 b	0.207 ab	47.5 ab	1.04 b	0.670 b	0.876 b
	3SppN		272 bc	14.2 b	7.00 b	433 b	0.219 b	48.3 ab	1.07 b	0.686 b	0.907 b
	DRT 8	А	274 B	14.8 B	7.26 B	437 B	0.225 B	49.1 B	1.03 A	0.737 B	0.908 B
	DKI §	D	259 A	11.8 A	5.57 A	389 A	0.198 A	46.9 A	1.08 B	0.610 A	0.870 A
	CC*DRT ¶		ns #	ns	ns	ns	ns	ns	ns	ns	ns

† Fallow, no cover crop; Clover, medium red clover; Rye, cereal rye; Radish, forage radish; 3SppN, cereal rye, Austrian winter pea, and medium red clover.

CC, cover crop.
DRT, drought treatment (ambient or drought).
CC*DRT, interaction between drought treatment and cover crop.
ns, not significantly different at the alpha = 0.05 level with a Tukey correction for multiple comparisons.

113

The lack of interaction between DRT and CC in models predicting total and kernel biomass suggests that cover crops neither ameliorated nor exacerbated drought yield loss in the following maize on an absolute basis. To account for the possibility that yield loss differed by CC as a percent of ambient yields, relative yield loss (DS_{rel}) between paired ambient and drought plots was assessed (Fig. 4-16, Table 4-8).

The drought treatment reduced yield by ~15-30%. Drought stress was stronger in 2014 than in 2015, reducing total biomass by 26.8% as compared to 14.7%, respectively (p = 0.0389), and reducing kernel biomass by 31.9% as compared to 17.0%, respectively (marginally significant, p = 0.0587; Fig. 4-16). Across both years, drought reduced kernel yield more than total biomass (23.2% v. 20.2%, p < 0.0001), indicating that drought stress was stronger during reproductive growth than during vegetative growth. This finding is in line with past studies that imposed terminal drought on maize (Wolfe et al. 1988a, Stone et al. 2011).

There were no differences in DS_{rel} of either total or kernel biomass by CC, providing further evidence that cover crops did not affect maize drought yield losses. Wolfe et al. (1988a) similarly found that the percent yield reduction due to drought was not substantially different between high-and low-N treatments.

Table **4-8**: Relative drought stress effects (DS_{rel}) caused by rainout shelters for maize grown following various cover crop treatments. Negative values indicate a reduction relative to maize grown under ambient conditions. For all DS_{rel} measures, means are not significantly different by cover crop at the alpha = 0.05 level with a Tukey correction for multiple comparisons.

Year	Cover	Final	Total	Kernel	Kernel	Kernel	Harvest
	Crop†	Height	Biomass	Biomass	Number	Mass	Index
	Fallow	-7.39	-24.9	-32.6	-9.4	-12.4	-9.89
	Clover	-7.67	-10.6	-19.2	-17.9	-8.4	-8.85
	Rye	-9.76	-23.1	-30	-14.4	-10.1	-8.64
2014	Radish	-12.6	-27.3	-33.2	-24.6	-11.6	-8.34
	3SppN	-14.9	-42	-41	-18.1	-16.8	1.38
	Overall Mean	-10.5	-25.7	-31.3	-17	-12	-6.78
	Fallow	-1.56	-13.1	-17	-11.6	-13.7	-4.19
	Clover	3.19	-15.8	-16.4	3.96	-12.3	-0.952
	Rye	-3.15	-14	-20.4	-0.397	-14.2	-3.55
2015	Radish	-2.07	-13.1	-15.2	-12.3	-5.07	-2.43
	3SppN	0.699	-16.1	-17.1	-2.45	-13.6	-1.34
	Overall Mean	-0.527	-14.5	-17.2	-4.19	-11.7	-2.34

[†] Fallow, no cover crop; Clover, medium red clover; Rye, cereal rye; Radish, forage radish; 3SppN, cereal rye, Austrian winter pea, and medium red clover.

‡ CC, cover crop.

¶ ns, not significantly different at the alpha = 0.05 level with a Tukey correction for multiple comparisons.



Figure 4-16: Maize kernel yield loss due to drought by cover crop and year (mean and standard deviation).

The rye treatment limited maize yield more severely than the drought treatment, reducing total biomass by 27.4% and kernel biomass by 33.6% compared to the mean of all other cover crops. In contrast to the drought effect, the yield drag following rye was larger in 2015 than in 2014 (39.1% v. 29.7% for kernel yield). This may be because rye-induced N deficiency was a relatively stronger limiting factor when drought stress was less severe and yield potential was higher.

4.3.10 Yield Components

Overall, differences in kernel number (KN) and mass (KM) paralleled the differences in kernel biomass and total biomass, with differences by DRT and CC but no interaction (Table 4-7). Drought reduced KN and KM in both years. Kernel number was also lower following rye than following all other cover crops, and KM was lower following rye than following clover and 3SppN.

Comparison of drought effects on KN and KM illuminates the temporal dynamics of drought stress. Drought reduced KN by 16.9% in 2014 but only by 4.56% in 2015 (p < 0.0001; Table 4-8). These results confirm prior evidence that drought stress during early reproductive growth was

stronger in 2014 than in 2015. In contrast, drought reduced KM by 11.9% overall, with no difference between years (p = 0.900). This does not indicate that drought stress was identical during grain filling in the two years. Instead, it is likely that greater KN limitation in 2014 resulted in an equivalent balance of photosynthate supply and demand during grain filling across both years, despite stronger drought stress in 2014.

Harvest index differed by both DRT and CC but there was no interaction (Table 4-7). Drought stress reduced HI from 46.1% to 43.0% in 2014 (p = 0.00187), reflecting substantial drought-induced declines in both KN and KM, but did not affect it in 2015 (p = 0.237). These results align with those from drought studies in Florida, in which moderately-severe drought did not affect HI (Sinclair et al. 1990). However, severe N- and drought-stresses have been reported to decrease HI to near zero (Wolfe et al. 1988a). Across the two years, the rye treatment reduced HI relative to clover. The lack of interactions between CC and DRT for KN, KM and HI suggests that drought- and N-stresses developed relatively independently.

Drought-induced limitation of KN also affected source-sink dynamics for kernel N. The rye treatment reduced kernel %N compared to all other treatments (Table 4-7). There were no differences in %N by DRT in 2014 (p = 0.971), nor was there an interaction between CC and DRT across the two years. However, the drought treatment increased kernel %N in 2015 (p < 0.0001), suggesting that the ambient plants built more sink capacity relative to available N than the drought plants.

4.3.11 Integrative Regression Model

The integrative model confirmed that cover crops and drought primarily affected maize yield through effects on radiation capture and use efficiency. The final model included Hts₀, RI_s, and SPAD_{last} and explained 88.7% of the variation in kernel yield (R^2_m). Adding DRT, CC, or their interaction to the final model did not improve it (p = 0.640, 0.156, and 0.0921, respectively). This indicates that cover crop and drought effects on maize yield formation are primarily mediated by canopy development and N nutrition, when accounting for plant population and early-season vigor. These results are in line with previously published results (Wolfe et al. 1988a), despite the more moderate drought stress in this study.

In contrast, g_s was not a significant predictor (p = 0.963) in the final model. This may reflect the nature of the drought stress applied, which was consistent and terminal, but only moderate in

severity. Under severe drought conditions, osmotic adjustment may be at a premium, as it would delay turgor loss, cell damage, and ultimately plant death.

4.3.12 Yield Stability

Cover crops strongly influenced the kernel yield stability of the following maize crop across years and moisture conditions (Fig. 4-17). Kernel yield following clover was among the highest across all environments and had a moderate slope against the EI (Table 4-9). Fallow produced equivalent yield and yield stability to clover, while radish produced lower but equally stable yield. In contrast, yield following rye was both lower and more stable—an undesirable condition indicating little upside yield potential in favorable environments. However, diversifying the rye treatment with Austrian winter pea and red clover, as in the 3SppN treatment, led to very different results. Despite high levels of rye biomass in 3SppN, maize grown following this mixture yielded similarly to that following clover in all but the lowest-yielding environments. As a result, yield following 3SppN was very unstable, but overall mean yield was not different than following clover. These results suggest that N supply from leguminous cover crops is generally beneficial under both drought and well-watered conditions, though it may not always be able to overcome the yield drag from high-C:N ratio rye biomass. Beneficial effects of leguminous cover crops on maize yields have been shown in a wide range of environments (Marcillo and Miguez 2017), but never before in a controlled drought study.

Table 4-9: Mean maize kernel yield estimated marginal mean and stability analysis regression slope by cover crop treatment. Means within columns that share a letter are not significantly different at the alpha = 0.05 level with a Tukey correction for multiple comparisons.

	Maize Kernel Yield Estimated Marginal Mean	Regression Slope
	Mg ha ⁻¹	-
Clover	7.37 a	1.10 b
Rye	4.45 c	0.575 c
Radish	6.32 b	0.911 bc
3SppN	7.00 a	1.49 a
Fallow	6.84 ab	1.04 b



Figure 4-17: Kernel yield stability analysis for the two years and drought treatments. Environmental index is the mean yield of all treatments in an environment. The order of environments across the X axis is 2014 drought, 2014 ambient, 2015 drought, 2015 ambient. A slope of one indicates mean stability for this set of treatments, lower slope indicates greater stability, and higher slope indicates lower stability. The dashed black line has a slope of one and an intercept of zero.

4.4 Conclusions

This study provides evidence that cover crops affect the drought physiology of the following maize crop by altering short-term nutrient dynamics. Cover crop effects were similar in both drought and ambient conditions. Maize following N-mineralizing cover crops, such as red clover, developed more robust canopies with higher chlorophyll content, increasing both radiation capture and photosynthetic capacity. This resulted in higher and more stable maize yield across years and moisture conditions. Maize growth was suppressed following N-immobilizing cover crops, such as cereal rye. There was limited evidence that higher maize N status enabled physiological buffering of water stress through osmotic adjustment, but this effect did not help explain the final yield. This suggests that physiological factors that promoted radiation capture and use efficiency across the season were more important for yield formation than those that enabled short-term adaptation to highly stressful conditions.

While cover crops did not affect soil water supply to the following maize crop in this study, either by depleting moisture in the spring or conserving moisture in the summer, cover crop N provisioning strongly influenced the effectiveness of maize water use (Blum 2009). Nitrogen limitation following cereal rye severely compromised maize performance in both ambient and drought conditions. This shows the importance of ensuring sufficient nutrient availability during cover crop decomposition, especially in organic systems. Diversifying a rye cover crop with legumes in the 3SppN treatment enabled more effective water use in most environments, but produced worryingly low yield in the worst environment. The risk of rye-induced N limitation and subsequent maize stress could be further reduced by modifying the mixture composition to increase the proportion of legume biomass (Finney et al. 2016), substituting a less-aggressive N scavenger for rye, terminating the cover crop earlier, applying a higher rate of manure N, or, in conventional systems, applying synthetic fertilizer.

Our results suggest cover crops are unlikely to harmfully reduce spring soil moisture in the humid Eastern U.S., though caution is warranted in drier climes and droughty soils (Unger and Vigil 1998). There was no evidence that maize acclimation to nutrient stress improved tolerance of moisture stress, or vice versa, as has been hypothesized (Radin and Parker 1979). Instead, the additive combination of the two stresses led to consistent poor performance.

Over the long term, cover cropping and other soil-building practices have the potential to improve soil properties that control water and nutrient dynamics, such as aggregation and organic matter content. Numerous long-term studies have shown that soil improvement can help mitigate crop water stress (Lotter et al. 2003, Mallory and Porter 2007, Gaudin et al. 2015). Further research is needed to understand how the rapid nutrient dynamics observed in this study interact with soils improved through long-term use of conservation cropping systems. Combining soil improvement with appropriate cover crop-based nutrient management has the potential to promote high and stable yields across moisture environments and thereby underpin a more resilient agriculture.

4.5 References

- Ashraf, M., and M.R. Foolad. 2007. Roles of glycine betaine and proline in improving plant abiotic stress resistance. Environ. Exp. Bot. 59: 206–216. doi: 10.1016/j.envexpbot.2005.12.006.
- Baker, J.M., and T.J. Griffis. 2009. Evaluating the potential use of winter cover crops in cornsoybean systems for sustainable co-production of food and fuel. Agric. For. Meteorol. 149: 2120–2132. doi: 10.1016/j.agrformet.2009.05.017.

- Banziger, M., G. Edmeades, D. Beck, and M. Bellon. 2000. Breeding for Drought and Nitrogen Stress Tolerance in Maize: From Theory to Practice. Mexico, D.F.
- Baraibar, B., M.C. Hunter, M.E. Schipanski, A. Hamilton, and D.A. Mortensen. 2018. Weed Suppression in Cover Crop Monocultures and Mixtures. Weed Sci. 66: 121–133. doi: 10.1017/wsc.2017.59.
- Bartoń, Kamil. 2016. MuMIn: Multi-Model Inference. R package version 1.15.6. https://CRAN.R-project.org/package=MuMIn
- Basche, A. 2017. Turning Soils into Sponges: How Farmers Can Fight Floods and Droughts. Washington, DC.
- Basche, A., and M. DeLonge. 2017. The Impact of Continuous Living Cover on Soil Hydrologic Properties: A Meta-Analysis. Soil Sci. Soc. Am. J. 81: 1179–1190. doi: 10.2136/sssaj2017.03.0077.
- Bates, Douglas, Martin Maechler, Ben Bolker, Steve Walker. 2015. Fitting Linear Mixed-Effects Models Using Ime4. Journal of Statistical Software, 67, 1-48. doi:10.18637/jss.v067.i01.
- Bennett, J.M., J.W. Jones, B. Zur, and L.C. Hammond. 1986. Interactive Effects of Nitrogen and Water Stresses on Water Relations of Field-Grown Corn Leaves. Agron. J. 78: 273. doi: 10.2134/agronj1986.00021962007800020012x.
- Bennett, J.M., L.S.M. Mutti, P.S.C. Rao, and J. W. Jones. 1989. Interactive Effects of Nitrogen and Water Stresses on Biomass Accumulation, Nitrogen Uptake, and Seed Yield of Maize. F. Crop. Res. 19: 297–311.
- Blum, A. 2009. Effective use of water (EUW) and not water-use efficiency (WUE) is the target of crop yield improvement under drought stress. F. Crop. Res. 112: 119–123. doi: 10.1016/j.fcr.2009.03.009.
- Bodner, G., A. Nakhforoosh, and H.-P. Kaul. 2015. Management of crop water under drought: a review. Agron. Sustain. Dev. 35: 401–442. doi: 10.1007/s13593-015-0283-4.
- Boomsma, C.R., and T.J. Vyn. 2008. Maize drought tolerance: Potential improvements through arbuscular mycorrhizal symbiosis? F. Crop. Res. 108: 14–31. doi: 10.1016/j.fcr.2008.03.002.
- Campbell, G.S., and J.M. Norman. 1998. An Introduction to Environmental Biophysics. 2nd ed. Springer-Verlag, New York, NY.
- Campbell, R.B., D.L. Karlen, and R.E. Sojka. 1984. Conservation tillage for maize production in the U.S. Southeastern Coastal Plain. Soil Tillage Res. 4: 511–529.

- Campos, H., M. Cooper, J.E. Habben, G.O. Edmeades, and J.R. Schussler. 2004. Improving drought tolerance in maize: A view from industry. F. Crop. Res. 90: 19–34. doi: 10.1016/j.fcr.2004.07.003.
- Casa, R., F. Castaldi, S. Pascucci, and S. Pignatti. 2015. Chlorophyll estimation in field crops: an assessment of handheld leaf meters and spectral reflectance measurements. J. Agric. Sci. 153: 876–890. doi: 10.1017/S0021859614000483.
- Chen, G., and R.R. Weil. 2010. Penetration of cover crop roots through compacted soils. Plant Soil 331(1–2): 31–43. doi: 10.1007/s11104-009-0223-7.
- Chou, B., C. O'Connor, and L. Bryant. 2015. Climate-Ready Soil: How Cover Crops Can Make Farms More Resilient to Extreme Weather Risks. New York, NY.
- Connor, D.J., R.S. Loomis, and K.G. Cassman. 2011. Crop ecology: Productivity and Management in Agricultural Systems. Cambridge University Press, Cambridge, UK.

CTIC/SARE. 2013. 2012 – 2013 Cover Crop Survey. West Lafayette, IN.

- Denmead, O.T., and R.H. Shaw. 1960. The effects of soil moisture stress at different stages of growth on the development and yield of corn. Agron. J. 52: 272–274. doi: 10.2134/agronj1960.00021962005200050010x.
- Earl, H.J., and M. Tollenaar. 1997. Maize leaf absorptance of photosynthetically active radiation and its estimation using a chlorophyll meter. Crop Sci. 37: 436–440.
- Earl, H.J., and R.F. Davis. 2003. Effect of Drought Stress on Leaf and Whole Canopy Radiation Use Efficiency and Yield of Maize. Agron. J. 95: 688–696. doi: 10.2134/agronj2003.6880.
- Ekstrøm, Claus Thorn. 2017. MESS: Miscellaneous Esoteric Statistical Scripts. R package version 0.4-15. https://CRAN.R-project.org/package=MESS
- Ewing, R.P., M.G. Wagger, and H.P. Denton. 1991. Tillage and Cover Crop Management Effects on Soil Water and Corn Yield. Soil Sci. Soc. Am. J. 55: 1081–1085.
- Finlay, K.W., and G.N. Wilkinson. 1963. The Analysis of Adaptation in a Plant-Breeding Program. Aust. J. Agric. Res. 14: 742–54.
- Finney, D.M., E.G. Murrell, C.M. White, B. Baraibar, M.E. Barbercheck, B.A. Bradley, S. Cornelisse, M.C. Hunter, J.P. Kaye, D.A. Mortensen, C.A. Mullen, and M.E. Schipanski. 2017. Ecosystem Services and Disservices Are Bundled in Simple and Diverse Cover Cropping Systems. Agric. Environ. Lett. 2: 170033 (2017). doi: 10.2134/ael2017.09.0033.
- Finney, D.M., C.M. White, and J.P. Kaye. 2016. Biomass production and carbon/nitrogen ratio influence ecosystem services from cover crop mixtures. Agron. J. 108: 39–52. doi: 10.2134/agronj15.0182.

- Frye, W.W., R.L. Blevins, M.S. Smith, S.J. Corak, and J.J. Varco. 1988. Role of annual legume cover crops in efficient use of water and nitrogen. In: W.L. Hargrove, ed. Cropping Strategies for Efficient Use of Water and Nitrogen. ASA Special Publication 51, American Society of Agronomy, Inc., Madison, WI. 129-154.
- Fuchs, M., G. Stanhill, and S Moreshet. 1976. Effect of increasing foliage and soil reflectivity on the solar radiation balance of wide-row sorghum. *Agronomy Journal* 68:865-871.
- Gaudin, A.C.M., T.N. Tolhurst, A.P. Ker, K. Janovicek, C. Tortora, R.C. Martin, and W. Deen. 2015. Increasing crop diversity mitigates weather variations and improves yield stability. PLoS One 10: e0113261. doi: 10.1371/journal.pone.0113261.
- Gonzalez-Dugo, V., J.-L. Durand, and F. Gastal. 2010. Water deficit and nitrogen nutrition of crops. A review. Agron. Sustain. Dev. 30: 529–544. doi: 10.1051/agro/2009059.
- Gray, S.B., O. Dermody, S.P. Klein, A.M. Locke, J.M. McGrath, R.E. Paul, D.M. Rosenthal, U.M. Ruiz-Vera, M.H. Siebers, R. Strellner, E.A. Ainsworth, C.J. Bernacchi, S.P. Long, D.R. Ort, and A.D.B. Leakey. 2016. Intensifying drought eliminates the expected benefits of elevated carbon dioxide for soybean. Nat. Plants 2(9): 16132. doi: 10.1038/nplants.2016.132.
- Hatfield, J.L., K.J. Boote, B. a. Kimball, L.H. Ziska, R.C. Izaurralde, D. Ort, a. M. Thomson, and D. Wolfe. 2011. Climate Impacts on Agriculture: Implications for Crop Production. Agron. J. 103(2): 351. doi: 10.2134/agronj2010.0303.
- Hayhoe, K., C.P. Wake, T.G. Huntington, L. Luo, M.D. Schwartz, J. Sheffield, E. Wood, B. Anderson, J. Bradbury, A. DeGaetano, T.J. Troy, and D. Wolfe. 2007. Past and future changes in climate and hydrological indicators in the US Northeast. Clim. Dyn. 28: 381–407. doi: 10.1007/s00382-006-0187-8.
- Horneck, Donald A. and Robert O. Miller. 1998. Determination of total nitrogen in plant tissue. In Y.P. Kalra (ed.) Handbook and Reference Methods for Plant Analysis. CRC Press, New York.
- Hothorn, Torsten, Frank Bretz and Peter Westfall. 2008. Simultaneous Inference in General Parametric Models. Biometrical Journal 50(3), 346-363.
- Huber, S.C., T. Sugiyama, and R.S. Alberte. 1989. Photosynthetic Determinants of Growth in Maize Plants: Effects of Nitrogen Nutrition on Growth, Carbon Fixation and Photochemical Features. Plant Cell Physiol. 30: 1063–1072.

- Hunter, M.C., R.G. Smith, M.E. Schipanski, L.W. Atwood, and D.A. Mortensen. 2017. Agriculture in 2050: Recalibrating targets for sustainable intensification. Bioscience 67: 386–391. doi: 10.1093/biosci/bix010.
- Jackson, R.B., L.J. Anderson, and W.T. Pockman. 2000. Measuring water availability and uptake in ecosystem studies. p. 199–214. *In* Sala, O.E., Jackson, R.B., Mooney, H.A., Howarth, R.W. (ed.), Methods in Ecosystem Science. Springer-Verlag, New York, NY.
- Jones, J., J. Moody, and J. Lillard. 1969. Effects of tillage, no tillage, and mulch on soil water and plant growth. Agron. J.: 719–721.
- Jones, J.W., B. Zur, and H.M. Bennett. 1986. Interactive Effects of Water and Nitrogen Stresses on Carbon and Water Vapor Exchange of Corn Canopies. Agric. For. Meteorol. 36: 113–126.
- Kabir, Z., and R.T. Koide. 2002. Effect of autumn and winter mycorrhizal cover crops on soil properties, nutrient uptake and yield of sweet corn in Pennsylvania, USA. Plant Soil 238: 205– 215.
- Kaye, J.P., and M. Quemada. 2017. Using cover crops to mitigate and adapt to climate change. A review. Agron. Sustain. Dev. 37: 1–17. doi: 10.1007/s13593-016-0410-x.
- Kniss, A. R. and J. C. Streibig. 2015. Statistical Analysis of Agricultural Experiments with R. http://rstats4ag.org/.
- Krueger, E.S., T.E. Ochsner, P.M. Porter, and J.M. Baker. 2011. Winter Rye Cover Crop Management Influences on Soil Water, Soil Nitrate, and Corn Development. Agron. J. 103: 316–323. doi: 10.2134/agronj2010.0327.
- Lambers, H., F.S.I. Chapin, and T.L. Pons. 2008. Plant Physiological Ecology, 2nd Edition. Springer New York, New York, NY.
- Leakey, A.D.B. 2006. Photosynthesis, Productivity, and Yield of Maize Are Not Affected by Open-Air Elevation of CO2 Concentration in the Absence of Drought. Plant Physiol. 140: 779–790. doi: 10.1104/pp.105.073957.
- Lenth, Russell. 2018. emmeans: Estimated Marginal Means, aka Least-Squares Means. R package version 1.1. https://CRAN.R-project.org/package=emmeans.
- Lotter, D.W., R. Seidel, and W. Liebhardt. 2003. The performance of organic and conventional cropping systems in an extreme climate year. Am. J. Altern. Agric. 18: 146. doi: 10.1079/AJAA200345.
- Mallory, E.B., and G.A. Porter. 2007. Potato yield stability under contrasting soil management strategies. Agron. J. 99: 501–510. doi: 10.2134/agronj2006.0105.

- Manderscheid, R., M. Erbs, and H.J. Weigel. 2014. Interactive effects of free-air CO2enrichment and drought stress on maize growth. Eur. J. Agron. 52: 11–21. doi: 10.1016/j.eja.2011.12.007.
- Marcillo, G.S., and F.E. Miguez. 2017. Corn yield response to winter cover crops: An updated metaanalysis. J. Soil Water Conserv. 72: 226–239. doi: 10.2489/jswc.72.3.226.
- Markelz, R.J.C., R.S. Strellner, and A.D.B. Leakey. 2011. Impairment of C 4 photosynthesis by drought is exacerbated by limiting nitrogen and ameliorated by elevated [CO 2] in maize. J. Exp. Bot. 62(9): 3235–3246. doi: 10.1093/jxb/err056.
- Melchiori, R.J.M., and O.P. Caviglia. 2008. Maize kernel growth and kernel water relations as affected by nitrogen supply. F. Crop. Res. 108: 198–205. doi: 10.1016/j.fcr.2008.05.003.
- Munawar, A., R.L. Blevins, W.W. Frye, and M.R. Saul. 1990. Tillage and Cover Crop Management for Soil Water Conservation. Agron. J. 82: 773–777.
- Murrell, E.G., M.E. Schipanski, D.M. Finney, M.C. Hunter, M. Burgess, J.C. Lachance, B. Baraibar, C.M. White, D.A. Mortensen, and J.P. Kaye. 2017. Achieving Diverse Cover Crop Mixtures: Effects of Planting Date and Seeding Rate. Agron. J. 109: 1–13. doi: 10.2134/agronj2016.03.0174.
- Nakagawa, S., and H. Schielzeth. 2013. A general and simple method for obtaining R2 from generalized linear mixed-effects models. Methods Ecol. Evol. 4: 133–142. doi: 10.1111/j.2041-210x.2012.00261.x.
- NeSmith, D.S., and J.T. Ritchie. 1992. Maize (Zea mays L.) response to a severe soil water-deficit during grain-filling. F. Crop. Res. 29: 23–35. doi: 10.1016/0378-4290(92)90073-I.
- Pella, E. 1990. Elemental organic analysis. Part 1. Am. Lab 22: 116-125
- Pinheiro, J.C., and D.M.C.N.-J. or A.B.R.R.Q. 73. S.P. 2000 J. or A.B.R.R.-S.O.Q. 73. S.P. 2000 Bates. 2000. Mixed-effects models in S and S-PLUS. Springer-Verlag, New York, NY.
- R Core Team. 2013. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. www.R-project.org.
- Radin, J.W., and L.L. Parker. 1979. Water Relations of Cotton Plants under Nitrogen Deficiency. Plant Physiol. 64: 499–501.
- Reicosky, D.C., R.B. Campbell, and C.W. Doty. 1975. Diurnal Fluctuation of Leaf-water Potential of Corn as Influenced by Soil Matric Potential and Microclimate. Agron. J. 67: 380–385.
- Sanchez, R.A., A.J. Hall, and N. Trapani. 1983. Effects of water stress on the chlorophyll content, nitrogen level and photosynthesis of leaves of two maize genotypes. Photosynth. Res. 4: 35–47. doi: 10.1007/BF00041799.

Sinclair, T.R., J.M. Bennett, and R.C. Muchow. 1990. Relative Sensitivity of Grain Yield and Biomass Accumulation to Drought in Field-Grown Maize. Crop Sci. 30: 690. doi: 10.2135/cropsci1990.0011183X003000030043x.

Social Science Computing Cooperative (SSCC). 2016. Mixed Models: Diagnostics and Inference. University of Wisconsin – Madison.

http://www.ssc.wisc.edu/sscc/pubs/MM/MM_DiagInfer.html (accessed Feb. 16, 2018).

- Stöckle, C.O., and A.R. Kemanian. 2009. Crop Radiation Capture and Use Efficiency: A Framework for Crop Growth Analysis. p. 145–170. *In* Sadras, V.O., Calderini (eds.), Crop Physiology: Applications for Genetic Improvement and Agronomy. 1st ed. Academic Press, Cambridge, MA.
- Stone, P.J., D.R. Wilson, J.B. Reid, and R.N. Gillespie. 2001. Water deficit effects on sweet corn. I. Water use, radiation use efficiency, growth, and yield. Aust. J. Agric. Res. 52: 103–113. doi: 10.1071/AR99146.
- Taiz, L., and E. Zeiger. 2010. Plant physiology. 5th ed. Sinauer Associates, Sunderland, MA.
- Tollenaar, M. and L.M. Dwyer. 1998. Physiology of maize. In: D.L. Smith and C. Hamel, eds. Crop yield, physiology and processes. Springer, New York, NY. 169-204.
- Tollenaar, M., and E.A. Lee. 2002. Yield potential, yield stability and stress tolerance in maize. F. Crop. Res. 75: 161–169.
- Tonitto, C., M.B. David, and L.E. Drinkwater. 2006. Replacing bare fallows with cover crops in fertilizer-intensive cropping systems: A meta-analysis of crop yield and N dynamics. Agric. Ecosyst. Environ. 112: 58–72. doi: 10.1016/j.agee.2005.07.003.
- Torbert, H.A., D.W. Reeves, and R.L. Mulvaney. 1996. Winter legume cover crop benefits to corn: Rotation vs. fixed-nitrogen effects. Agron. J. 88: 527–535. doi: 10.2134/agronj1996.00021962008800040005x.
- Uhart, S.A., and F.H. Andrade. 1995. Nitrogen Deficiency in Maize: II. Carbon-Nitrogen Interaction Effects on Kernel Number and Grain-Yield. Crop Sci. 35: 1384–1389.
- van der Kooi, C.J., M. Reich, M. Löw, L.J. De Kok, and M. Tausz. 2016. Growth and yield stimulation under elevated CO2and drought: A meta-analysis on crops. Environ. Exp. Bot. 122: 150–157. doi: 10.1016/j.envexpbot.2015.10.004.
- Venables, W. N. & Ripley, B. D. (2002) Modern Applied Statistics with S. Fourth Edition. Springer, New York.

- Walthall, C.L., J. Hatfield, P. Backlund, L. Lengnick, E. Marshall, M. Walsh, S. Adkins, M. Aillery, E.A. Ainsworth, C. Ammann, C.J. Anderson, I. Bartomeus, L.H. Baumgard, F. Booker, B. Bradley, D.M. Blumenthal, J. Bunce, K. Burkey, S.M. Dabney, J.A. Delgado, J. Dukes, A. Funk, K. Garrett, M. Glenn, D.A. Grantz, D. Goodrich, S. Hu, R.C. Izaurralde, R.A.C. Jones, S.-H. Kim, A.D.B. Leaky, K. Lewers, T.L. Mader, A. McClung, J. Morgan, D.J. Muth, M. Nearing, D.M. Oosterhuis, D. Ort, C. Parmesan, W.T. Pettigrew, W. Polley, R. Rader, C. Rice, M. Rivington, E. Rosskopf, W.A. Salas, L.E. Sollenberger, R. Srygley, C. Stöckle, E.S. Takle, D. Timlin, J.W. White, R. Winfree, L. Wright-Morton, and L.H. Ziska. 2013. Climate Change and Agriculture in the United States: Effects and Adaptation. USDA Technical Bulletin 1935. Washington, DC.
- Wang, D., S. a Heckathorn, X. Wang, and S.M. Philpott. 2012. A meta-analysis of plant physiological and growth responses to temperature and elevated CO(2). Oecologia 169(1): 1–13. doi: 10.1007/s00442-011-2172-0.
- Wang, J., X. Fu, F. Zhao, and U.M. Sainju. 2018. Response of soil carbon fractions and dryland maize yield to mulching. Soil Sci. Soc. Am. J. 82(2): 371–381. doi: 10.2136/sssaj2017.11.0397.
- White, C.M., S.T. DuPont, M. Hautau, D. Hartman, D.M. Finney, B. Bradley, J.C. LaChance, and J.P. Kaye. 2017. Managing the trade off between nitrogen supply and retention with cover crop mixtures. Agric. Ecosyst. Environ. 237: 121–133. doi: 10.1016/j.agee.2016.12.016.
- White, C.M., D.M. Finney, A.R. Kemanian, and J.P. Kaye. 2016. A Model–Data Fusion Approach for Predicting Cover Crop Nitrogen Supply to Corn. Agron. J. 108: 2527–2540. doi: 10.2134/agronj2016.05.0288.
- Wolfe, D.W., D.W. Henderson, T.C. Hsiao, and A. Alvino. 1988. Interactive Water and Nitrogen Effects on Senescence of Maize. II. Photosynthetic Decline and Longevity of Individual Leaves. Agron. J. 80: 865–870.
- Wolfe, D.W., D.W. Henderson, T.C. Hsiao, and A. Alvino. 1988. Interactive Water and Nitrogen Effects on Senescence of Maize. I. Leaf Area Duration, Nitrogen Distribution, and Yield. Agron. J. 80(June 1987): 859–864.
- Wolfe, D.W., A.T. Degaetano, G.M. Peck, M. Carey, L.H. Ziska, J. Lea-cox, and A.R. Kemanian. 2018. Unique challenges and opportunities for northeastern US crop production in a changing climate. Clim. Change 146: 231–245.
- Wortman, S.E., C. a. Francis, M.L. Bernards, R. a. Drijber, and J.L. Lindquist. 2012. Optimizing Cover Crop Benefits with Diverse Mixtures and an Alternative Termination Method. Agron. J. 104: 1425–1435. doi: 10.2134/agronj2012.0185.
- Xia, Y., K. Mitchell, M. Ek, J. Sheffield, B. Cosgrove, E. Wood, L. Luo, C. Alonge, H. Wei, J. Meng, B. Livneh, D. Lettenmaier, V. Koren, Q. Duan, K. Mo, Y. Fan, and D. Mocko. 2012.
 Continental-scale water and energy flux analysis and validation for the North American Land Data Assimilation System project phase 2 (NLDAS-2): 1. Intercomparison and application of model products. J. Geophys. Res. Atmos. 117: D03109. doi: 10.1029/2011JD016048.

Chapter 5

Drought-Resistant Soil: An Initial Scoping Analysis

5.1 Introduction

Drought is a major yield-limiting factor in rainfed agricultural systems and is projected to increase in frequency and severity in many regions due to climate change. In the main cropping region of the United States, increased temperature and water stress are projected to reduce maize (*Zea mays* L.) yield by up to 30-40% by the end of the 21st century under a high-emissions scenario (Jin et al. 2017). Volatile and diminished yields will threaten human nutritional security and may spur agricultural intensification efforts that lead to negative environmental outcomes, such as conversion of native ecosystems to agricultural use and increased nutrient losses to waterways (Hunter et al. 2017). To help avoid these negative impacts of climate change-driven drought, researchers and farmers are pursuing a variety of strategies to mitigate drought stress in crops, including traditional breeding, genetic modification, crop switching, and irrigation (Harrison et al. 2014, Nuccio et al. 2018, Alauddin et al. 2014).

Here we assess the potential for another strategy, long-term soil improvement, to mitigate drought yield losses. Agricultural management strategies strongly influence surface soil hydraulic properties when deployed over long time-scales. For instance, cover crops, crop rotation, perennials, reduced tillage, and organic amendments may increase soil organic matter (SOM), reduce bulk density (BD), and improve soil structure (Bronick and Lal 2005, Blanco-Canqui et al. 2015, Basche and Edelson 2017). These changes, in turn, may increase soil infiltration rate (IR) and available water capacity (AWC), enabling soils to capture and store more water for use during precipitation deficits. However, the quantitative effects of changes in soil hydraulic properties on drought-related yield losses have not been rigorously assessed.

Existing literature differs as to the potential for soil improvement to mitigate drought. Farmer survey data (CTIC/SARE 2012) and the results of some long-term cropping system trials (Lotter et al. 2003, Mallory and Porter 2007, Gaudin et al. 2015) suggest that soil-building practices such as cover crops and crop rotation reduce vulnerability to drought. Likewise, Williams et al. (2016) found that increased water-holding capacity consistently reduced temporal yield variability across four U.S.
States. Recent meta-analyses have found that conservation management practices increase field capacity (FC) by an average of 9.3%, with stronger effects for studies that lasted over 10 years, and may increase IR by 50% or more (Basche and DeLonge 2017, Basche 2017). When the results of these meta-analyses were applied to a hydrologic model of the state of Iowa, soil improvement led to an increase in crop transpiration of up to 16% during drought (Basche 2017).

However, a recent review of pedotransfer functions (PTFs) that relate soil texture and organic carbon content to AWC concluded that building soil carbon is unlikely to substantially increase plant-available water storage in soils (Minasny and McBratney 2017). Likewise, a field evaluation in the state of Iowa found that long-term cover cropping did not increase maize yield during a drought year, despite increasing AWC by over 20% (Basche et al. 2016). As farmers consider management options for adapting to increasing drought stress, it is important to clarify the potential effects of soil improvement.

Traditional field and modeling approaches both offer limited potential to satisfactorily evaluate the relationship between management-induced changes in soil hydraulic properties and crop drought stress. Field evaluation is logistically difficult. Long-term sites are needed due to the slow rate of change of soil hydraulic properties. Manipulation of soil moisture availability is challenging in humid sites, requiring the use of rainout shelters (Chapter 2), though it can be relatively straightforward in arid sites equipped with irrigation (Wolfe et al. 1988, Jones et al. 1986). Moreover, in field studies, management treatments that influence IR and AWC may also affect nutrient cycling, confounding the interpretation of yield responses to drought stress (e.g., Lotter et al. 2003, Mallory and Porter 2007, Gaudin et al. 2015).

Modeling studies, in turn, are limited by the models' ability to simulate long-term, management-induced changes in soil hydraulic properties. Infiltration rate and AWC are determined by soil structural properties such as pore-size distribution and connectivity (Pachepsky et al. 2006). Modeling these properties is very challenging (Connolly 1998), as they change three-dimensionally and across time in response to tillage, settling, precipitation, rooting, microbial activity, and freezethaw cycles. To avoid this challenge, most infiltration modules represent the soil as a uniform porous matrix, though some account for macropore flow under saturated soil conditions (Lepore et al. 2009, Huth et al. 2012, Arrington et al. 2013). Models typically estimate hydraulic conductivity and AWC with PTFs that relate soil texture and organic matter to hydraulic properties. Despite dozens of efforts to establish widely-applicable PTFs, large discrepancies remain (Schaap and Leij 1998, Minasny and McBratney 2017), likely due to wide variability among soils in physical and biological properties and management history. As a result, it is challenging for cropping system models to account for soil structural changes and their effects on hydraulic properties.

A new approach is needed to overcome the limitations of traditional field and modeling studies. We have combined the strengths of each approach by parameterizing the Cycles agroecosystem model with field-measured soil hydraulic properties from a 49-year tillage study in Ohio, USA (Kumar et al. 2012a,b). We assessed the effects of IR and AWC on maize yield under both historical and projected future climate conditions. Our results will illustrate the scope for mitigating drought stress by improving soil hydraulic properties through management.

5.2 Methods

Cycles is a process-based numerical agroecosystem simulation model that shares modules with C-Farm (Kemanian and Stöckle 2010) and CropSyst (Stöckle et al. 2014). The model is driven by daily weather data, including temperature, precipitation, solar radiation, relative humidity, and windspeed. Most processes operate on a daily timestep, though water infiltration and redistribution occur on a sub-daily scale. Cycles simulates crop growth above and below ground, as well as microbially-mediated soil carbon and nitrogen dynamics. The soil is modeled as a stack of layers.

Crop water uptake is simulated in Cycles based on biophysical principles. Uptake is determined by plant water conductance and the difference in water potential between the soil and the leaves, with feedbacks that represent stomatal closure and constrain maximum transpiration rate. This method has been shown to more accurately represent crop water uptake from a soil profile than simpler methods that do not represent the water potential gradient (Camargo and Kemanian 2016).

Crop water stress is determined as the ratio between water supply and demand, with the latter determined by reference evapotranspiration (ET) calculated with the Penman-Monteith equation (Monteith 1965). This approach to simulating water stress has been shown to be critical for assessing drought and heat effects on maize yield (Lobell et al. 2013). Higher temperatures affect crop yield by increasing ET demand and also shorten the growing season by increasing accumulation of growing degree days. The effect of increasing atmospheric carbon dioxide concentration ([CO₂]) is not accounted for in our simulations.

Soil water infiltration is controlled by the Natural Resources Conservation Service (NRCS) runoff curve number (CN). The CN approach was developed to estimate total runoff for a given amount of total rainfall in a 24-hour period (NRCS 2004). A CN for a given land area can be

calculated based on NRCS methodology (Cronshey et al. 1986). Inputs to the calculation include land cover, use, and management, as well as the soil's hydrologic group and hydrologic condition. Given its simplicity and ease of use, the CN is widely used to partition infiltration and runoff in agroecosystem models (Connolly 1998; e.g. SPAW, Saxton 2008 and SWIM/APSIM, Huth et al. 2012). In Cycles, CN is set by the user and then adjusted automatically in response to soil saturation, with IR declining when the topsoil is saturated.

Available water capacity is the difference between the field capacity (FC) and permanent wilting point (PWP) of the soil. These properties are typically calculated with a PTF (Saxton and Rawls 2006) but can be directly input by the user, as we do here. Soil saturated hydraulic conductivity (K_{sat}) controls redistribution and is also calculated by PTF.

Kumar et al. (2012a,b) report water content at FC (-33 kPa), water content at PWP (-1500 kPa), BD, and SOM concentration, and steady-state infiltration rate (q_s) for soils following a 49-year tillage experiment (Table 5-1). The study was conducted on a Wooster silt loam soil in northeast Ohio, USA. Mean particle size distribution in the top 40 cm was 18.5% clay, 22.9% sand, and 58.5% silt. Tillage treatments included conventional tillage (CT) with a moldboard plow, minimum tillage (MT) with a chisel plow, no tillage (NT), and an undisturbed woodlot (WL) control. Soil cores 5.35 cm in diameter and 6 cm in depth, as well as loose soil samples, were used to characterize 10 cm-thick soil layers down to 40 cm. The study included both a continuous maize (*Zea mays* L.) system and a maize-soybean (*Glycine max* L.) rotation. Hydraulic properties were influenced more by tillage than by rotation, so the mean of the two rotations was used.

Soil Management	FC	PWP	AWC	BD	SOM	qs	CN	Hydrologic Soil Group ^a	Hydrologic Condition ^b
		— cm —		g cm ⁻³	%	mm h ⁻¹			
WL	16.4	3.05	13.4	1.28	2.62	157	71	А	Good
NT	14.7	4.42	10.2	1.41	1.79	34.7	80	В	Good
MT	12.9	4.26	8.61	1.43	1.74	18.6	83	В	Poor
СТ	11.0	4.91	6.13	1.49	1.53	8.21	89	С	Poor

Table **5-1**: Hydraulic properties in the top 40 cm of soils following 49 years of contrasting disturbance regimes.

Abbreviations: FC, field capacity; PWP, permanent wilting point; AWC, available water capacity; BD, soil bulk density; SOM, soil organic matter; q_s, steady-state infiltration rate; CN, curve number; WL, woodlot; NT, no tillage; MT, minimum till; CT, conventional till.

^{a,b} Hydrologic soil group and hydrologic condition are needed to calculate CN.

Soils in Cycles were parameterized with field-measured FC, PWP, BD, and SOM down to 40 cm. Soil particle size distribution (percent sand, silt, and clay) and SOM below 40 cm were based on a pedon from the USDA Soil Characterization Database (NCSS; pedon WN-S02) that matches the soil series and surface soil characteristics of the field site (Kumar et al. 2012a,b). Bulk density below 40 cm was based on the Wooster-Riddles silt loam soil description in the Web Soil Survey (WSS 2018). Total soil depth was 270 cm and AWC below 40 cm was 26.6 cm. A slope of 3.5% was used based on site characteristics reported by Van Doren et al. (1976).

A CN was calculated for each tillage system following standard methodology (Cronshey et al. 1986). With the Soil Survey (Soil Conservation Service 1984) as a starting point, assumptions were made for hydrologic soil group and hydrologic condition (Table 5-1) to approximate the range of infiltration rates reported by Kumar et al. (2012b). Calculated CN ranged from 71 in the WL soil to 89 in the CT soil (Table 5-1). (Note: IR increases as CN decreases.) These calculated CN values were used in the main simulations. To isolate the effects of IR and AWC, a sensitivity analysis was run in which soils reflecting the water-holding properties (FC, PWP, and AWC) resulting from the four tillage systems were tested at CN values of 70, 80, and 90.

Effects of soil hydraulic properties on drought stress were assessed by simulating maize yield in both historical and projected future climate conditions. A virtual phytometer crop of continuous no-till maize was grown with automatic nitrogen (N) fertilization to eliminate confounding effects of N stress. In the main simulations, maize residues were retained on the soil surface. An alternative scenario with residues removed was also simulated to test the effect of residues on soil moisture conservation and maize yield. The model was calibrated with maize yield reported from the most recent years of the long-term field experiment (Kumar et al. 2012a). Planting date varied automatically based on spring temperature, enabling adaptation to temperature increase, with a minimum planting date of Julian day 90 (March 31st in non-leap years). Scenarios were run as a continuous sequence of years, but soil hydraulic properties were held constant across the simulations, so years are essentially independent.

Scenarios were run over historical (1950-2005) and projected future (2006-2099) climate conditions using daily weather variables from the National Center for Atmospheric Research Community Climate System Model 4 (CCSM4; Gent et al. 2011). Model simulations used were generated for the Coupled Model Intercomparison Project 5 (CMIP5; Taylor et al. 2012) and downscaled to 4-km resolution with the MACAv2-METDATA methodology (Abatzoglou and Brown 2012, Abatzoglou 2013). Future radiative forcing was from the Representative Concentration Pathway 8.5 high-emissions scenario (IPCC 2013). Compared to other global climate models,

CCSM4 projects a relatively modest increase in temperature and a limited reduction in growing season precipitation (Xu et al. 2016), which suggests that projected increases in drought stress may be relatively conservative.

The standardized precipitation-evapotranspiration index (SPEI; Vicente-Serrano et al. 2010) was used to quantify drought severity across the months of June-August. The SPEI, which is based on the balance between precipitation and ET demand, has shown superior performance in identifying summer droughts (Vicente-Serrano et al. 2012). Zipper et al. (2016) found that, among 3-month SPEI values, those for June-August were the best predictor of detrended U.S. maize yield. While these authors found an even stronger relationship for 1-month July SPEI values, this is likely due to the heat and drought sensitivity of critical flowering and kernel development processes (Hatfield et al. 2011), which are not explicitly represented in Cycles. The span of months used here (June-August) represents the period of the growing season in which water availability has the largest effect on simulated biomass.

The historical period (1950-2005) was used as the reference for calculating SPEI values, so moisture conditions are relative to historical conditions. For the purposes of this analysis, SPEI values were mapped to the following moisture categories: severe drought, moderate drought, balance, moderate surplus, and extreme surplus. Moisture categories, from driest to wettest, are delimited by the following SPEI values: -6, -1.5, -0.5, 0.5, 1.5, 6.

All statistical analysis was performed in R (R Core Team 2018). Most analyses were performed with mixed-effect linear models with a random intercept for year specified with the lmer function of the lme4 package (Bates et al. 2015). The significance of individual predictors was determined by comparing the model with and without that predictor using the anova function (R core team 2018; Kniss 2017). A t-test was used to compare maize yield and relative yield gain between modeling scenarios. The overall response of yield to SPEI values was tested with a simple linear model using the lm function (R core team 2018). An alpha value of 0.05 was used to assess statistical significance. Pairwise comparisons were evaluated with the emmeans function (Lenth 2018) with correction for multiple comparisons. Final models were evaluated to ensure they met the assumptions of independence and normality of residuals and random effects (Pinheiro and Bates 2000, SSC 2016).

5.3 Results and Discussion

Climate model projections from CCSM4 show a substantial increase in temperature and precipitation between the beginning (2000-2029) and the end of the century (2070-2099). Mean annual temperature increases by 3.7 °C, from 11.0 °C to 14.7 °C, and mean annual precipitation increases 37 mm, from 1,080 mm to 1,043 mm. Mean temperature increases by a similar amount during the April-October growing season: 3.9 °C, from 17.6 to 21.5. However, mean precipitation drops during the growing season by 21 mm, from 706 mm to 685 mm, in contrast to the annual trend.

Kumar et al. (2012a) report the mean maize grain yield across tillage treatments was 12.1 Mg ha⁻¹ for 2007-2011. Simulated mean yield for a 30-year period encompassing these years (2000-2029) was 13.8 Mg ha⁻¹. This yield discrepancy is reasonable given that simulated maize yield was not limited by N stress, pests, or pathogens.

Simulated maize yield declined steadily under future climate, with the rate of decline accelerating after mid-century (Fig. 5-1A). Yield decline was closely related to increasing drought stress: SPEI values explained 70.1% of yield variability across soils (p < 0.0001; Fig. 5-1B). Mean yield across all soils declined by 3 Mg ha⁻¹, or 21.8%, from 13.8 Mg ha⁻¹ at the beginning of the century (2000-2029) to 10.8 Mg ha⁻¹ at the end of the century (2070-2099).

This level of yield loss is commensurate with previous findings for the Midwest US when simulations do not account for elevated $[CO_2]$ (Bassu et al. 2014, Xu et al. 2016, Jin et al. 2017). Unlike in Xu et al. (2016) and Jin et al. (2017), the yield decline reported here is not driven by the shortening of the growing season caused by higher growing season temperature. Instead, it is entirely attributable to increased water stress.



Figure 5-1: Maize grain yield (A) and standardized precipitation-evapotranspiration index (B; SPEI) for historical (1950-2005) and projected future (2006-2099) climate conditions. The simulation in A was run with crop residues retained. The shaded area in B represents the 95% confidence interval.

Differences among soil management treatments were primarily driven by differences in CN, FC, and PWP. Soils with increased AWC and IR produced higher simulated maize yield across the broad range of moisture conditions simulated for 1950-2099 (Figs. 5-1A and 5-2). Yield gain relative to CT was greatest under moderate drought and balanced moisture conditions. Under moderate drought, soil conditioned by long-term MT increased grain yield by 4.41% (Table 5-2). No-till soil increased yield by 7.97% and WL soil by 13.3% under moderate drought. The yield benefit was

generally smaller under severe drought: 3.88% in MT soil, 7.16% in NT soil, and 11.7% in WL soil. While increasing soil AWC and IR substantially raised maize yield under moderate to severe drought, improved soil hydraulic properties could not fully mitigate drought yield loss, even under the bestcase scenario of undisturbed WL soil.



Figure **5-2**: Soil management effects on maize grain yield (A) and yield relative to conventional tillage (B) across the range of standardized precipitation-evapotranspiration index (SPEI) values simulated for 1950-2099. The simulation was run with crop residues retained. The shaded areas in B represent the 95% confidence intervals, which were adjusted for multiple comparisons with a Tukey correction.

Table 5-2: Mean maize grain yield by residue management scenario, soil management treatment, and moisture category for 1950-2099. Values in parentheses represent percent differences in mean yield between each soil management category and conventional till. Within each residue-management scenario, means within each moisture category that share a letter are not significantly different at the alpha = 0.05 level with a Bonferroni correction for multiple comparisons.

		Moisture Category						
Residue	Soil	Severe	Moderate	Balance	Moderate	Extreme	Overall	
Management	Management	drought	drought		surplus	surplus	mean	
Retained	Woodlot	10.1 a	13.2 a	14.5 a	15.3 a	15.2 a	13.4 a	
	woodiot	(11.7)	(13.3)	(12.3)	(7.38)	(3.89)	(11)	
	No Till	9.69 b	12.6 b	13.9 b	15.0 a	15.2 ab	13.0 b	
	NO TIII	(7.16)	(7.97)	(8)	(5.54)	(3.19)	(7.1)	
	Minimum Till	9.40 c	12.2 c	13.5 c	14.7 b	15.0 ab	12.6 c	
	Iviiiiiiiiiiiiiiiiiiiiiiiiiiiiiiiiiiii	(3.88)	(4.41)	(4.85)	(3.46)	(2.14)	(4.14)	
	Conventional Till	9.05 d	11.7 d	12.9 d	14.3 c	14.7 b	12.2 d	
Removed	Woodlat	8.88 A	11.3 A	13.0 A	14.8 A	15.2 A	12.2 A	
	woodiot	(9.85)	(7.69)	(8.76)	(10.3)	(6.87)	(8.92)	
	M. T.11	8.89 A	11.4 A	13.0 A	14.7 AB	15.1 A	12.2 A	
	NO TIII	(9.85)	(8.29)	(8.42)	(8.8)	(5.9)	(8.63)	
	Minimum Till	8.91 A	11.4 A	12.9 A	14.5 B	15.0 A	12.1 A	
	IVIIIIIIIIIIIIIIIIIIIIIIII	(10.2)	(8.73)	(7.77)	(7.27)	(4.79)	(8.25)	
	Conventional Till	8.14 B	10.5 B	12.0 B	13.5 C	14.3 B	11.2 B	

Note: Moisture categories, from driest to wettest, are delimited by the following values of the standardized precipitation-evapotranspiration index: -6, -1.5, -0.5, 0.5, 1.5, 6.

Improved IR and AWC led to greater increases in simulated maize grain yield at the end of the century than at the beginning (p < 0.0001). Across all moisture categories, WL soil increased yield over CT soil by 12.5% in 2070-2099, but only 10.3% in 2000-2029. Likewise, NT soil increased yield 8.15% at the end of the century, but only 6.65% at the beginning. These differences are primarily driven by the distribution of moisture conditions, with greater incidence of moderate and severe drought at the end of the century, and lower incidence of moisture surplus (Fig. 5-3). Yield gain in absolute terms was nearly equivalent between the beginning and the end of the century, but percent increase rose as mean yield declined.



Figure **5-3**: Percent of years in each moisture category between the beginning (2000-2029) and end (2070-2099) of the 21st century.

The potential for soil management to buffer drought yield losses may decline at levels of drought stress beyond those simulated here. Trends suggest that the benefit of increased AWC and IR erodes as the SPEI value drops below -3 (Fig. 5-2B). This is likely because soil moisture availability is not limited by either storage capacity or infiltration rate under severe drought, when precipitation events are typically both few in number and small in size. Therefore, soil improvement may be a less effective drought adaptation strategy in more arid regions or under more severe climate change.

Increases in both AWC and IR led to higher simulated maize yield. Under moderate-tosevere drought (SPEI < -0.5), AWC had a larger impact on yield than IR (Fig. 5-4). Increasing AWC in the top 40 cm of soil from 6.13 to 13.4 cm increased mean yield by 8.52%, averaged across all curve numbers tested. In contrast, decreasing the curve number from 90 to 70 only increased mean yield by 3.33%, averaged across all levels of AWC. There was no interaction between AWC and IR (p = 0.199).

The relative importance of AWC and IR for soil water supply is influenced by the size distribution of rain events. Proportionally more water is lost to runoff as rain events increase in size, so IR has more influence on soil moisture availability when precipitation occurs in fewer large events. The size distribution of rain events during the growing season does not shift dramatically in the CCSM4 climate projection used here. Recent analyses have disagreed about the magnitude and statistical significance of projected changes in extreme rain events in Ohio (Kunkel et al. 2013, Walsh et al. 2014), but extreme events are generally expected to become more common. Therefore, increased IR may be more beneficial under drought than it appears in this analysis.



Figure 5-4: Sensitivity analysis of maize yield response to available water capacity (AWC) in the top 40 cm of soil and infiltration rate (IR) as determined by the curve number (CN). Mean yield is from all years from 1950-2099 in which moderate-to-severe drought occurred in June-August (values of the standardized precipitation-evapotranspiration index less than or equal to -0.5). Values of AWC reflect the legacy of four long-term soil management regimes. Curve numbers represent the range between the highest (woodlot) and lowest (conventional tillage) infiltration rates for these management regimes. (Note: IR increases as CN decreases.) The simulation was run with crop residues retained.

Retaining crop residue reduces evaporation from the soil, conserving water for crop growth (Jones et al. 1969, Hatfield et al. 2001). Under moderate-to-severe drought, simulated maize yield was 13.0% higher in the main scenario with residue retained than in the scenario with residue removed (average of all four soils; p < 0.00001; Fig. 5-5). Residue retention was also critical for reaping the benefit of enhanced AWC. Holding more soil moisture in the surface layers increases the risk of evaporative losses, especially in the absence of residue cover and under high evaporative demand driven by increased temperature. These losses offset the benefit of high AWC and may turn this generally-beneficial soil property into a liability.



Figure 5-5: Soil management effects on maize grain yield with crop residue retained (A) and crop residue removed (B) across the range of standardized precipitation-evapotranspiration index values simulated for 1950-2099. Best-fit lines from B are plotted in gray on A for comparison, and vice versa.

This effect is best illustrated when scenarios are compared at a constant infiltration rate. With residue removed and CN = 80, soil management legacy had no effect on maize grain yield and there was a trend toward lower yield in high-AWC soils under drought (Fig. 5-6). This indicates that soil moisture conservation is most effective with a systems approach that simultaneously addresses all the major water loss pathways (runoff, drainage, and evaporation) by increasing IR, AWC, and surface cover.



Figure 5-6: Soil management effects on maize grain yield across the range of standardized precipitation-evapotranspiration index (SPEI) values simulated for 1950-2099 with crop residue removed and equal infiltration rate for all soils (curve number = 80).

Most agronomic management systems that improve soil hydraulic properties, such as reduced tillage and cover cropping, also increase surface residue cover. However, it is possible to improve IR and AWC in systems that rely on tillage, such as root crops (Mallory and Porter 2007) and organic field crops (Lotter et al. 2003, Williams et al. 2017), by incorporating manure, crop residues, and other organic materials. Innovative management practices are needed to reduce surface evaporation and maximize the benefits of soil improvement in these systems. Options may include narrower row spacing, planting into rolled cover crop residue (Wallace et al. 2017), and planting into living cover crops, also known as "planting green" (Le Gall and Tooker 2017). While the latter strategy runs the risk of depleting soil moisture prior to crop establishment, adaptive management may enable farmers to conserve moisture in dry springs with early termination, while allowing the cover crop to dry down soil for planting in wet springs.

Due to the slow rate of change of soil physical properties, the full yield benefits shown here would not accrue immediately upon adoption of soil-building practices. However, rapid changes in soil structure and hydraulic properties have been reported (Folorunso et al. 1992, Gulick et al. 1994, Blanco-Canqui et al. 2015), so farmers could reap some water conservation benefits in under a decade. Moreover, soil-building management practices such as reduced tillage, crop rotation, incorporation of perennials, and cover cropping are also likely to increase soil carbon and improve

nutrient cycling (McDaniel et al. 2017); protect soil from extreme rainfall (Blanco-Canqui et al. 2015); reduce waterlogging (Ernst et al. 2018); break up pest and disease cycles (Ratnadass et al. 2012); and enhance yield stability (Lotter et al. 2003, Mallory and Porter 2007, Smith et al. 2007, Grover et al. 2009, Gaudin et al. 2015, Ernst et al. 2016).

Taking a systems approach to improve soil hydraulic properties could therefore provide cobenefits that accrue alongside increased AWC and IR, and in some cases more quickly, increasing the economic and environmental return on investment. Since our analysis did not account for these factors, the yield increases reported here may serve as a lower estimate of the potential drought adaptation benefits of improved soil management. Further research is needed to understand how these factors interact and to develop management strategies that optimize abiotic and biotic growing conditions under drought.

Additional research is also needed to determine the benefits of soil improvement in the presence of elevated $[CO_2]$ and physiological heat stress, since our results only reflect increased drought stress. Elevated $[CO_2]$ has been shown to substantially increase maize transpiration efficiency and yield under drought stress in studies conducted in the field, in growth chambers, and with models (Manderscheid et al. 2014, van der Kooi et al. 2016, Bassu et al. 2014, Jin et al. 2017). Moreover, a comparison with field data indicates that crop models likely underestimate this effect (Durand et al. 2016). If elevated $[CO_2]$ greatly increases maize transpiration efficiency, drought-induced yield losses would be mitigated and improving soil water supply would be less important for maintaining yield.

On the other hand, the physiological effects of heat stress, which are not directly accounted for in this analysis, may drastically reduce maize yield. In a global modeling study, Deryng et al. (2014) found that heat stress at anthesis was responsible for nearly half of climate-induced maize yield loss. Likewise, Jin et al. (2017) found that the phenological and physiological effects of high temperature will be the dominant drivers of U.S. maize yield losses at the end of the century, especially when accounting for elevated [CO₂]. Much of the effect of extreme heat on maize yield is due to its effects on ET demand and water stress, at least under historical climate conditions (Lobell et al. 2013). However, it is likely that the temperature environment projected for the end of the century would exceed critical thresholds of maize heat tolerance and depress yields (Schlenker and Roberts 2009). While heat stress would further decrease yields compared to our results, it may also increase the relative benefit of enhanced soil water supply, since transpirative cooling can mitigate heat-related yield loss.

Despite these uncertainties, our results indicate that improving soil hydraulic properties may help underpin agricultural production and food security under climate change. Political and economic incentives for soil-building practices should be strengthened, and popular campaigns such as the "soil health movement" should be supported to increase adoption of these practices. Timely and sustained action to enhance the ability of our soils to capture and store water may pay dividends in the warmer, drier, and more variable world that lies ahead.

5.4 References

- Abatzoglou, J.T. 2013. Development of gridded surface meteorological data for ecological applications and modelling. Int. J. Climatol. 33: 121–131. doi: 10.1002/joc.3413.
- Abatzoglou, J.T., and T.J. Brown. 2012. A comparison of statistical downscaling methods suited for wildfire applications. Int. J. Climatol. 32: 772–780. doi: 10.1002/joc.2312.
- Alauddin, M., and M.A.R. Sarker. 2014. Climate change and farm-level adaptation decisions and strategies in drought-prone and groundwater-depleted areas of Bangladesh: An empirical investigation. Ecol. Econ. 106: 204–213. doi: 10.1016/j.ecolecon.2014.07.025.
- Arrington, K.E., S.J. Ventura, and J.M. Norman. 2013. Predicting Saturated Hydraulic Conductivity for Estimating Maximum Soil Infiltration Rates. Soil Sci. Soc. Am. J. 77: 748–758. doi: 10.2136/sssaj2012.0288.
- Basche, A. 2017. Turning Soils into Sponges: How Farmers Can Fight Floods and Droughts. Washington, DC.
- Basche, A.D., S. V. Archontoulis, T.C. Kaspar, D.B. Jaynes, T.B. Parkin, and F.E. Miguez. 2016. Simulating long-term impacts of cover crops and climate change on crop production and environmental outcomes in the Midwestern United States. Agric. Ecosyst. Environ. 218: 95– 106. doi: 10.1016/j.agee.2015.11.011.
- Basche, A.D., and O.F. Edelson. 2017. Improving water resilience with more perennially based agriculture. Agroecol. Sustain. Food Syst. 41: 799–824. doi: 10.1080/21683565.2017.1330795.
- Basche, A.D., T.C. Kaspar, S. V. Archontoulis, D.B. Jaynes, T.J. Sauer, T.B. Parkin, and F.E. Miguez. 2016. Soil water improvements with the long-term use of a winter rye cover crop. Agric. Water Manag. 172: 40–50. doi: 10.1016/j.agwat.2016.04.006.
- Basche, A., and M. DeLonge. 2017. The Impact of Continuous Living Cover on Soil Hydrologic Properties: A Meta-Analysis. Soil Sci. Soc. Am. J. 81: 1179–1190. doi: 10.2136/sssaj2017.03.0077.

- Bassu, S., N. Brisson, J.-L. Durand, K.J. Boote, J. Lizaso, J. Jones, C. Rosenzweig, A. Ruane, M. Adam, C. Baron, B. Basso, C. Biernath, H. Boogaard, S. Conijn, M. Corbeels, D. Deryng, G. de Sanctis, S. Gayler, P. Grassini, J. Hatfield, S. Hoek, C. Izaurralde, R. Jongschaap, A. Kemanian, C. Kersebaum, S.-H. Kim, N. Kumar, D. Makowski, C. Muller, C. Nendel, E. Priesack, M.V. Pravia, F. Sau, I. Shcherbak, F. Tao, E. Teixeira, D. Timlin, and K. Waha. 2014. How do various maize crop models vary in their responses to climate change factors? How do various maize crop models vary in their responses to climate change factors? Glob. Chang. Biol.: gcb.12520. doi: 10.1111/gcb.12520.
- Bates, D., M. Mächler, B. Bolker, and S. Walker. 2015. Fitting Linear Mixed-Effects Models Using lme4. J. Stat. Softw. 67: 1–48. doi: 10.18637/jss.v067.i01.
- Blanco-Canqui, H., T.M. Shaver, J.L. Lindquist, C.A. Shapiro, R.W. Elmore, C.A. Francis, and G.W. Hergert. 2015. Cover Crops and Ecosystem Services: Insights from Studies in Temperate Soils. Agron. J. 107: 2449–2474. doi: 10.2134/agronj15.0086.
- Bronick, C.J., and R. Lal. 2005. Soil structure and management: A review. Geoderma 124: 3–22. doi: 10.1016/j.geoderma.2004.03.005.
- Camargo, G.G.T., and A.R. Kemanian. 2016. Six crop models differ in their simulation of water uptake. Agric. For. Meteorol. 220: 116–129. doi: 10.1016/j.agrformet.2016.01.013.
- Connolly, R. 1998. Modelling effects of soil structure on the water balance of soil-crop systems: a review. Soil Tillage Res. 48: 1–19. doi: 10.1016/S0167-1987(98)00128-7.
- Cronshey, R., R. McCuen, N. Miller, W. Rawls, S. Robbins, and D. Woodward. 1986. Urban Hydrology for Small Watersheds TR-55. Natural Resources Conservation Service. Washington, DC.
- CTIC/SARE. 2013. 2012 2013 Cover Crop Survey. West Lafayette, IN.
- Deryng, D., D. Conway, N. Ramankutty, J. Price, and R. Warren. 2014. Global crop yield response to extreme heat stress under multiple climate change futures. Environ. Res. Lett. 9: 034011. doi: 10.1088/1748-9326/9/3/034011.
- Durand, J.L., K. Delusca, K. Boote, J. Lizaso, R. Manderscheid, H.J. Weigel, A.C. Ruane, C. Rosenzweig, J. Jones, L. Ahuja, S. Anapalli, B. Basso, C. Baron, P. Bertuzzi, C. Biernath, D. Deryng, F. Ewert, T. Gaiser, S. Gayler, F. Heinlein, K.C. Kersebaum, S.H. Kim, C. Müller, C. Nendel, A. Olioso, E. Priesack, J.R. Villegas, D. Ripoche, R.P. Rötter, S.I. Seidel, A. Srivastava, F. Tao, D. Timlin, T. Twine, E. Wang, H. Webber, and Z. Zhao. 2016. How accurately do maize crop models simulate the interactions of atmospheric CO₂ concentration levels with limited water supply on water use and yield? Eur. J. Agron.: 1–9. doi: 10.1016/j.eja.2017.01.002.
- Ernst, O.R., A.R. Kemanian, S.R. Mazzilli, M. Cadenazzi, and S. Dogliotti. 2016. Depressed attainable wheat yields under continuous annual no-till agriculture suggest declining soil productivity. F. Crop. Res. 186: 107–116. doi: 10.1016/j.fcr.2015.11.005.

- Ernst, O.R., S. Dogliotti, M. Cadenazzi, and A.R. Kemanian. 2018. Shifting crop-pasture rotations to no-till annual cropping reduces soil quality and wheat yield. F. Crop. Res. 217: 180–187. doi: 10.1016/j.fcr.2017.11.014.
- Folorunso, O.A., D.E. Rolston, T. Prichard, and D.T. Loui. 1992. Soil surface strength and infiltration rate as affected by winter cover crops. Soil Technol. 5: 189–197. doi: 10.1016/0933-3630(92)90021-R.
- Gaudin, A.C.M., T.N. Tolhurst, A.P. Ker, K. Janovicek, C. Tortora, R.C. Martin, and W. Deen. 2015. Increasing crop diversity mitigates weather variations and improves yield stability. PLoS One 10: e0113261. doi: 10.1371/journal.pone.0113261.
- Gent, P.R., G. Danabasoglu, L.J. Donner, M.M. Holland, E.C. Hunke, S.R. Jayne, D.M. Lawrence, R.B. Neale, P.J. Rasch, M. Vertenstein, P.H. Worley, Z.L. Yang, and M. Zhang. 2011. The Community Climate System Model Version 4. J. Clim. 24: 4973–4991. doi: 10.1175/2011JCLI4083.1.
- Grover, K.K., H.D. Karsten, and G.W. Roth. 2009. Corn grain yields and yield stability in four long-term cropping systems. Agron. J. 101: 940–946. doi: 10.2134/agronj2008.0221x.
- Gulick, S.H. 1994. Cover-crop-enhanced water infiltration of a slowly permeable fine sandy loam. Soil Sci. Soc. Am. J. 58: 1539–1546. doi: 10.2136/sssaj1994.03615995005800050038x.
- Harrison, M.T., F. Tardieu, Z. Dong, C.D. Messina, and G.L. Hammer. 2014. Characterizing drought stress and trait influence on maize yield under current and future conditions. Glob. Chang. Biol. 20: 867–878. doi: 10.1111/gcb.12381.
- Hatfield, J.L., K.J. Boote, B. a. Kimball, L.H. Ziska, R.C. Izaurralde, D. Ort, a. M. Thomson, and D. Wolfe. 2011. Climate Impacts on Agriculture: Implications for Crop Production. Agron. J. 103: 351. doi: 10.2134/agronj2010.0303.
- Hatfield, J.L., T.J. Sauer, and J.H. Prueger. 2001. Managing Soils to Achieve Greater Water Use Efficiency: A Review. Agron. J. 93: 271–280.
- Hunter, M.C., R.G. Smith, M.E. Schipanski, L.W. Atwood, and D.A. Mortensen. 2017. Agriculture in 2050: Recalibrating targets for sustainable intensification. Bioscience 67: 386–391. doi: 10.1093/biosci/bix010.
- Huth, N.I., K.L. Bristow, and K. Verburg. 2012. Swim3: Model Use, Calibration, and Validation. Trans. ASABE 55: 1303–1313.
- Jin, Z., Q. Zhuang, Z. Tan, J.S. Dukes, B. Zheng, and J.M. Melillo. 2016. Do maize models capture the impacts of heat and drought stresses on yield? Using algorithm ensembles to identify successful approaches. Glob. Chang. Biol. 22: 3112–3126. doi: 10.1111/gcb.13376.
- Jones, J., J. Moody, and J. Lillard. 1969. Effects of tillage, no tillage, and mulch on soil water and plant growth. Agron. J.: 719–721.

- Jones, J.W., B. Zur, and H.M. Bennett. 1986. Interactive Effects of Water and Nitrogen Stresses on Carbon and Water Vapor Exchange of Corn Canopies. Agric. For. Meteorol. 36: 113–126.
- Kemanian, A.R., and C.O. Stöckle. 2010. C-Farm: A simple model to evaluate the carbon balance of soil profiles. Eur. J. Agron. 32: 22–29. doi: 10.1016/j.eja.2009.08.003.
- Kniss, A.R., and J.C. Streibig. 2015. Statistical Analysis of Agricultural Experiments with R.
- Kumar, S., A. Kadono, R. Lal, and W. Dick. 2012a. Long-Term No-Till Impacts on Organic Carbon and Properties of Two Contrasting Soils and Corn Yields in Ohio. Soil Sci. Soc. Am. J. 76: 1798–1809. doi: 10.2136/sssaj2012.0055.
- Kumar, S., A. Kadono, R. Lal, and W. Dick. 2012b. Long-Term Tillage and Crop Rotations for 47-49 Years Influences Hydrological Properties of Two Soils in Ohio. Soil Sci. Soc. Am. J. 76: 2195– 2207. doi: 10.2136/sssaj2012.0098.
- Kunkel, K.E., L.E. Stevens, S.E. Stevens, L. Sun, E. Janssen, D. Wuebbles, S.D. Hilberg, M.S. Timlin, L. Stoecker, N.E. Westcott, and J.G. Dobson. 2013. Regional Climate Trends and Scenarios for the U.S. National Climate Assessment. Part 3. Climate of the Midwest U.S. NOAA Tech. Rep. NESDIS 142-3: 103 pp.
- Le Gall, M., and J.F. Tooker. 2017. Developing ecologically based pest management programs for terrestrial molluscs in field and forage crops. J. Pest Sci. (2004). 90: 825–838. doi: 10.1007/s10340-017-0858-8.
- Lenth, R. 2018. emmeans: Estimated Marginal Means, aka Least-Squares Means.
- Lepore, B.J., C.L.S. Morgan, J.M. Norman, and C.C. Molling. 2009. A Mesopore and Matrix infiltration model based on soil structure. Geoderma 152: 301–313. doi: 10.1016/j.geoderma.2009.06.016.
- Lobell, D.B., G.L. Hammer, G. McLean, C. Messina, M.J. Roberts, and W. Schlenker. 2013. The critical role of extreme heat for maize production in the United States. Nat. Clim. Chang. 3: 497–501. doi: 10.1038/nclimate1832.
- Lotter, D.W., R. Seidel, and W. Liebhardt. 2003. The performance of organic and conventional cropping systems in an extreme climate year. Am. J. Altern. Agric. 18: 9 pp. doi: 10.1079/AJAA200345.
- Mallory, E.B., and G.A. Porter. 2007. Potato yield stability under contrasting soil management strategies. Agron. J. 99: 501–510. doi: 10.2134/agronj2006.0105.
- Manderscheid, R., M. Erbs, and H.J. Weigel. 2014. Interactive effects of free-air CO₂ enrichment and drought stress on maize growth. Eur. J. Agron. 52: 11–21. doi: 10.1016/j.eja.2011.12.007.
- Mcdaniel, M.D., L.K. Tiemann, and A.S. Grandy. 2017. Does agricultural crop diversity enhance soil microbial biomass and organic matter dynamics? A meta-analysis. Ecol. Appl. 24: 560–570.

- Minasny, B., and A.B. Mcbratney. 2017. Limited effect of organic matter on soil available water capacity. Eur. J. Soil Sci.: 12475. doi: 10.1111/ejss.12475.
- Mockus, V., and A.T. Hjelmfelt. 2004. Part 630 Hydrology National Engineering Handbook Chapter 10 Estimation of Direct Runoff from Storm Rainfall. Natural Resources Conservation Service. Washington, DC.
- Monteith, J.L. 1965. Evaporation and environment. p. 205–234. *In* Symposia of the Society for Experimental Biology. University Press, Cambridge, UK.
- National Cooperative Soil Survey (NCSS). 2018. Soil Characterization Database. Washington, DC.
- NRCS. 2018. Web Soil Survey. Washington, DC.
- Nuccio, M.L., M. Paul, N.J. Bate, J. Cohn, and S.R. Cutler. 2018. Where are the drought tolerant crops? An assessment of more than two decades of plant biotechnology effort in crop improvement. Plant Sci. doi: 10.1016/j.plantsci.2018.01.020.
- Pachepsky, Y., D. Timlin, and W. Rawls. 2003. Generalized Richards' equation to simulate water transport in unsaturated soils. J. Hydrol. 272: 3–13.
- Pinheiro, J.C., and D. Bates. 2000. Mixed-effects models in S and S-PLUS. Springer-Verlag, New York, NY.
- Ratnadass, A., P. Fernandes, J. Avelino, and R. Habib. 2012. Plant species diversity for sustainable management of crop pests and diseases in agroecosystems: A review.
- Saxton, K., and W. Rawls. 2006. Soil Water Characteristic Estimates by Texture and Organic Matter for Hydrologic Solutions. Soil Sci. Soc. Am. J. 70: 1569–1578. doi: 10.2136/sssaj2005.0117.
- Saxton, K.E., and P.H. Willey. 2005. The SPAW Model for Agricultural Field and Pond Hydrologic Simulation. p. 1–37. *In* Watershed Models. CRC Press, Boca Raton, FL.
- Schaap, M.G., F.J. Leij, and M.T. Van Genuchten. 1998. Neural network analysis for hierarchical prediction of soil hydraulic properties. Soil Sci. Soc. Am. J. 62: 847–855.
- Schlenker, W., and M.J. Roberts. 2009. Nonlinear temperature effects indicate severe damages to U.S. crop yields under climate change. Proc. Natl. Acad. Sci. U. S. A. 106: 15594–15598. doi: 10.1073/pnas.0906865106.

Soil Conservation Service. 1984. Soil Survey of Wayne County, Ohio. Washington, DC.

- Smith, R.G., F.D. Menalled, and G.P. Robertson. 2007. Temporal yield variability under conventional and alternative management systems. Agron. J. 99: 1629–1634. doi: 10.2134/agronj2007.0096.
- Social Science Computing Cooperative (SSCC). 2016. Mixed Models: Diagnostics and Inference. Univ. Wisconsin Madison.

- Stöckle, C.O., A.R. Kemanian, R.L. Nelson, J.C. Adam, R. Sommer, and B. Carlson. 2014. CropSyst model evolution: From field to regional to global scales and from research to decision support systems. Environ. Model. Softw. 62: 361–369. doi: 10.1016/j.envsoft.2014.09.006.
- Taylor, K.E., R.J. Stouffer, and G.A. Meehl. 2012. An overview of CMIP5 and the experiment design. Bull. Am. Meteorol. Soc. 93: 485–498. doi: 10.1175/BAMS-D-11-00094.1.
- van der Kooi, C.J., M. Reich, M. Löw, L.J. De Kok, and M. Tausz. 2016. Growth and yield stimulation under elevated CO₂ and drought: A meta-analysis on crops. Environ. Exp. Bot. 122: 150–157. doi: 10.1016/j.envexpbot.2015.10.004.
- Van Doren, D.M., G.B. Triplett, and J.E. Henry. 1976. Influence of Long Term Tillage, Crop Rotation, and Soil Type Combinations on Corn Yield. Soil Sci. Soc. Am. J. 40: 100. doi: 10.2136/sssaj1976.03615995004000010027x.
- Vicente-Serrano, S.M., S. Beguería, and J.I. López-Moreno. 2010. A multiscalar drought index sensitive to global warming: The standardized precipitation evapotranspiration index. J. Clim. 23: 1696–1718. doi: 10.1175/2009JCLI2909.1.
- Vicente-Serrano, S.M., S. Beguería, J. Lorenzo-Lacruz, J.J. Camarero, J.I. López-Moreno, C. Azorin-Molina, J. Revuelto, E. Morán-Tejeda, and A. Sanchez-Lorenzo. 2012. Performance of drought indices for ecological, agricultural, and hydrological applications. Earth Interact. 16: 27 pp. doi: 10.1175/2012EI000434.1.
- Wallace, J.M., A. Williams, J.A. Liebert, V.J. Ackroyed, R.A. Vann, W.S. Curran, C.L. Keene, M.J. VanGessel, M.R. Ryan, and S.B. Mirsky. 2017. Cover crop-based, organic rotational no-till corn and soybean production systems in the mid-Atlantic United States. : 1–21. doi: 10.3390/agriculture7040034.
- Walsh, J., D. Wuebbles, K. Hayhoe, J. Kossin, K. Kunkel, G. Stephens, P. Thorne, R. Vose, M. Wehner, J. Willis, D. Anderson, S. Doney, R. Feely, P. Hennon, V. Kharin, T. Knutson, F. Landerer, T. Lenton, J. Kennedy, and R. Somerville. 2014. Ch 2: Our Changing Climate. p. 19–67. *In* Melillo, J.M., Richmond, T. (T. C., Yohe, G.W. (eds.), Climate Change Impacts in the United States: The Third National Climate Assessment. U.S. Global Change Research Program.
- Williams, A., M.C. Hunter, M. Kammerer, D.A. Kane, N.R. Jordan, D.A. Mortensen, R.G. Smith, S. Snapp, and A.S. Davis. 2016. Soil water holding capacity mitigates downside risk and volatility in US rainfed maize: Time to invest in soil organic matter? PLoS One 11: 1–11. doi: 10.1371/journal.pone.0160974.
- Williams, D.M., H. Blanco-Canqui, C.A. Francis, and T.D. Galusha. 2017. Organic farming and soil physical properties: An assessment after 40 years. Agron. J. 109: 600–609. doi: 10.2134/agronj2016.06.0372.
- Wolfe, D.W., D.W. Henderson, T.C. Hsiao, and A. Alvino. 1988. Interactive Water and Nitrogen Effects on Senescence of Maize. I. Leaf Area Duration, Nitrogen Distribution, and Yield. Agron. J. 80: 859–864.

- Xu, H., T.E. Twine, and E. Girvetz. 2016. Climate Change and Maize Yield in Iowa. PLoS One 11: 1–20. doi: 10.1371/journal.pone.0156083.
- Zipper, S.C., J. Qiu, and C.J. Kucharik. 2016. Drought effects on US maize and soybean production: spatiotemporal patterns and historical changes. Environ. Res. Lett. 11: 094021.

Chapter 6

Epilogue

Grad school has been one of the most stimulating and enriching experiences of my life. I have loved it in large part because it has given me the opportunity to think and learn about such a wide variety of interesting topics: how plants grow, how water moves in soil, how to inspire students to think critically about agroecological systems, how to shape a big-picture scientific narrative, how to format a legend in ggplot – the list could go on and on. Most importantly, grad school has been valuable because I've been surrounded by smart, diligent people who are able to act on their values while avoiding dogma. I have come to believe that this set of qualities is uniquely prevalent among scientists and practitioners who engage with the natural world, which makes me excited to continue working in agricultural science.

As I wrap up this phase and think ahead to the next, I have been reflecting that the value of my work depends on its impact on people. Often, agriculture and the environment are discussed with respect to their biophysical, environmental, and economic characteristics. These are important, but they primarily matter insofar as they are relevant to *people* today and in the future. Completing my dissertation is a good opportunity to remember that this work, while often caught up in the minutiae of ecophysiology or statistics, is ultimately relevant to a few basic human needs: nutritious food, clean water, dignified livelihoods, and beauty.

Of course, the people affected most comprehensively by the food system are farmers themselves, who depend on agriculture for both sustenance and income. Whether on a 200-cow Pennsylvania dairy or a 2-hectare smallholding in the developing world, farmers should be able to earn a living wage for honest work. Already, farmers must balance conflicting priorities: short-term economic viability, long-term sustainability, uncertain land tenure, regulations, stress, family life, etc. In the United States, commodity crop production is a high-volume, low-margin business, which limits farmers' economic flexibility. Yet, society continues to demand more of farmers, from ever-cheaper food to water-quality protection, climate mitigation, and reduced chemical use. This is a wicked problem crying out for creative solutions.

Going forward, I hope to work with farmers, policymakers, and other food system actors to find these solutions. At the agronomic production level, my goal is to build collaborative innovation

teams including farmers, other researchers, extension, and industry. Working together, we will iteratively test new cropping systems and management strategies to fine-tune their productivity and environmental performance. These teams will serve as a platform for engagement with broader issues such as market structure, supply chains, and policy. Yes, the barriers to systemic change are formidable, but groups of committed and hopeful people have overcome bigger challenges in the past. I am confident that such collaborations can make a difference for at least some people and landscapes. And I am hopeful that, over the course of my career, these efforts can contribute to achieving nutritional security for all, a thriving environment, and a prosperous agriculture.

Appendix

Root Pit Data

The effects of the cover crop treatments on maize rooting density by depth was assessed with the root intercept method. Root pits were dug with a backhoe following maize harvest in 2015 (10/6-10/15). Pits were dug between the two rows of maize in the inner sampling area. Pits were one meter deep except where bedrock restricted their depth. Pit faces were parallel to and directly below the maize rows. Following excavation, the faces of the pit were scraped with a shovel to remove smeared areas that would reduce visibility of intersecting roots.

Up to four faces were photographed in each pit (north and south wall, east and west side). Only clean, vertical faces directly below the maize plants were photographed; those that caved in were ignored. Photographs were taken perpendicular to the face with a camera mounted a constant distance from a 30 cm by 30 cm metal frame. Photographs were taken at three depths: 0-30 cm, 30-60cm, and 60-90 cm. The number of root intersections at each depth was counted on a computer screen by a single research assistant to ensure consistency.

Results were analyzed with linear models using the lm function in R and are presented in Figure A-1. Drought increased the number of root intersections by 35.0% in the top 30 cm (p = 0.0103) and by 45.6% at 30-60 cm (p = 0.0947), though the effect was marginal in the latter. Drought did not affect the number of root intersections at 60-90 cm (p = 0.988). There were more root intersections following rye than following fallow at both 0-30 cm (26.6% increase, p = 0.0918) and 30-60 cm (73.9% increase, p = 0.0585), though in both cases the difference is only marginally significant. Clover did not lead to a different number of root intersections than the fallow treatment at any depth.

These results indicate that both water and N limitation stimulated additional root growth, as is commonly seen. However, it is unclear to what degree this enhanced root exploration would have improved maize water access, given that the top 40 cm of soil became very dry in the drought treatment. This greater root allocation may have been beneficial early on during the drought event, when water was still stored in the upper layers. However, building these additional roots diverted

carbon resources from aboveground growth. Enhanced root proliferation in deeper soil layers would have been more likely to improve maize water relations.



Figure A-1: Root intersections per square inch of vertical soil face under the maize row, by cover crop and drought treatment. Root pits were dug following maize harvest in 2015 (10/6-10/15).

VITA

MITCHELL CLAYTON HUNTER

Department of Plant Science	mchunter@psu.edu, 814-865-9021		
The Pennsylvania State University University Park PA 16802	www.ecoagronomy.org		
	i witter. @ccougronoinist		
EDUCATION			
Penn State University, University Park, PA Ph.D. in Agronomy, Minor in Ecology	2018		
Harvard University, Cambridge, MA B.A. in Government , Magna Cum Laude, Phi Beta Kappa	2009		
University of Minnesota, Minneapolis, MN	2006		
Deep Springs College, Deep Springs, CA	2003-2005		
PROFESSIONAL EXPERIENC	ES		
Graduate Research Assistant, Department of Plant Science, Penn State National Science Foundation (NSF) Graduate Research Fellow Instructor, Department of Plant Science, Penn State Federal Policy Manager for Conservation, American Farmland Trust, Was Greenhouse Gas Reduction Coordinator, Harvard University, Cambridge,	2012-2018 2012-2017 2016 shington, DC MA 2009-2010		
GRANTS and FELLOWSHIPS	8		
NSF Graduate Research Fellowship, NSF, Arlington, VA (\$100,000) G.A. Harris Research Instrumentation Fellowship, Decagon Devices, Pul	2012-2017 Iman, WA (\$5,000) 2015		
HONORS and AWARDS			
Crop Science Graduate Student Scholarship, Crop Sci. Soc. Am. Alumni Association Dissertation Award, Penn State Graduate School (GS) Outstanding Dissertation Award, Penn State College of Agricultural Scien Paul Hand Award for Graduate Student Research Achievement, Penn St Best Graduate Student Paper, Global Climate Change Community, Am. Sc Harold F. Martin Graduate Assistant Outstanding Teaching Award, Per Future Leaders in Science Award, ASA-CSSA-SSSA Paul Hand Award for Graduate Student Teaching Achievement, Penn St	2018 2018 2018 2018 2018 2018 2018 2017 2016 2016 2016 2015 2015 2015		
TEACHING			
Graduate School Teaching Certificate, Penn State University Lead Instructor - Principles of Weed Management, Penn State University Co-Instructor - Plant Ecology, Penn State University	2017 2016 2014		
SERVICE			
Graduate Student Representative to Board of Trustees, Am. Soc. of Agro Science Policy Committee, Am. Soc. of Agronomy Reviewer, Ag. J., Crop Sci., PLOS One, Clim. Chg., Ren. Ag. Food. Sys. Graduate Student Leadership Committee, Penn State Dept. of Plant Scient Planning Committee, Sustainable Intensification Community, Am. Soc. of A Farm Bill Task Force, Agronomy, Crop, and Soil Science Societies Steering Committee, Sustainable Food Systems Program, Penn State	onomy 2017-2018 2018 2014-2017 Agronomy 2016-2017 2017 2014-2016		