A HOLISTIC ASSESSMENT FOR BENCHMARKING THE SUSTAINABILITY OF MAIZE PRODUCTION IN THE US MIDWEST

BY

SARA MAGDALENA RICCETTO AGUIRREZABALA

THESIS

Submitted in partial fulfillment of the requirements
for the degree of Master of Science in Crop Sciences
in the Graduate College of the
University of Illinois at Urbana-Champaign, 2018

Urbana, Illinois

Master's committee:

Assistant Professor Cameron Pittelkow, Chair
Professor Adam Davis
Assistant Professor Kaiyu Guan

ABSTRACT

Achieving efficient and environmentally sustainable agricultural systems is a key issue for the US Midwest, the world's largest maize producer. In this study we benchmarked the sustainability of maize production using an integrated set of performance criteria to identify regions where desirable outcomes are occurring, while also highlighting opportunities for improvement. We calculated the following indicators for Illinois (IL), Indiana (IN), and Iowa (IA) evaluated from 1995-2012: Yield gaps (Yg), water productivity (Wp), nitrogen partial productivity (Npp), nitrogen surplus (Ns), minimum yield potential (Myp) and coefficient of variation of yield (Cv). Our analysis of this geospatial dataset revealed high spatial and temporal variability of these indicators, with several notable trends detected over the study period. Statewide averages ranged from 20.1-24.7% for Yg, 13.8-14.7 kg mm^{-1} for Wp, 13.1-17.3 kg ha^{-1} for Ns, 46.9- 53.2 for Npp, 14.4-17.9 % for Cv and 6- 7.3 Mg ha^{-1} for Myp. Southern IA was generally the region associated with a decreasing performance across indicators, while western IA was the region that showed the greatest improvement over time. When integrating different indicators, coldspots (defined as regions with undesirable outcomes) were roughly six times as frequent as hotspots (regions with desirable outcomes), highlighting the challenge in balancing agronomic and environmental goals to achieve sustainable production in this region. In particular, southern regions of the three states were associated with the most concerning performance, while the northern regions exhibited more favorable outcomes. When pairwise relationships between Yg, Wp and Npp were evaluated to identify potential synergies and tradeoffs, our results showed that Yg and Wp were positively related in most of the study area, while no consistent synergies or tradeoffs were detected between Yg and Npp, and between Wp and Npp. This study is one of the first to assess maize yield performance at the county-scale with resource use efficiency and

environmental indicators in a holistic analysis to advance sustainable intensification efforts for this region.

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1. INTRODUCTION

Agricultural systems are facing the global challenge of increasing crop production to meet growing food demand (FAO, 2012; Hunter et al. 2017; Tilman et al., 2011). Given land and resource limitations which would be required to support global cropland expansion, the intensification of agriculture (i.e. increasing yields on existing land) is promoted as a promising strategy (Garnett et al. 2013; Rockstrom et al. 2017). Yet, it is widely recognized that further boosts in agricultural productivity must be achieved in an environmentally sustainable way (Foley et al 2011; Rockstrom et al. 2017; Tilman et al 2011). Major challenges facing modern agriculture include pollution of water bodies due to nutrient losses, elevated levels of soil greenhouse gas (GHG) emissions which contribute to climate change, and excessive consumption of water resources and nitrogen (N) fertilizer, both of which are necessary to support high yields but are often associated with low efficiencies at the global scale (Foley et al. 2011; Mueller et al., 2012; West et al. 2014). Moreover, the increasing climate variability coupled with extreme weather events will threaten crop yields in the future (Jin et al., 2017; Lesk et al., 2016; Lobell and Field 2007; Urban et al., 2012), highlighting the need to strive for increased crop productivity while maintaining yield stability under adverse environmental conditions.

Sustainable intensification (SI) is generally referred to as the process of increasing agricultural production without the need of converting non-agricultural area and without detrimental effects on the environment (Garnett et al., 2013; Pretty and Bharucha, 2014). Despite increasing calls for SI in agriculture, few assessments of major crop production regions of the world have been performed to simultaneously evaluate changes in crop productivity, resource use efficiencies, and environmental quality, particularly across large spatial scales and multiple sustainability indicators. A recent global analysis of leverage points for improving food security while reducing environmental impacts found that reducing yield gaps, GHG emissions, fertilizer application and increasing water productivity are among some of the key strategies to enhance sustainability while increasing food production (West et al., 2014). The spatial variability reported by West et al. (2014) revealed that some of the world's most productive cropping systems are associated with disproportionately large environmental footprints, highlighting that improvements in each of these practices in specific areas could have major impacts on caloric increases or reductions in environmental costs (i.e: yield gap reductions in under-performing regions of Africa, East Europe and Asia, or reductions in fertilizer application in China, US and India). To support the development of more targeted and actionable strategies at a regional scale, studies which integrate across indicators considering the spatial variability of outcomes are of critical importance to guide future SI efforts.

Maize production in the US Midwest holds national and global importance: the states of Illinois (IL), Indiana (IN), and Iowa (IA) account for 40% of US maize production (NASS, 2017) and 14% of total global production (USDA, 2017). To our knowledge, a holistic analysis linking crop yield performance with resource use efficiency and environmental indicators at the county-level scale has not been performed for this region, which may limit the progress towards sustainably meeting future food security challenges. Regional studies have addressed important issues associated with maize production in the US Midwest: Lobell et al. (2017) assessed yield gaps ("yield heterogeneity") across and within fields through time, which revealed that yield heterogeneity has increased over the last 20 years. Separately, Williams et al. (2016) evaluated maize yield stability in terms of minimum yield potential and yield volatility, and the underlying factors affecting it, reporting that higher yield stability is associated with higher soil water holding capacity. Nitrogen balances in the Midwest have been quantified by David et al. (2010), suggesting there is a large amount of spatial variability in N leaching depending on N fertilizer inputs and river runoff. However, to support agricultural intensification efforts while minimizing environmental costs, it is necessary not only to quantify individual indicators, but to use an integrated approach that captures the spatial variability of the relationships and changes over time. Indeed, because crop production and environmental goals are often conflicting (Tilman et al., 2011), such a holistic framework is critical for assessing synergies and tradeoffs between indicators.

In this study we benchmarked the sustainability of maize production using an integrated set of performance criteria to identify regions where desirable outcomes are already occurring, while also highlighting opportunities for future improvement. We synthesized publicly available data at the county-level for the US Midwest to evaluate the following 6 indicators from 1995-2012: yield gaps, yield stability, water productivity, nitrogen partial productivity, and nitrogen surplus. Our specific objectives were to 1) identify regions associated with higher productivity, resource use efficiencies, and yield stability, 2) determine regions where indicators improved in time, 3) evaluate whether it is easier to achieve sustainable than unsustainable production, and 4) assess whether there are positive synergies between Yg, Npp and Wp.

2. MATERIALS AND METHODS

2.1 Six indicators

A total of 6 indicators were calculated at the county level scale for the states of IL, IN and IA from 1995-2012. The indicators included in the analyses were: Yield gaps (Yg), two yield stability indicators (minimum yield potential (Myp) and coefficient of variation of yield (Cv)), N partial productivity (Npp), water productivity (Wp), and N surplus (Ns). The indicators were calculated for a total of 268 counties with 10 or more years of yield data (90 counties in IL, 79 in IN and 99 in IA).

Yield data was retrieved from the National Agricultural Statistics Service (NASS) of the US Department of Agriculture (USDA). This dataset was used for mean yield and water productivity calculations at the county-level.

Yield gaps were defined as the difference between mean yield and maximum attainable yield based on farm-level records, as follows:

$$Yg\ (\%) = Maximum\ yield\ (Mg\ ha^{-1})\ -\ Mean\ yield\ (Mg\ ha^{-1})\ /\ Maximum\ yield\ (Mg\ ha^{-1})\ *\ 100,$$

where maximum yield is the top 5% of yield reported for each county, and mean yield is the average yield obtained for each county. The database used to calculate percent gaps was obtained from the Risk Management Agency (RMA) as reported by Lobell et al. (2014). Yield records and sowing date information for 100 fields per county from 1995-2012 were used in this study.

Nitrogen input data was retrieved from the Nutrient Use Geographic Information System (NuGIS). This is a publicly available spatial database with the goal of assessing nutrient balances for crop production in different regions of the world (IPNI, 2012). This database is built based on county-level fertilizer sales data. Data on N inputs was available for the census years of 1997, 2002, 2007, 2010, 2011 and 2012. For this study, the last three consecutive years were averaged. This database reported county-level data on inorganic N inputs (fertilizer), estimated annual recovery of N from organic inputs (manure), maize yield, maize area harvested, and maize grain N concentration. For this study, N recovered from manure averaged 5.6% of inorganic inputs for all counties-years. Yield reported in the NuGIS dataset was used for the calculations of N surplus and N partial productivity as follows:

$$Ns\ (kg\ ha^{-1}) = Inorganic\ N\ (kg\ ha^{-1}) + Organic\ N\ recovered\ (kg\ ha^{-1}) - N\ removed\ (kg\ ha^{-1}),$$

where Inorganic N was N fertilizer, Organic N recovered was the N recovered from manure, and N removed was the N exported via grain, assuming a grain N concentration of 1.2 % (0.67 lb bu^{-1}).

In order to characterize resources use efficiency, we defined two indicators that could explain N and water use efficiency. We defined them as N partial productivity (Npp) and Water productivity (Wp). Nitrogen partial productivity was defined as the amount of yield obtained per kg of N applied (organic + inorganic). Results of *Ns* higher than 50 kg ha^{-1} and *Npp* higher than 100 kg kg^{-1} were excluded from the analysis.

$$Npp\ (kg\ kg^{-1}) = Yield\ (kg\ ha^{-1}) / Total\ N\ inputs\ (kg).$$

Water productivity is defined as the amount of maize obtained per mm of water:

$$Wp\ (kg\ mm^{-1}) = maize\ yield\ (kg\ ha^{-1}) / total\ water\ (mm),$$

where total water is the sum of precipitation and available water in the root zone (awrz). Precipitation data was retrieved from gridded weather dataset PRISM (Oregon State University and RMA) and was averaged to the county level. The period of time considered to account for precipitation was from sowing day to 120 days after sowing (DAS). Sowing day was determined averaging the planting day reported for 100 fields per county by the RMA (Lobell et al., 2014) for the period from 1995-2012. The awrz was obtained from gssurgo at a spatial resolution of 10 m, and awrz was calculated for the maize area within each county. Cropland data was obtained from NASS cropland data layer (spatial resolution 30 m) and the year of highest area of maize planted was used for each state (2012 for IA, 1999 for IL, and 2001 for IN). Calculations of average awrz where performed using zonal statistics in Arcgis 10.4 (Environmental Systems Research Institute, 2016), while precipitation was assumed homogeneous within each county.

Minimum yield potential and CV of yield (%).

Counties Myp and Cv are measures of yield stability that characterizes the resiliency of the agricultural systems. These indicators were calculated within state. Myp is defined as the minimum yield obtained under the most unfavorable environmental conditions. The concept of environmental index in used to do the calculations (Finlay and Wilkinson, 1963), where an enhancement in environmental conditions (edaphic or climatic) determine higher values of environmental indexes. Following Williams et al. (2016) approach, we ranked the state-wide yields and used a linear mixed effect model to characterize counties yield responses to increases in environmental indexes (Annex I). The intercept of the line determines the lowest yield obtained for a county under low suitable conditions, while the slope represents the yield response to better environmental conditions. Counties cv were calculated as:

Cv (%)=Yield standard deviation / mean yield

2.2 Hotspots and coldspots analysis

The hotspots and coldspots analysis has been previously used by Qiu and Turner (2013), who applied this method as a way to assess the richness of ecosystem services encountered in the Yahara watershed in Wisconsin. Similarly to Qiu and Turner (2013), we defined hotspots as those regions where desirable outcomes are occurring, while coldspots are those regions where undesirable outcomes are obtained. Hotspots were defined as those regions where it was possible to find desirable attributes in the upper 20, 30 and 40% percentile (Wp, Npp, Myp) and undesirable attributes in the lower 20, 30 and 40% percentile (Ns, Yg and Cv), while coldspots were defined in the opposite way. In order to add more flexibility to these definitions, we used different number of indicators that met the criteria. This means that within each percentile, hotspots and coldspots could be defined as those regions where at least 4 of the calculated indicators (6) fell in that percentile, up to 6 indicators falling in that percentile. Comparisons were done within each state. This is a parsimonious but effective method that allowed us to identify regions with high and low supply of desirable indicators, thus revealing the sustainable performance of each county.

2.3 Synergies and tradeoffs analysis

Synergies and tradeoffs analysis evaluates the spatial correlations between indicators. One possible method to evaluate such relationships among ecosystem services is factor analysis which was applied by Qiu and Turner (2013) to evaluate synergies and tradeoffs occurring among 10 different ecosystem services in a watershed of WI. This study also used Spearman's correlations between services to quantify their degree of relationship. Similarly, we estimated Pearson's pairwise correlations using R statistical software. Synergies were defined as a positive correlation between desirable outcomes (i.e Wp and Npp) or negative correlation between a desirable and undesirable outcome (i.e Wp and Yg), while tradeoffs were considered those relationships that determined a positive outcome in one indicator and an undesirable in another indicator. Synergies and tradeoffs were classified into strong (r > |0.6|), medium (r = |0.2- 0.6|), or weak relationship (r = -0.2- 0.2).

3. RESULTS AND DISCUSSION

3.1 Benchmarking sustainability indicators

Our holistic analysis focused on agronomic and environmental aspects of maize production, while also considering yield stability metrics which will become increasingly important under climate change. Mean data for each indicator over the study period is presented in Table 1. Results for each indicator are discussed individually below.

Table 1: Mean of the indicators by state for the period 1995-2012.

	Ymax (Mg ha^{-1})	Ymean (Mg ha^{-1})	Yg (%)	Wp (kg mm^{-1})	Ns (kg ha^{-1})	Npp (kg kg^{-1})	Cv (%)	Myp (Mg ha^{-1})
IL	11.7	9.1	22.8	14.4	13.1	53.2	17.9	6.0
IN	11.4	8.8	24.7	14.7	17.3	46.9	16.8	6.1
IA	11.9	9.6	20.1	13.8	14.1	52.8	14.4	7.3

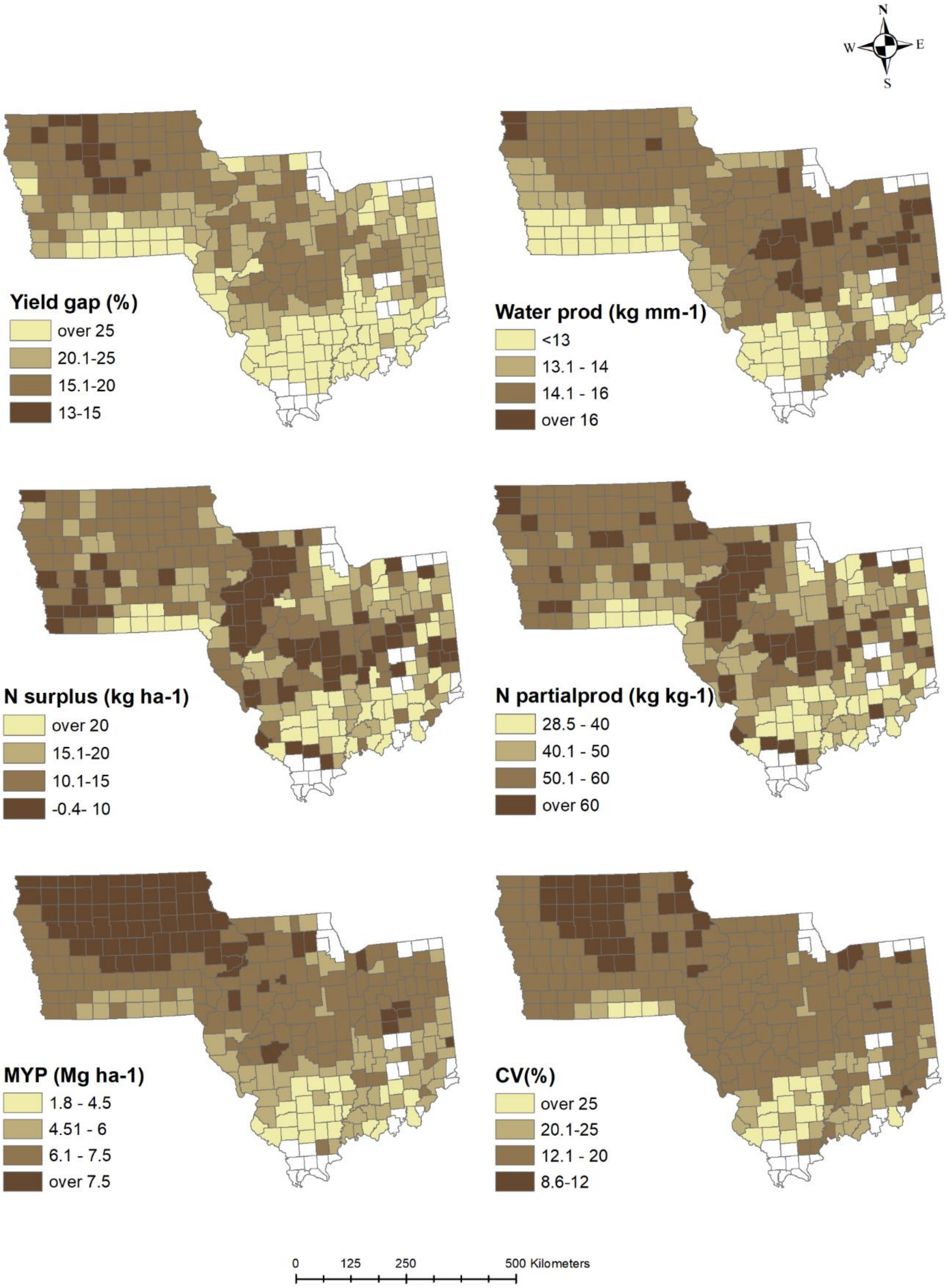

Figure 1: Spatial pattern of the mean indicator values for the period 1995-2012.

In our study, the average Yg for each state over the study period was greater than 20%, which is relatively large for a highly-productive cropping system located on fertile soils and utilizing modern technologies (Table 1). Moreover, the spatial variability of Yg in this region was large (Fig. 1), with some regions having double the Yg compared to others. These results which are based on farmer-reported data are supported by the global yield gap atlas, which shows a 26% relative yield gap for this climate zone (http://www.yieldgap.org/united-states). While the latter estimate was determined with process-based crop models using data on local climate, soil properties, and management practices to estimate regional yield potential, recent research on soybean yield gaps in this region suggests that empirical and model-based methods can be expected to produce similar results (Rattalino Edreira et al. 2017). In our study, the lower values of Yg (13-20 %) were located in the upper region of IA, while values above 25% were located in the southern region of the three states. Although many counties in northern IA and central IL had small Yg, the majority (62% of all the counties analyzed) had Yg over 20%. Similar to our findings, Lobell and Azzari (2017) used satellite-based yield estimation methods and observed higher yield heterogeneity in lower yielding regions, which corresponded to the southern regions of IL, IN, and IA.

Completely closing yield gaps is unlikely due to natural variations in environmental conditions and technological constraints, in addition to economic considerations as the most profitable returns to crop management may occur below yield potential (Farmaha et al., 2016; Lobell et al. 2009). However, this dataset can be used to estimate short-term potential production increases in the US Midwest by comparing the average Yg to the smallest Yg. We observed that relatively small Yg values of 13% are possible to achieve in this region compared to an overall average Yg of 22.4%, suggesting that an increase of nearly 10% in production might be attained if the limiting factors to production are addressed. This could be accomplished by more targeted studies investigating the underlying factors contributing to

Yg in a region with the aim of identifying management practices which increase yields under similar environmental conditions. For example, Rattalino Edreira et al. (2017) determined that planting date, tillage, and foliar fungicide and/or insecticide application were explanatory causes for yield variation in half or more of 10 technology extrapolation domains for soybean production in the US Midwest.

Agricultural systems are highly dependent on available soil water to sustain crop growth and increase production. There is a pressing need to optimize the use of available water resources, as water shortages are expected to occur in many regions of the world as a response to increased temperatures and more variable precipitation patterns (Altieri et al., 2015; Dai, 2013). Water productivity reflects the amount of water used per unit of maize grain production, providing an estimate of the total water footprint associated with rainfed agriculture, compared to crop water use efficiency (WUE) which is based primarily on evapotranspiration. Quantifying Wp can help identify system inefficiencies due to excessive water use or yield limitations by low water use (Carr et al., 2016). As shown in Fig 1, Wp values ranged from 10 to 17 kg mm^{-1}, which reflects a relatively low amount of variation in this indicator compared to others. The higher values of Wp were found in high yielding regions, whereas the lower values were located in the southern regions of the three states.

Changes in Wp were mainly driven by changes in yield, as the region is quite homogeneous in terms of available water in the root zone and precipitation during sowing and maturity (120 DAS) (Annex I). The range of Wp for this study was lower than that reported in the Yield Gap Atlas (an average of 19 kg maize mm^{-1} of water for this region), mainly because of differences in the methods of calculation. Our present study only considered total water inputs instead of the amount of water that is available for crop use after discounting losses due to runoff, deep percolation, and water remaining in the soil profile after maize physiological maturity.

Nitrogen partial productivity reflects the amount of N applied per unit of maize grain production, and is not only important for the environmental costs associated with N losses but for its economic importance as a primary production input (Zhang et al., 2015b). Major efforts have been dedicated to improving the efficiency of N fertilizer, but for important production regions it remains low (Lassaleta et al. 2014). There is growing recognition that optimizing Npp is critical for SI efforts (Davidson et al., 2015; Zhang et al., 2015a), as higher Npp not only indicates higher fertilizer use efficiency but also a lower carbon footprint associated with the manufacturing and transport of N fertilizers, in addition to the direct emissions of soil nitrous oxide, a potent greenhouse gas. In our study, IL had the highest Npp overall, with notable values occurring in several counties in the northwest and center of IL (>60 kg maize per kg of N applied), which agrees with results reported by Fixen et al. (2015).

The pollution of water bodies due to nutrient losses is a major concern in the US Midwest. Nitrogen balances (Ns) is considered a robust and easy to calculate estimate of N losses (McLellan et al., 2018) as it reflects how much N is not being used by the crop and ends up being lost through leaching, volatilization, denitrification or surface runoff. Regions of higher Ns values are southern IL, IA and IN, as well as some counties in northern IN, while the opposite occurs with Npp, as these two indicators are strongly negative correlated (r = -0.90). Ns averaged 14.7 kg ha^{-1} for the study area, with very heterogeneous outcomes spatially. Only 23% of the counties presented Ns values below 10 kg ha^{-1}, while counties with values between 20-30 kg ha^{-1} represented almost the 60%. Ns values of over 30 kg N ha^{-1} were obtained in 15% of the counties (most of them located in southern IN), representing the less efficient regions in terms of N use. However, these values are well below the average values of N losses in the US reported by Lassaletta et al. (2014) of over 50 kg N ha^{-1}.

Climate change is expected to have negative impacts on agricultural systems (Jin et al., 2017; Lesk et al., 2016; Lobell and Field 2007; Urban et al., 2012). Moreover, interannual climate variability also leads to important yield fluctuations, thus yield stability is an important component to consider. Yield stability was characterized by analyzing the minimum yield obtained under the worst environmental conditions (Myp) and the variations in yield over time (cv). These values are the result of inherent soil physical, biological, and chemical characteristics as well as regional climatic conditions. The higher values of Myp correspond to the regions of northern IA, in the Des Moines Lobe. This region also presents very low values of cv (<13%), which reflects high yield stability in this area. In an opposite way, Myp decreases to the southern regions of each state, and the lowest values are located in southern IL and some southern counties of IN. Similar to what was reported by Williams et al. (2016), the higher yield variability (cv) is found in southern IL. Regions that obtain high yields under the most unfavorable weather conditions (i.e northern IA), will be the ones capable of not only supplying with food in times of stresses, but also ensuring economic and social stability.

3.2 Temporal changes of the indicators

To assess the temporal tendencies of the indicators, we calculated their percent change from the period 1995-1999 to 2008-2012 (Figure 2).

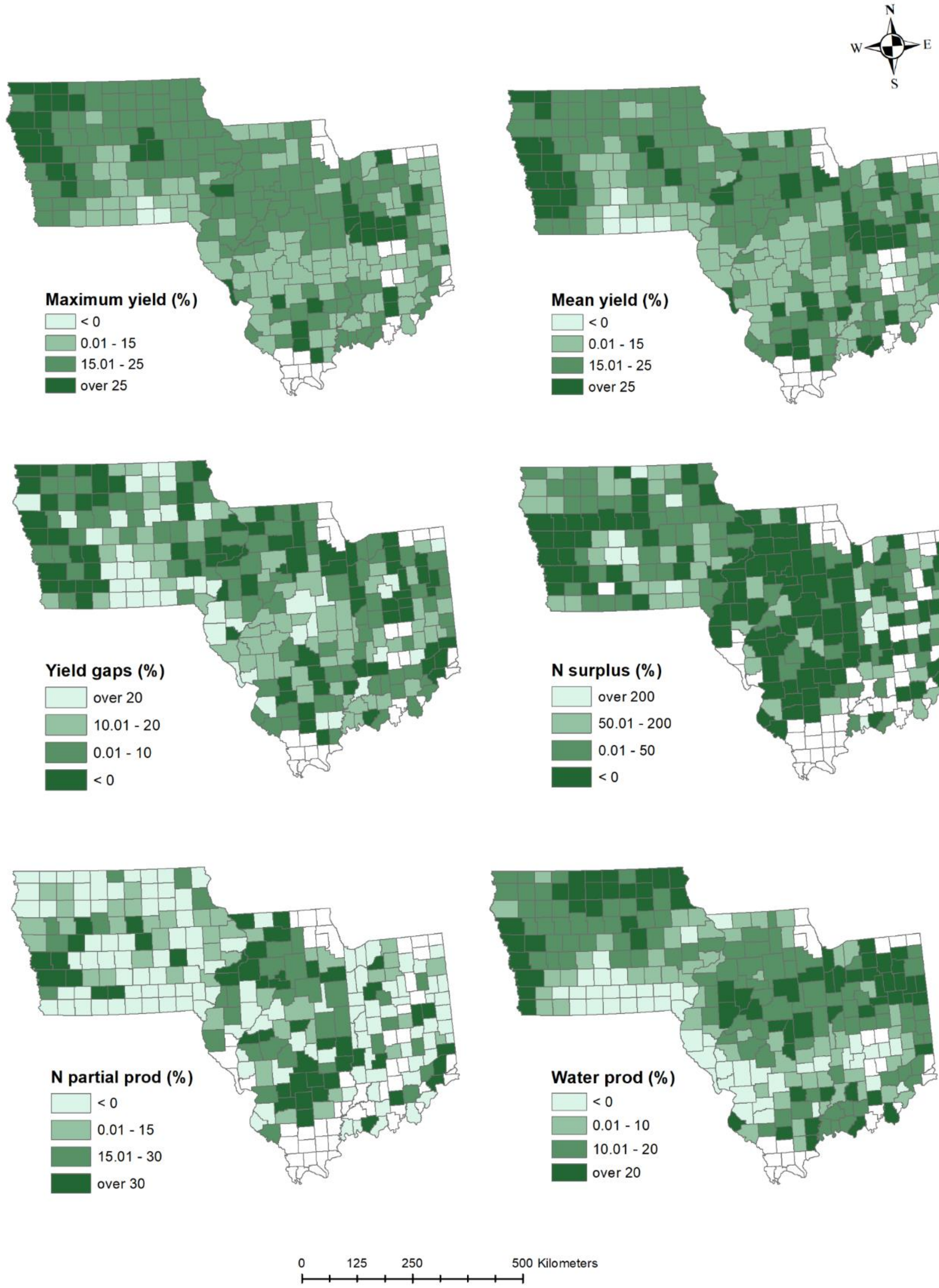

Figure 2: Temporal changes (%) of the six indicators from period 1995-1999 to period 2008-2012.

To meet the SI goals in the US Midwest, it is necessary to understand the trajectory of indicators over time and the spatial variation underlying these trends. In the case of crop productivity indicators, most of them improved in a positive way (mean yield increased 18.1%, maximum yield increased 17.1% and Wp increased 11.4%). However, there are some concerning results regarding Yg (6.7% increase), Npp (0.4% increase) and Ns (4.6% increase).

An increase in Yg reflects that the increase in maximum yield was higher than the mean yield increase (yield heterogeneity within a county has increased). This finding is consistent with Lobell and Azzari (2017), who found rising yield heterogeneity in maize production over time. Interestingly, in the current scenario where mean yields are increasing, it should be expected that Npp would increase as well. However, only 52 % of counties have increased Npp, while 55% have increased Ns as well, which reflects that the current rate at which these indicators are changing may not be enough to achieve N reduction goals.

The varied responses of different indicators do not allow generalizations that indicators are improving or worsening as a whole. However, there are concerning regional trends. In most cases, the areas identified as “good” from the average data analysis are also getting better over time (i.e: western IA), while areas with lower relative performance (i.e: southern IA) are getting worse over time.

Temporal trends, which reflect changes in land use and crop management, indicate that regions as western IA have improved both agronomic and environmental indicators over time. Southern IA, which has experienced a clear detriment in agronomic indicators, does not show a clear trend on environmental outcomes. Maize yields in this area have decreased over time, which influences the performance of most indicators. When integrating outcomes of individual indicators and their evolution in time, the data suggests that there are regions where achieving sustainable maize production will continue to be a challenge, and special efforts may need to be directed in order to increase yields and resource use efficiencies in these areas.

3.3 Integration of indicators: Hotspots and coldspots analysis

In order to analyze the behavior of the indicators as a whole and identify regions where sustainable production is occurring and areas where sustainability could be considered at risk, we performed a hotspot and coldspot analysis using the averaged indicators for the period 1995-2012 (Figure 3).

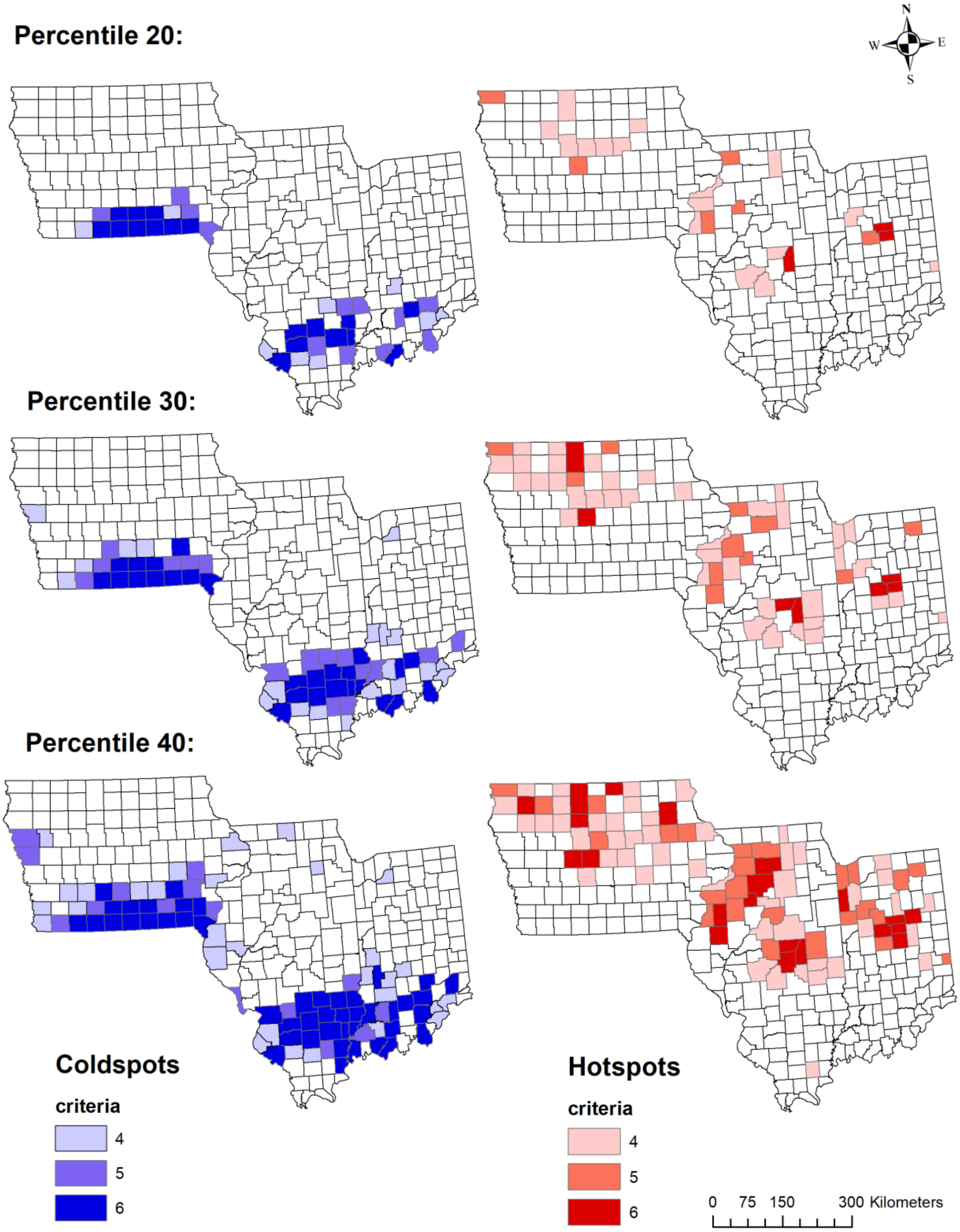

Figure 3: Coldspots representing areas of lower sustainability and hotspots representing more sustainable production

How to combine crop production and environmental indicators in a way that makes it possible to determine how spatial heterogeneity affects these relationships is a key issue in SI efforts. Some of the proposed methodologies is multicriteria analysis, which has been recently used in agriculture (Bonner et al., 2016; Qiu and Turner, 2013; Singha & Swain, 2016). A more simplistic approach determining hotspots and coldspots has also proved to be effective in determining areas of high or low supply of ecosystem services (Qiu and Turner, 2013). Following this method, we assessed the presence of desirable outcomes evaluating the performance of all the indicators as a whole.

A major finding revealed by our analysis is that in general the number of coldspots is higher than hotspots (relation of 6:1 under the strictest criteria), indicating that unsustainable production is more frequent than sustainable production. When using an intermediate criterion (30^{th} percentile and at least 5 criteria are met), almost ¼ of the counties of the most productive maize region in the US are considered coldspots. There are some studies that have reported concerning outcomes of individual indicators in some areas of this region as high yield heterogeneity (Lobell & Azzari, 2017), N losses (David et al., 2010) and yield volatility (Williams et al., 2016). However, it results surprising that there are no previous integrated assessments reporting such alerting results for this region.

From the regional patterns, we can see that the southern regions of the three states present the highest frequency of coldspots. These regions could be considered less suitable for maize production, as they are less efficient in the use of resources, the most heterogeneous in terms of productivity, the most contaminating in terms of N surplus, and the most vulnerable to external perturbations. Under a scenario of climate change, where drought effects in crops are gaining increasing importance over time (Zipper et al., 2016), these regions may suffer the most under more extreme climate events. Furthermore, the relative high rate of N application in relation to the yields obtained makes these regions a concern when trying to meet N efficiency goals. The negative outcomes obtained in the integrated assessment and their trends over time indicate that there is an opportunity for improvement in these areas, and an in-depth analysis on management practices would be appropriate in order to identify the limiting factors, or evaluate whether these regions are suitable for maize production.

3.4 Relationship between indicators: synergies and tradeoffs analysis

In order to understand the interaction between different indicators, it is necessary to analyze the relationships between indicators to identify tradeoffs. From the hotspots and coldspots analysis, we are able to see how indicators interact in a positive way (hotspots represent positive synergies) and how they interact in a negative way (coldspots represent negative synergies). However, this analysis does not consider possible tradeoffs between indicators.

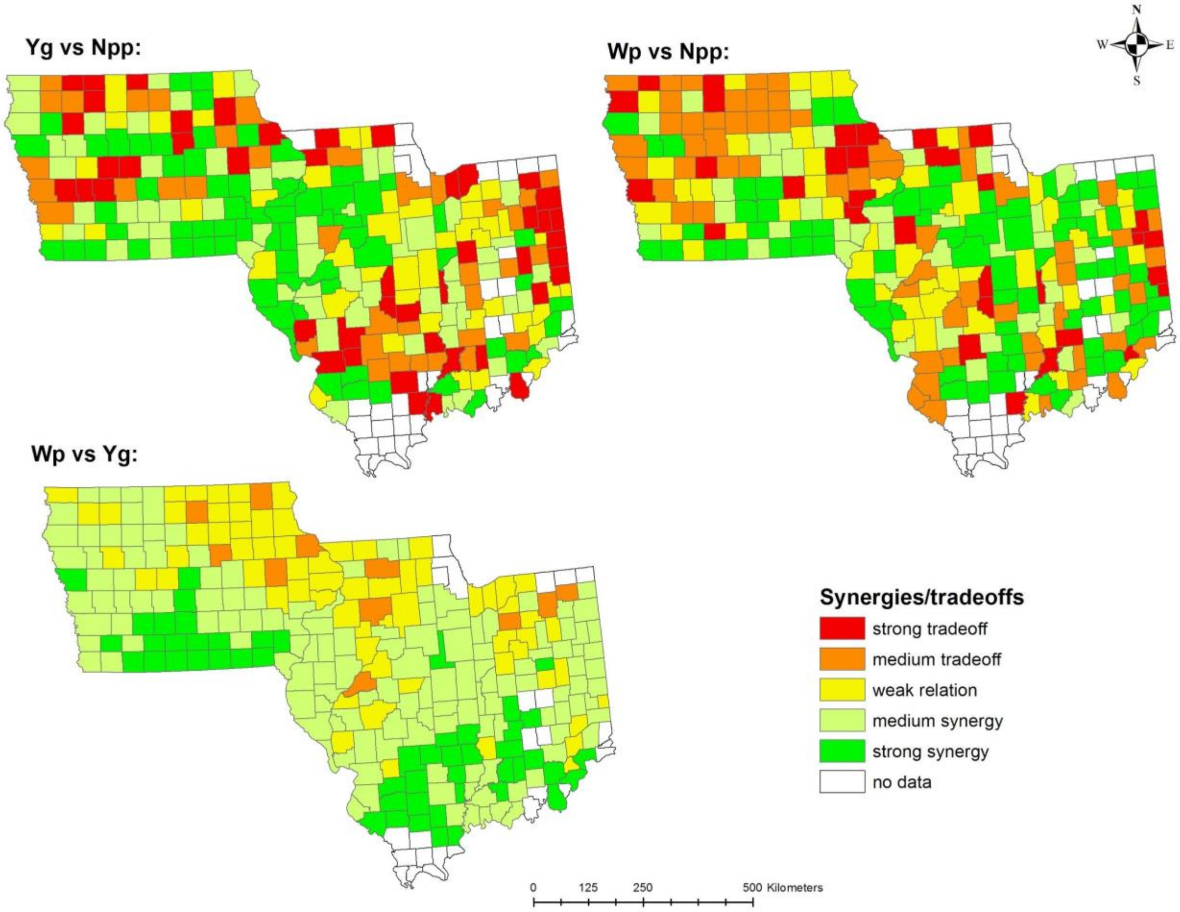

Figure 4: Synergies and tradeoffs between Wp, Npp and Yg.

Optimizing outcomes across multiple indicators requires knowledge that when aiming to improve some of these indicators, it can bring an improvement or a detriment in another indicator. Here we found that there are indicators that are clearly negatively correlated such as Wp and Yg (Fig 4) and others that are positively correlated. Interestingly, no indicators are consistently positively correlated in the whole study area. In this sense, if we aim to reduce Yg for example, this will certainly bring a positive outcome that is an improvement of Wp. Or vice-versa, if the goal was to increase Wp, a reduction in Yg could be expected. The relationship between Npp and Yg is not clearly defined, as synergies or tradeoffs among them vary regionally. In the case of Npp and Wp, these two indicators have a strong positive correlation in 30% of counties, while a strong negative correlation was found in 13% of them. Studies evaluating synergies and tradeoffs between ecosystem services have found that tradeoffs occur between crop production and water quality (Qiu and Turner, 2013).

From a practical perspective, knowing these relationships can allow us to plan for possible strategies to improve indicators. For example, in a region where the relationship between Wp and Yg is very strong, but the relationship between Npp and Yg is weak, we can know that management practices that improve Wp will have a more direct effect on Yg rather than it will have an improvement in N fertilization management. The knowledge on how indicators interact represent an additional tool to support management decisions when aiming for sustainable crop production, as this holistic approach requires the understanding of the benefits and consequences of improving the performance of every particular indicator.

3.5 Strengths and limitations of the study

The major strengths of this study are that the approaches used here can be applied to the farm level scale which will inform farmers of their current field performance and allow them to plan on future actions according to their outcomes. The availability of this information is not only useful to assess particular farmers, but can be used to support efforts from private companies and retailers to support sustainable production. This could be a tool to be implemented not only to maximize efficiencies in the use of resources, but could represent a marketing advantage, as farms could be certified to accomplish sustainable production. Crop production happening at farms is the first step in the production chain, and knowing the footprint of the product adds value to the final product. Furthermore, at the current scale at which this study was done, it can help policy makers to prioritize areas for improvement.

On the other hand, we recognize that this is not an exhaustive list and more holistic indicators are needed, particularly for environmental dimensions. Regarding environmental indicators, the calculation of Ns is too broad and more precise estimates of N losses through leaching or denitrification are needed to understand potential water quality impacts or contributions to GHG emissions and therefore global warming. Moreover, the spatial estimates of N fertilizer inputs derived from NuGIS are based on sales data which may not be perfectly accurate. However, this is the only publicly available data at the county scale and it has been used previously in spatial research (Metson et al., 2017).

4. CONCLUSIONS

In the present study, we quantified indicators that enabled us to assess maize production sustainability in one of the most important crop production regions of the world, the US Midwest. There are no previous studies that have linked agronomic and environmental outcomes in this region using publicly available data at the county level, which makes this study a stepping-stone for future efforts that aim to sustainable intensification of agricultural production. Our study effectively identified regions where sustainability at risk, and these regions are also where opportunities exit for improvement. Importantly, regions where sustainability is compromised are more frequent than regions where desirable outcomes occur. Further research needs to be done in order to identify the limitations in each region and take action to help solve them. While further work is necessary based on more holistic environmental criteria, results from this effort can be used as an initial tool to help decision makers and researchers identify important trends and prioritize sustainable intensification efforts in this region.

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6. APPENDIX- Figures

Figure A. 1: Temporal changes (%) of indicators from 1995-1999 to 2008-2012.

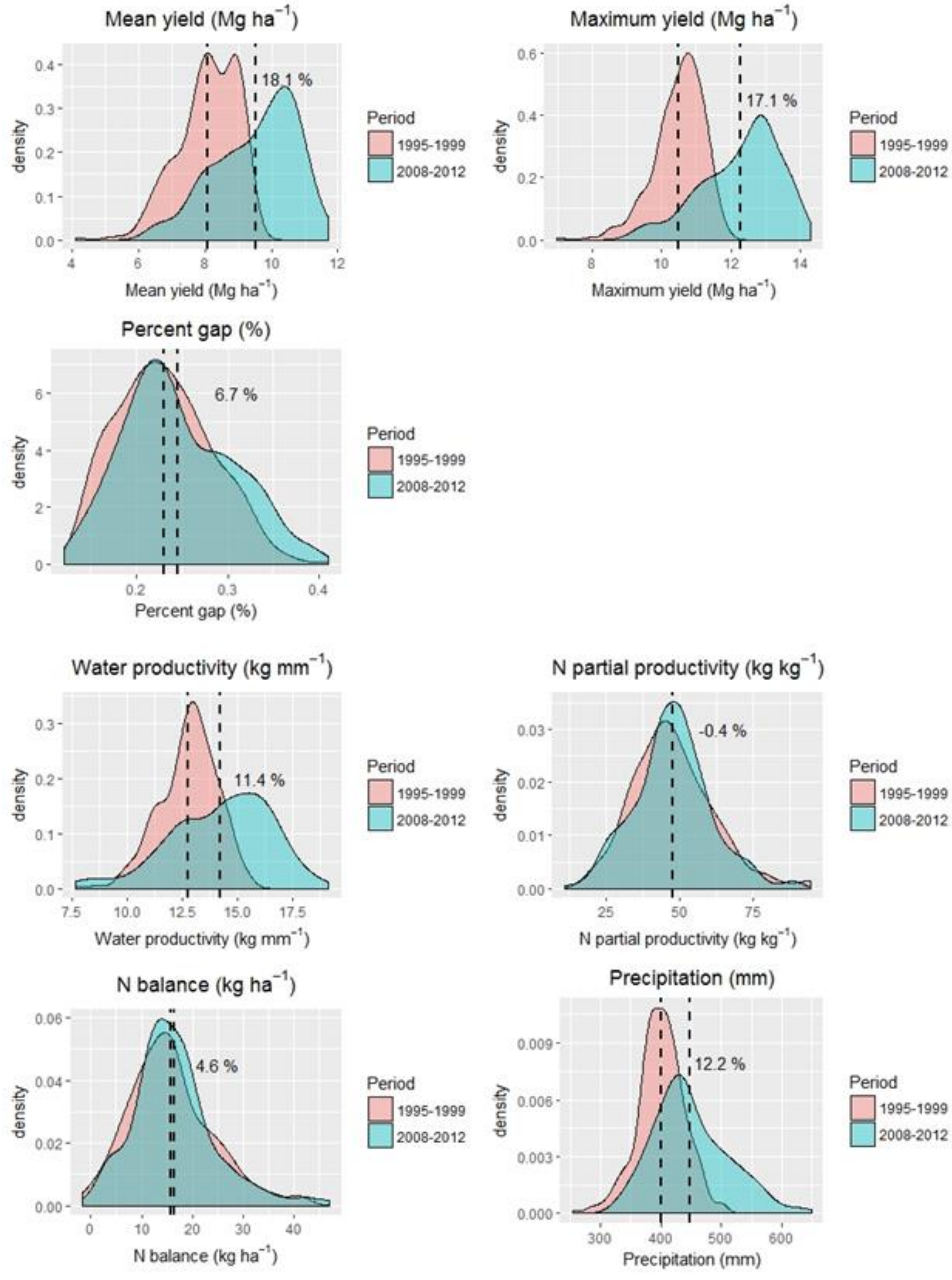

Figure A. 2: LME for the calculation of Myp

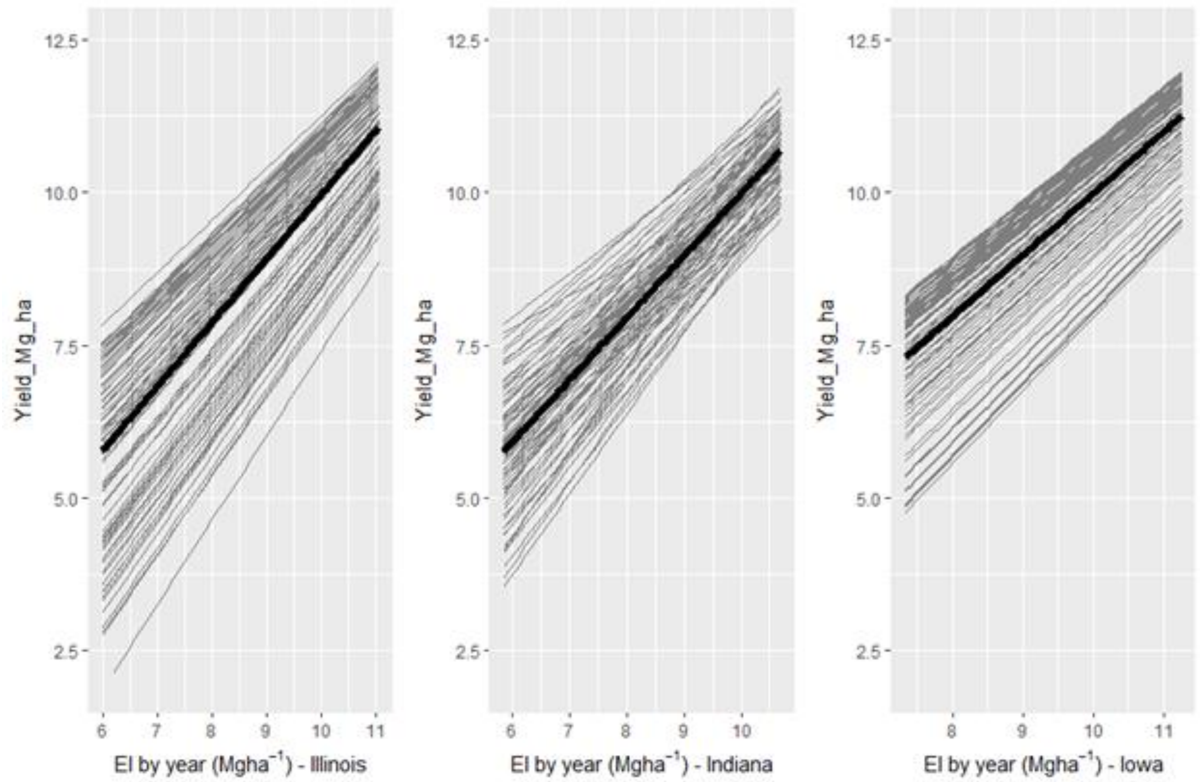

Figure A. 3: Spatial variability of components of Wp