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A Decade of Precision Agriculture Impacts on Grain Yield and Yield Variation

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Abstract. *Targeting management practices and inputs with precision agriculture has high potential to meet some of the grand challenges of sustainability in the coming century, including simultaneously improving crop yields and reducing environmental impacts. Although the potential is high, few studies have documented long-term effects of precision agriculture on crop production and environmental quality. More specifically, long-term impacts of precision conservation practices such as cover crops, no-tillage, diversified crop rotations, and precision nutrient management on field-scale crop production across landscapes are not well understood. To better understand these impacts, a 36-ha field in central Missouri was monitored for over a decade as both a conventional (1991-2003) and a precision agriculture system (PAS) (2004-2014). Conventional management was annual mulch-tillage in a 2 yr corn (Zea mays L.)-soybean [Glycine max (L.) Merr.] rotation. Key aspects of the PAS were the addition of no-tillage, cover crops, winter wheat (Triticum aestivum L.) instead of corn on areas with shallow topsoil and low corn profitability, and variable-rate nutrient (N, P, K, and lime) applications. The objective of this research was to evaluate how over a decade of PAS influenced temporal and spatial dynamics of grain yield. In the northern half of the field, wheat in PAS had higher relative grain yield and reduced temporal yield variation on shallow topsoil, but reduced relative grain yield on deep soil in the drainage channel compared to pre-PAS corn. In the southern half of the field where corn remained in production, PAS did not increase yield, but did reduce temporal yield variability. Across the whole field, soybean yield and temporal yield variation were only marginally influenced by PAS. Spatial yield variation of any crop was not altered by PAS. Therefore, the greatest production advantage of a decade of precision agriculture was reduced temporal yield variation, which leads to greater yield stability and resilience to changing climate.*

Keywords. *Precision conservation, Precision nutrient management, Integrated Precision practices, Crop production, No-till, Cover crops.*

Introduction

Most producers' primary justification for using precision agriculture is to improve profitability. Precision agriculture often can improve net return to grain crop production by either increasing yield, reducing yield variability, or reducing input costs (Bianchini and Mallarino 2002; Bongiovanni and Lowenberg-Deboer 2000; Scharf et al. 2011). A primary public-sector justification for precision agriculture is the premise of environmental protection through reduced agrochemical use, increased nutrient-use efficiency, and diminished off-field movement of soil and agrochemicals (Larson et al. 1997). From this premise, Berry et al. (2003) developed the idea of 'precision conservation', defined as using precision technologies and procedures, across spatial and temporal variability, to achieve conservation objectives. They further proposed that precision conservation ties efforts across multiple scales and is a key tool in achieving soil and water conservation goals. Since its inception, precision conservation has been evaluated in several short-term settings (Delgado et al. 2011), but its long-term potential has yet to be evaluated at a field scale.

Field and simulation studies conducted to determine the benefits of precision agriculture in general have been reviewed by Larson et al. (1997) and Pierce and Nowak (1999). Typically, these studies focused on a single management practice or input and compared spatially-varied to uniform management, with mixed results. Furthermore, few studies focused on environmental benefits. Often the likelihood that a precision agriculture approach improved production and/or reduced environmental impact depended on the degree of variability found in the experimental area. Decision rules developed for uniform management were sometimes inappropriate for use with a site-specific plan (Sadler et al. 2002). For some aspects of management (i.e., N), temporal changes had more impact than within-field spatial variability; thus temporal information may dictate the optimal management (Dinnes et al. 2002).

Significant spatial variability exists in many important soil and crop measurements on claypan-soil fields in Missouri, USA (Kitchen et al. 1999; Drummond et al. 2003; Sudduth et al. 2013). Yield within these fields varied as much as 4:1 from high- to low-yielding areas. Likewise, profitability was variable across fields (Massey et al. 2008). Yield-limiting factors varied from crop to crop, from year to year (i.e., weather), and from place to place within fields. Some soil and crop factors affecting yields are readily correctable (e.g., soil pH), and some are not (e.g., low plant-available water). Yield-limiting factors most often encountered on claypan-soil fields included soil/landscape, biotic, and management factors (Kitchen et al. 2005).

From 1991 to 2003, a 36-ha claypan-soil field in central Missouri was intensively spatially monitored for soil, plant, and water characteristics while being uniformly managed (i.e., no site-specific management). From this, a new management plan was developed and initiated during 2004 to 2014 where management was targeted to soil and slope characteristics varying within the field (Kitchen et al. 2005). The site-specific characterization of this field became the basis for this new plan called a 'precision agriculture system' (PAS). The hypothesis of this field-scale research was that PAS management would increase crop production and crop profitability, decrease crop production variability, and improve soil and water quality over the conventional uniform management of the years prior to PAS (pre-PAS). All of these hypotheses will be tested, but the objective of this paper is to compare the crop production and production variability of PAS with the uniform pre-PAS management. In 2014, a preliminary yield analysis of these data was presented at the International Conference on Precision Agriculture (Kitchen et al. 2014). This report is an update of that analysis and now includes 2013 and 2014 yield data, along with new tests and comparisons.

Materials and methods

Precision agriculture system development and management

The field site for the PAS investigation was a 36-ha claypan-soil field in central Missouri (39°13'45" N, 92°7'2" W). From 1991 to 2003, the field had conventional uniform management (Table 1) and was intensively monitored in order to characterize the spatial variability in the crop/soil system. Description and analysis of the pre-PAS data are presented by Kitchen et al. (2005) and Lerch et al. (2005). For brevity, only directly pertinent methods will be presented here.

Table 1 Generalized management description for pre-precision agriculture system (pre-PAS) during 1991 to 2003

Practice	Years	Description[a]
Crop rotation	Odd	Corn (grain sorghum [*Sorghum bicolor* L. Moench] in 1995 because of delayed planting caused by rain)
	Even	Soybean
Tillage	All	Spring mulch tillage and one or two field cultivations
Major herbicides	Odd	Corn: 2.2 kg ha^{-1} of both atrazine and alachlor from 1991 to 1995; 2.2 kg ha^{-1} of both atrazine and metolachlor from 1997 to 2003
	Even	Soybean: 2.2 kg ha^{-1} of alachlor from 1991 to 1995; 2.2 kg ha^{-1} metolachlor from 1996 to 2003; 0.13 L ha^{-1} of imazaquin all years
N fertilization,	Odd	Corn: 190 kg N ha^{-1}
pre-plant		Sorghum: 123 kg N ha^{-1}
broadcast, incorporated		Soybean: 0 kg N ha^{-1}
P, K fertilization,	1993	90 kg P_2O_5 ha^{-1}; 67 kg K_2O ha^{-1}
pre-plant broadcast,	1995	56 kg P_2O_5 ha^{-1}; 56 kg K_2O ha^{-1}
incorporated	2001	90 kg P_2O_5 ha^{-1}; 90 kg K_2O ha^{-1}
Lime	1999	6.7 Mg ha^{-1}

[a] alachlor (2-chloro-N-[2,6-diethylphenyl]- N-[methoxymethyl]acetamide), atrazine (6-chloro-N2-ethyl-N4-isopropyl-1,3,5-triazine-2,4 diamine), imazaquin (2-[4,5-dihydro-4-methyl-4-(1-methylethyl)-5-oxo-l*H*-imidazol-2-yl]-3-quinolinecarboxylic acid); metolachlor (acetamide, 2-chloro-N-[2-ethyl-6-methylphenyl]-N-[2-mehoxy-1-mehylethyl]-,[S])

Priorities for PAS were identified based on the foundation of improved crop profit, overlaid with priorities that would address prevalent soil and water quality issues (Kitchen et al. 2005). Using the pre-PAS 10-yr average profitability map (Massey et al. 2008) as a starting point, three major sub-field areas were delineated (Fig. 1). The PAS management was targeted to these areas to address specific production and conservation priorities (Kitchen et al 2005).

Management zone A encompassed much of the north half of the field, where crop production had not been profitable for much of the area. This zone is associated with shoulder and backslope landscape positions that historically have experienced severe topsoil loss and have been most prone to higher herbicide and nutrient losses (Lerch et al. 2005). Management zone B encompasses both the drainage channel and the footslope position in this field. This zone is one of the more productive areas of the field, although its ephemeral nature results in stand problems, and subsequent yield loss, for some years. Management zone B, like management zone A, represents a sensitive soil area and is prone to sediment loss. Management zone C includes approximately the southern half of the field and represents the broad summit and some shoulder landscape position soils. Profitability generally has been positive. This zone has low slope, less erosion, greater topsoil thickness, and greater soil organic matter than zone A (Fig. 2).

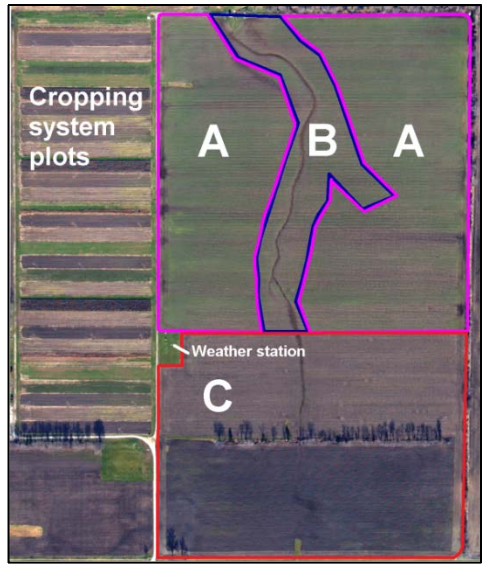

Fig. 1 Photograph of the precision agriculture system (PAS) study field and adjacent research plots, taken on 9 Dec. 2004 at initiation

The PAS was developed on the premise that spatial crop and soil information was fundamental to deciding which crops and management practices to adopt. A team of scientists and stakeholders reviewed existing spatial and temporal information from the field, considered the potential ability and adoptability of several practices to achieved priorities (Kitchen et al 2005), and then collectively decided which practices to include in the PAS. The agreed-upon PAS included a soybean-wheat-cover crop rotation for management zones A and B, and a soybean-corn crop rotation for management zone C (Table 2). Corn was excluded from the crop rotation in management zones A and B because more aggressive conservation management was needed in zone B and it was frequently not profitable in large parts of zone A (Kitchen et al. 2005). To reduce erosion, tillage was eliminated in all three zones.

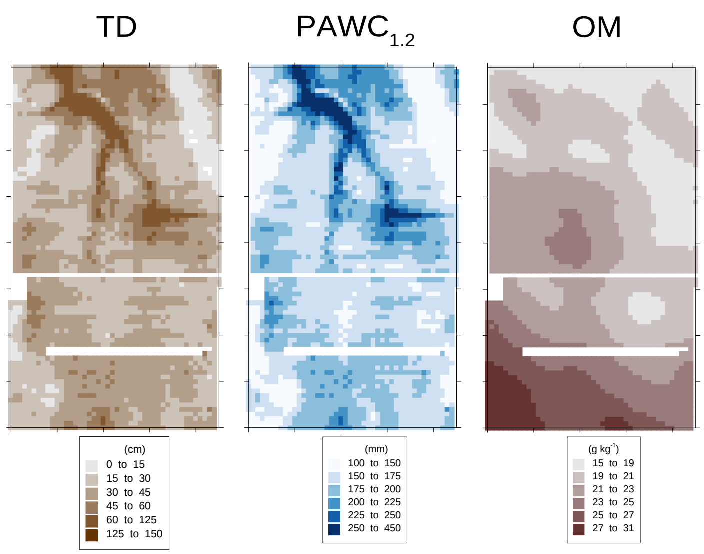

Fig. 2 Apparent electrical conductivity derived topsoil depth (TD) and plant available water content to 1.2 m ($PAWC_{1.2}$) in 2005, along with surface (15 cm) soil organic matter (OM) in 1995, all shown on 10-m square grid

Table 2 Management description for PAS during 2004 to 2014

Practice	Years	Zone(s)[a]	Description[b]
Crop rotation	Odd	A,B	Winter wheat (planted in fall of even years)
		C	Corn
	Even	A,B,C	Soybean
Cover crop	Odd	A,B	Medium red clover in 2005, sudangrass in 2007, legume and nonlegume mix in other years seeded after winter wheat harvest
		C	Cereal rye in 2005, legume and nonlegume mix in 2013 following corn harvest
	Even	A,B	Winter wheat seeded after soybean harvest
		C	Annual ryegrass in 2006, legume and nonlegume mix in other years seeded in fall after soybean harvest
Tillage	All	A,B,C	No-till (some grading work in zone B to shape the central water-way, spring 2007 and 2009; added 7 m^{-3} topsoil in 2013)
Major herbicides	Odd	A,B	Winter wheat: most years none, otherwise as needed to control ryegrass
		C	Corn: generally 2.2 to 2.8 kg ha^{-1} of atrazine, split-applied, some pre-plant but most post-emerge; other post-emerge plant-active herbicides as needed
	Even	A,B,C	Soybean: burn-down and within-season applications using glyphosate, other post-emergence for glyphosate-resistant weeds
N fertilization	Odd	A,B	Winter wheat: 30-40 kg N ha^{-1} at fall planting; 50-110 kg N ha^{-1} variable rate using canopy reflectance sensors, early April
		C	Corn: 30-40 kg N ha^{-1} at planting; 80-160 kg N ha^{-1} variable rate, sidedress, using canopy reflectance sensors in June - July
	Even	A,B,C	Soybean: none
P, K fertilization, pre-plant, broadcast, zonal or variable rate	2004	A,B,C	76 kg P_2O_5 ha^{-1} uniform; 28 to 520 kg K_2O ha^{-1} variable rate
	2006	A,B	179 kg P_2O_5 ha^{-1}; 224 kg K_2O ha^{-1}, zonal
		C	90 kg P_2O_5 ha^{-1}; 224 kg K_2O ha^{-1}, zonal
		C_{south}	224 kg K_2O ha^{-1}, zonal
	2008	A,B	90 kg P_2O_5 ha^{-1}; 90 kg K_2O ha^{-1}, zonal
		C	45 kg P_2O_5 ha^{-1}; 90 kg K_2O ha^{-1}, zonal
	2013	A,B,C	11 to 217 kg P_2O_5 ha^{-1}; 108 to 243 kg K_2O ha^{-1} variable rate
	2014	A,B,C	11 to 217 kg P_2O_5 ha^{-1}; 108 to 243 kg K_2O ha^{-1} variable rate
Lime	2004	A,B,C	0 to 10.4 Mg ha^{-1}, variable rate

[a] C_{south} included all of the area south of the treeline that runs east-west in zone C

[b] Cereal rye (*Secale cereals* L.); medium red clover (*Trifolium pratense* L.); annual ryegrass (*Lolium multiflorum* Lam.); sudangrass (*Sorghum sudanense P. Stapf*); glyphosate (N-[phosphonomethyl] glycine in the form of its isopropylamine salt)

To further reduce erosion and to enhance soil quality, cover crops were used in all years in zones A and B (including wheat that acted as a cover) and most years in zone C. Furthermore, strips of switchgrass (*Panicum virgatum* L.) were established in several critical areas of the drainage channel within management zone B in the early spring of 2007. By the next year, the switchgrass had effectively been eliminated because herbicide applications for the grain crop required spraying sections of the grass strips. However, the erosion control from no-till and cover crops was so successful that further targeted management for zone B was not required. Correction of micro-relief and improved drainage was needed in the field. Therefore, soil scraping and leveling occurred during PAS along the drainage channel in zone B and a few other areas in the field in 2007 and 2009, and by adding 7 m^{-3} of topsoil at the northern part of zone B in front of the weir in 2013.

Nitrogen fertilizer for corn and wheat was applied at variable rates (Table 2) across the field using commercial ground-based canopy reflectance technologies (USDA-NRCS 2009; Kitchen et al. 2010). Zonal or variable-rate applications of P, K, and lime fertilization were based on 30-m grid-sample soil-test results and University of Missouri fertilizer recommendations (Buchholz et al. 2004). For most P and K applications, the fertilizer recommendation was adjusted to include a site-specific soil nutrient buffering index (Kitchen et al. 2005) calculated from soil and crop yield data during pre-PAS (Myers et al. 2003).

To initiate the PAS, uniform P and variable-rate K and lime were applied in the spring and wheat was established following soybean in management zones A and B in the fall of 2004. Other than grading to reduce water ponding, the remainder of the PAS components identified were initiated in 2005.

Weather, crop, and soil measurements

Daily precipitation and air temperatures were obtained from an on-site weather station (Sadler et al. 2015) and were used to calculate annual cumulative precipitation and cumulative growing degree days with a base of 10°C (GDD_{10}). The 30-yr (1981-2010) average cumulative total precipitation and average air temperature were obtained from the nearest National Weather Service station at Mexico, Missouri.

Annual grain yield was measured with field-scale combines equipped with commercially available yield sensing systems during 1993 to 2014. To represent the actual yield as closely as possible, yield data were cleaned using Yield Editor software (Sudduth and Drummond, 2007) to remove erroneous data caused by GPS positional error, abrupt combine speed changes, significant ramping of grain flow during entering or leaving the crop, unknown or variable crop swath width, or other factors. Cleaned yield monitor data was interpolated with the geostatistical technique of block kriging using Surfer 12.0 software (Golden Software Inc., Golden, CO). The best-fitting semivariogram interpolation function was determined separately each year and applied to estimate yield for each 10-m square grid within the field. One east-west transect (10 m wide × 450 m long) between zone A and C was removed because it was the border between zones that received extra machinery traffic and herbicide drift. Furthermore, the weather station and the east-west treeline in zone C (Fig. 1) were excluded.

Soil apparent electrical conductivity (EC_a) measured in 2005 using the shallow depth (1.2 m) of the DUALEM-2S sensor (Dualem Inc., Milton, ON, Canada) was correlated to measured topsoil depth (TD; Sudduth et al. 2006; Sudduth et al. 2010) and plant available water content to 1.2 m ($PAWC_{1.2}$; Jiang et al. 2007). The EC_a data was block-kriged to a 10-m square grid and was used to estimate TD using the calibration equation:

$$\text{TD (cm)} = -58.57 + 3913\ EC_a\ ((\text{mS m}^{-1})^{-1},\ r^2 = 0.61,\ \text{root mean square error} = 16.9\ \text{cm} \quad (1)$$

The shallow EC_a data also were calibrated to measured $PAWC_{1.2}$ using the equation:

$$PAWC_{1.2} \text{ (mm)} = 18.0 + 8161.8\ EC_a\ ((\text{mS m}^{-1})^{-1}),\ r^2 = 0.67, \text{ root mean square error} = 30 \text{ mm} \quad (2)$$

Surface soil organic matter to 15 cm depth was measured on a 30-m grid and on 40 random locations distributed throughout the field in 1995, and block-kriged to a 10-m grid as previously documented (Drummond et al. 2003).

Comparison of systems

The assessment of PAS was conducted like a paired watershed comparison across time rather than space. The rationale for conducting the study in time is that no two fields will ever have identical spatial variability; thus, the implementation of a PAS treatment is field-specific. For this paper, we rely on the empirical crop and soil measurements and on results from an adjacent replicated cropping system study on large plots (0.34 ha) to compare grain production between pre-PAS (1991-2003) and PAS (2004-2014).

The pre-PAS management in the field was replicated three times in adjacent large cropping system plots (Fig. 1) with three landscape positions (summit, backslope, footslope; Yost et al. 2016). Comparisons of crop production between the field and plots are only valid if their yield and yield variability are correlated. Thus, average corn and soybean yield and yield coefficient of variation (CV) across the entire field were linearly correlated to average plot yield across landscape positions and yield CV across replications and landscape positions during pre-PAS years (1993-2003) or all years (1993-2014) using the REG procedure of SAS (SAS Institute, 2011) at $\alpha \leq 0.10$. These adjacent plots also provided the opportunity to evaluate whether time (improved cultivars, equipment, or management) or weather conditions favored crop yield performance in PAS vs. pre-PAS years. To test this, linear correlations between time (1993-2014) and average soybean and corn plot yields and yield CV all with pre-PAS management across three landscape positions were evaluated using the REG procedure of SAS at $\alpha \leq 0.10$. Further, an ANOVA was conducted to test whether average soybean and corn plot yields and yield CV differed between pre-PAS (1993-2003) and PAS (2004-2014) years represented in the field.

In the field only, the yield of corn in zone C and soybean in all zones was compared between pre-PAS and PAS years. In addition, relative yield and yield variability were calculated to compare the performance of corn in pre-PAS vs. wheat in PAS (zone AB), and corn (zone C), soybean (all zones), or all crops (all zones) in both systems. Relative yield was determined by year and crop as the yield in each 10-m grid cell divided by the average yield across the pertinent zone or zones then multiplied by 100. Annual relative yield was then averaged by or across crops among pre-PAS or PAS years. Differences in within-grid cell actual and relative yield by or across crops between pre-PAS and PAS were determined using two-tailed *t*-tests at $\alpha \leq 0.10$.

Temporal yield variability was assessed by calculating the CV in yield across pre-PAS or PAS years for each 10-m grid cell. Because each grid cell had only one observation for each system, differences could not be detected with *t*- tests. Therefore, the percent difference in yield or relative yield CV from pre-PAS to PAS was used to compare temporal yield variability among systems. It was calculated as:

$$((CV_{PAS} - CV_{prePAS}) / CV_{prePAS}) * 100 \quad (3)$$

Negative differences indicated PAS reduced temporal yield variability and positive differences indicated higher variability. Absolute values of differences >25% were chosen to examine large changes in temporal variation caused by PAS; this was similar to the ≥30% used by Blackmore (2000). Spatial yield variability was defined as the CV of yield within years averaged across pre-PAS or PAS years and was compared among systems using two-tailed *t*-tests at $\alpha \leq 0.10$.

Results and discussion

The range in annual cumulative GDD_{10} and precipitation was similar in most odd-numbered years that were corn during pre-PAS and wheat during PAS years. Exceptions were above-average GDD_{10} in two PAS years (2007 and 2011) and above-average precipitation in one year of each system (Table 3). Pre-PAS in 1993 had above-average precipitation during much of June through December. Conversely, PAS in 2005 had above-average precipitation during much of January through April. Below-average precipitation occurred in both systems; in 1999 during pre-PAS starting in September, and in 2007 and 2011 during PAS starting in July. For most even years with soybean, the range in annual cumulative GDD_{10} and precipitation also was similar between systems (Table 3); exceptions were above-average GDD_{10} in 2012 and above-average precipitation beginning in July in 2008 and 2010 during PAS. Annual GDD_{10} and cumulative precipitation of all crops (Table 3) during pre-PAS and PAS years showed that three PAS years (2005, 2008, 2012) had the greatest deviations from the 30-year average. Therefore, both systems experienced similar weather conditions, but PAS had more large deviations (warm or wet) from average than pre-PAS years.

Yield comparison between the field and plots

Average corn and soybean yield and spatial yield variation (within-year CV) during the pre-PAS years (1993-2004) and all years (1993-2014) correlated between the field and plots ($P \leq 0.062$). Corn yield in zone C of the field was 3% higher than plot corn yield during pre-PAS years ($r^2 = 0.88$), but was 3% lower in all years ($r^2 = 0.87$). In contrast, soybean yield across the field was 1% lower than plot soybean yield during pre-PAS years ($r^2 = 0.93$), but was 5% higher in all years ($r^2 = 0.95$). Corn yield CV was 50 to 85% lower in the field than plots and had the lowest correlation ($r^2 = 0.29$-0.53). Soybean yield CV was more correlated ($r^2 = 0.85$-0.90) than corn and was 39% lower in the field than plots. Reasonable correlation in yield between the field and plots suggests that plot yield responses may be rather indicative of field responses. In the plots with pre-PAS management during 1993 to 2014, yield or yield CV of either corn or soybean did not increase with time ($P \geq 0.13$) and were not different between pre-PAS and PAS years ($P \geq 0.53$). Therefore, production advantages or disadvantages of PAS vs. pre-PAS in the field likely are not an artifact of improved growing conditions or management with time.

Corn pre-PAS / wheat PAS

Removing corn from the northern 21 ha in zones A and B for the PAS years resulted in higher relative grain yield in 22% of the area of these two zones (Table 4). Half of this area had between 25 and 50% higher relative wheat yield than relative corn yield (Fig. 3). Increased relative yield occurred primarily in the areas of zone A with the most eroded backslopes having surface-exposed argillic subsoil (Fig. 2). These chronic low-corn-producing areas in zone A often translated into negative profits during pre-PAS years (Massey et al. 2008), and were target areas for increasing production with PAS (Kitchen et al. 2005). Thus, wheat in PAS successfully increased relative grain yield on much of the area with eroded backslope positions.

Relative wheat yield during PAS was lower than relative corn yield during pre-PAS in 11% of the area in zones A and B (Table 4; Fig. 3). The vast majority of this yield reduction with PAS (25 to 125% lower than relative corn yield) occurred in the drainage channel represented by zone B where runoff exits the field. Extended wet soils in this area of the field negatively affected wheat stand and vigor, causing this yield depression. In contrast, zone B was among the most productive and profitable area in the field for corn during pre-PAS (Fig. 3) because of greater topsoil depth caused by over-washed alluvium on footslope areas (Fig. 2).

Relative wheat yield temporal variation (within-grid CV) was lower (|>25%| difference in CV) than corn in about one-third of the area across zones A and B (Table 4; Fig. 3); however, an equivalent area had higher variation. The areas with lower and higher temporal variation did not correspond to TD (Fig. 2) as directly as relative yield did. The majority of reduction in temporal variation occurred in zone A (Fig. 3), while the increase was dispersed mainly across the eastern halves of zones A and B. Spatial variation of wheat yield (within-year CV) during PAS was equal to that of corn yield during pre-PAS (P = 0.74) and averaged 25% in both systems. After only a decade, these results demonstrate potential production advantages of wheat in areas where corn was the least profitable.

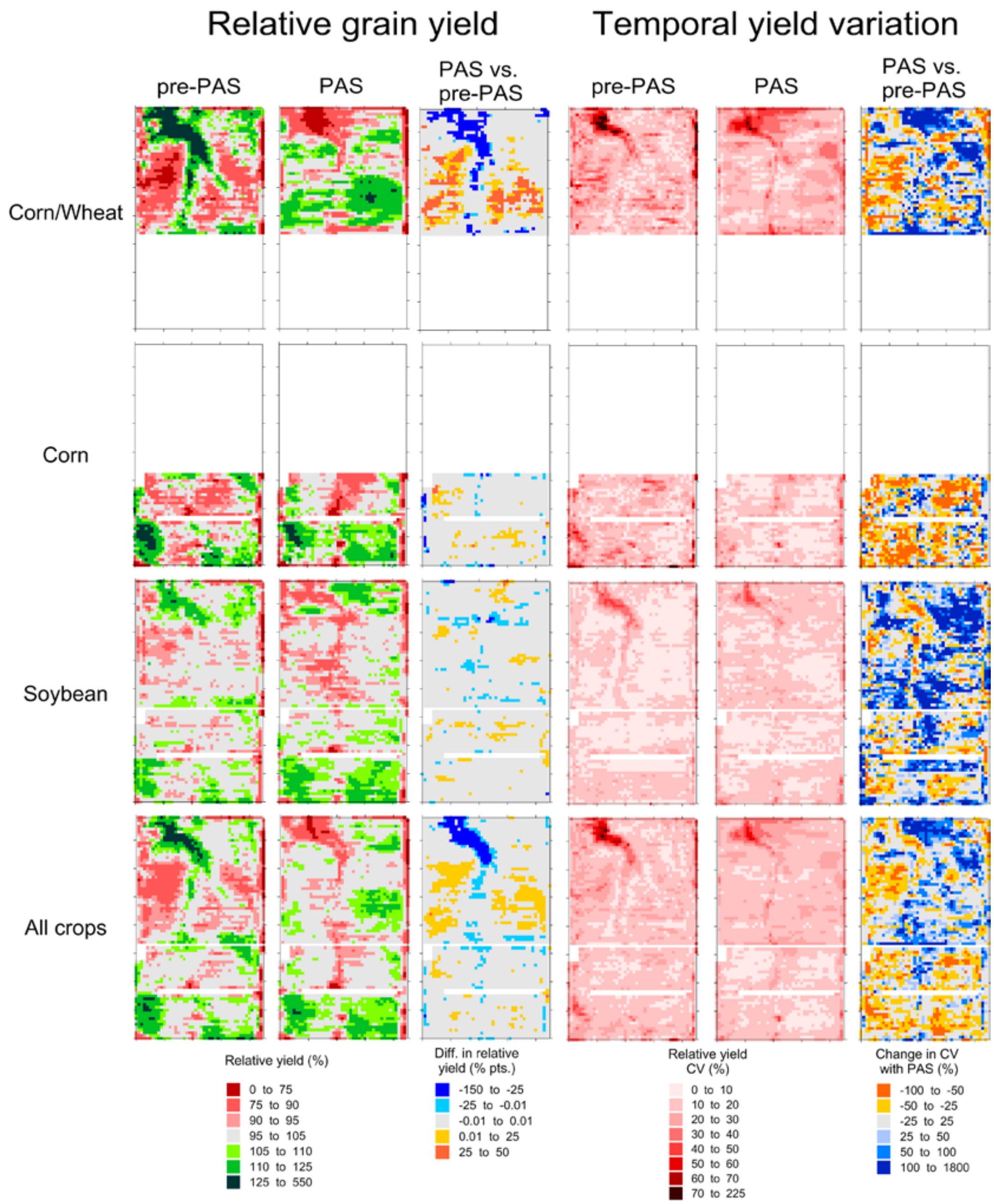

Fig. 3 Maps of relative crop yield and coefficient of variation (CV) in relative grain yield for pre-precision agriculture system (pre-PAS) and PAS years along with maps showing differences in relative yield between systems at $P \leq 0.10$ or percent change in CV from pre-PAS to PAS. Mapped areas in orange indicate PAS had higher average relative grain yield or PAS reduced within-grid cell CV in relative grain yield by |>25|

Corn

Only in zone C, or on the southern 15 ha, in odd years could corn production from PAS be compared to pre-PAS. Both corn yield and relative corn yield were used to contrast the performance of the two systems. Although average corn yield during PAS was numerically higher than during pre-PAS for much of the area in zone C, it was statistically equivalent between systems throughout the entire zone (Fig. 4; Table 4). Relative corn yield, which removes some of the environmental bias between the two systems, was increased with PAS in 7% (1.1 ha) of the area in zone C. This increase occurred mainly in two clusters; directly southeast of the weather station and in the southeast quarter of zone C. The cluster near the weather station had poor drainage which resulted in poor corn plant populations during pre-PAS. Correction of micro-relief and improved drainage in this area during PAS likely caused greater corn yield resulting from greater plant populations. It was unclear which factor or factors (soil characteristics, no-till, cover crops, site-specific nutrients) caused relative yield increase in the other cluster. About half as much area in zone C (4%; 0.6 ha) had lower relative corn yield with PAS. This area mainly was in the drainage channel north of the treeline and on the headlands or field edges. Negative impacts of compaction from increased traffic on headlands and cool, wet soil in the drainage channel could have been further exacerbated with no-till and cover crops (Teasdale and Mohler 1993; Unger and Kasper 1994; Drury et al. 1999) during PAS.

Corn yield temporal variation was more influenced by PAS than yield was. Corn yield variation or within-grid CV was lower with PAS than pre-PAS in 24% of the area in zone C (Fig. 4; Table 4). Most of this reduction in variance occurred south of the treeline in zone C. The trends in relative corn yield temporal variation were similar to yield variation, but the area with reduced CV (51%) doubled compared to yield and the extent of the reduction expanded to cover both the north and south parts of zone C (Fig. 3). Few parts of zone C had increased temporal variation in yield (4%), but almost four times as much area (19% or 3 ha) had increased temporal variation in relative yield during PAS. These increases in temporal variation occurred mainly on the western side of zone C for yield and throughout the zone for relative yield (Fig. 3, 4). Areas with lower or higher temporal yield or relative yield variation did not correspond well with estimated topsoil depth or plant available water content, or measured surface soil organic matter (Fig. 2). Increased temporal variation in relative grain yield during PAS could have been partially related to the fact that corn was replanted in three (2007, 2009, 2011) of the five corn years during PAS due to poor emergence from heavy cover crop residue and/or cool, wet soil conditions. Spatial corn yield variation, or within-year CV, was not influenced by PAS (P = 0.66) and averaged 19% for both systems.

Yield and yield variation results from two decades indicate that PAS had limited ability to increase corn yield or decrease corn yield spatial variation on claypan soils. However, PAS did greatly reduce temporal corn yield variation. These field-scale results confirm those in adjacent, replicated long-term plots where two conservation systems similar to PAS reduced corn temporal variability by up to 23% and increased corn yield stability by 16% above a system identical to pre-PAS across three landscape positions during 1994 to 2010 (Yost et al. 2016). Reduced temporal variability, or increased stability, with PAS is an important outcome because temporal variability caused by weather often can be much greater than spatial variability (Dinnes et al. 2002; Kitchen et al. 2005; Sadler et al. 2005). Thus, reducing temporal yield variation with PAS should improve the resiliency of grain-based cropping systems to erratic, changing climate.

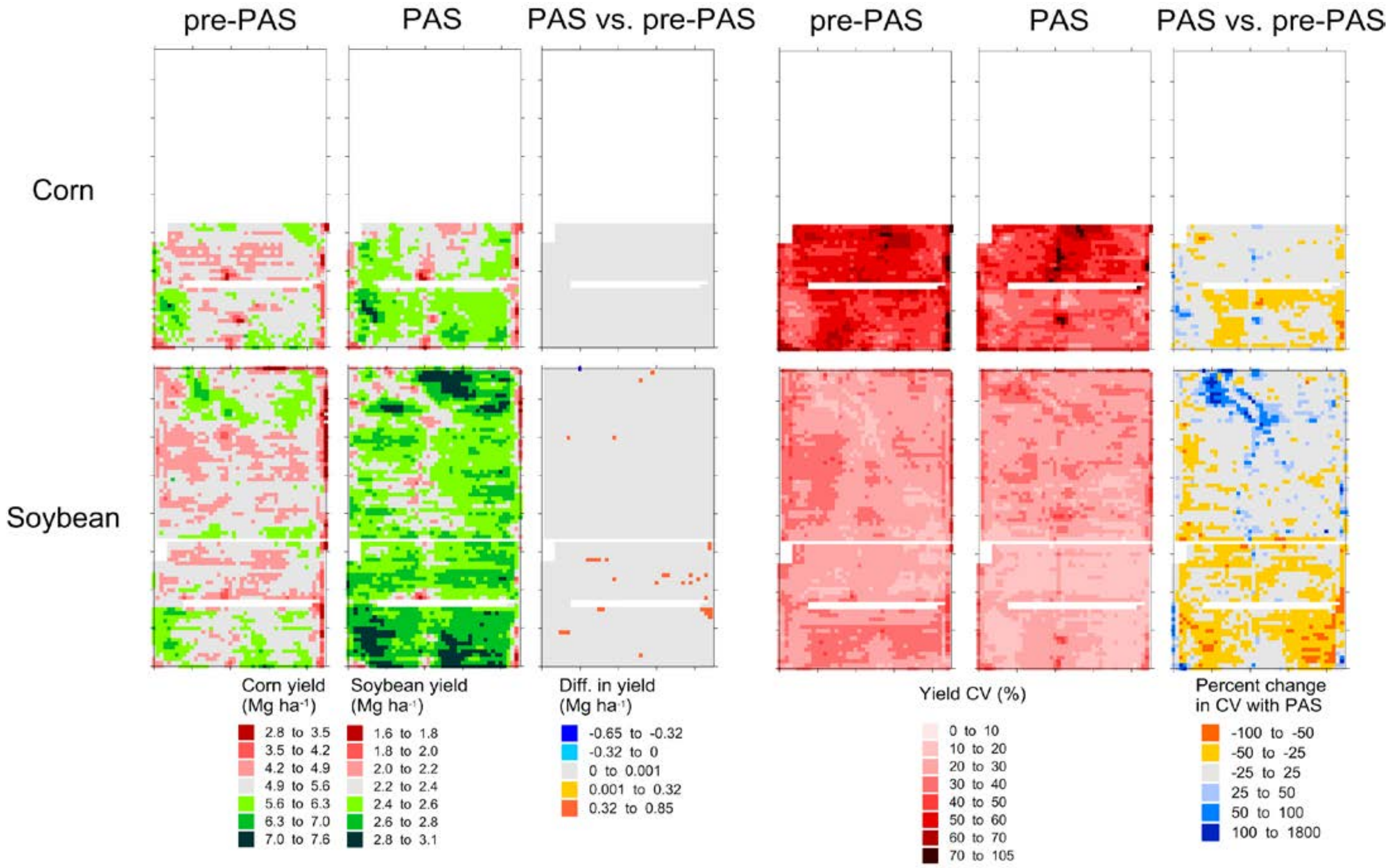

Fig. 4 Maps of corn and soybean yield and temporal yield coefficient of variation (CV) for pre-precision agriculture system (pre-PAS) and PAS years along with maps showing differences in yield between systems at $P \leq 0.10$ and differences in CV. Mapped areas in orange indicate PAS had higher average grain yield or that it reduced within-grid cell CV of yield by |>25%|

Soybean

Soybean production was compared in the entire field (36 ha) during all even years of both pre-PAS and PAS. Similar to corn yield results, average soybean yield was numerically higher in PAS than pre-PAS for most of the field, but PAS statistically improved yield in only 1% (0.4 ha) of the field area (Table 4). In this small area, mainly within zone C (Fig. 4) yield increased with PAS by 0.32 to 0.85 Mg ha^{-1}. Relative soybean yield increased with PAS in a greater percentage (5%; 2 ha) of the field than yield, but it also decreased in 4% of the field (Fig. 3; Table 4). The reduction in relative soybean yield occurred mainly in the alluvial soils of zone B where water accumulates in the central portion and flows north off the field (Fig. 3), while the increase was outside of zone B located in small patches throughout much of the field. Yield and relative yield both confirm that PAS had minor impacts on soybean yield. Longer-term (17 years) and annual comparisons from adjacent plots where two systems with similarities to PAS increased soybean yield on all landscape positions by 8 to 24% (Yost et al 2016) suggest that more time may be needed to realize increased soybean production with PAS at the field scale. Granted, timeframes required for increased production resulting from precision agriculture practices will vary widely, as evidenced by increased soybean production after three years of variable rate lime (Wiesz et al. 2003).

Temporal soybean yield variation or within-grid CV was reduced by |>25%| in 21% of the area in the field during PAS (Table 4). Conversely, 10% of the area had higher temporal yield variability. For yield, the increase in variability with PAS occurred mainly in zone B, while the majority of reduction was across much of zone C and the western side of zone A (Fig. 4). Excessive precipitation in some PAS years (e.g., 2008 and 2010; Fig. 4) could have caused greater variability in zone B due to soil saturation, but reduced variability in parts of zones A and C due to adequate PAWC on shallower soils (Fig. 2). Furthermore, cover crop type/growth and crop rotation differences between zones A and C likely contributed to the change in temporal yield variation. Spatial yield variability was not influenced by PAS (P = 0.58) and the average within-year CV was 13% across systems. This average spatial variability was nearly half that of the average for corn, showing greater yield stability in soybean across systems.

The trend in temporal relative yield variation change with PAS was not similar to the trend for temporal yield variation. Although a greater area (51%; 18 ha) had reduced CV than yield, a much greater area (19%; 7 ha) also had increased variation (Table 4). Furthermore, the distribution of the change was not similar to that of yield (Fig. 3). The reduction in relative yield CV was distributed across many areas of the field and was not concentrated in zone A and C, and the increase in variability occurred mainly in zone A and in the center of zone C. A major reason for the shift in the trend between yield and relative yield variability is that the latter removes some annual effects of weather.

All crops

The relative grain yield of all crops across the entire field were compared between pre-PAS and PAS to evaluate the total grain production of both systems. Relative grain yield increased with PAS in 13% (5 ha) of the field, but also decreased in nearly the same amount of area (9%; 3 ha) (Table 4). The major clustered areas of change in relative yield corresponded to changes observed by crop or within zones. Relative grain yield decreased mainly in the drainage channel (zone B) due to lower relative wheat yield with PAS than corn with pre-PAS (Fig. 3), as discussed above. It increased mainly in zone A on eroded backslope positions due to higher relative wheat yield than corn, and directly southeast of weather station and south of the treeline in zone C due to higher relative corn yield with PAS. Therefore, PAS did not improve overall grain production for much of the field. It was, however, successful at increasing relative grain production on vulnerable, eroded backslope positions.

Table 3 The annual cumulative precipitation and growing degree days (GDD_{10}) with base of 10°C for the pre-precision agriculture system (PAS) and PAS, along with the difference from the 30-year (1981-2010) averages in parenthesis

Pre-PAS			PAS		
Year	Cumul. Precip.	Cumul. GDD_{10}	Year	Cumul. Precip.	Cumul. GDD_{10}
	mm	°C		mm	°C
1993	1340 (291)	2092 (-106)	2004	1138 (89)	2143 (-55)
1994	857 (-192)	2241 (43)	2005	941 (-108)	2469 (271)
1995	1150 (101)	2215 (17)	2006	933 (-116)	2369 (171)
1996	875 (-174)	2097 (-101)	2007	753 (-296)	2545 (347)
1997	941 (-108)	2145 (-53)	2008	1581 (532)	2090 (-108)
1998	1158 (109)	2464 (266)	2009	1236 (187)	2059 (-139)
1999	824 (-225)	2398 (200)	2010	1283 (234)	2426 (228)
2000	926 (-123)	2397 (199)	2011	768 (-281)	2402 (205)
2001	1028 (-21)	2377 (179)	2012	838 (-211)	2696 (498)
2002	860 (-189)	2352 (154)	2013	936 (-113)	2262 (64)
2003	1076 (27)	2256 (58)	2014	1045 (-4)	2216 (18)

Table 4 The percentage of a zone or zones where relative yield, yield, or yield coefficient of variation (CV) was influenced by the precision agriculture system (PAS), as summarized from the difference maps in Fig. 3 and 4

Attribute	Yield or CV with PAS was…	Corn/wheat (zones A,B)	Corn (zone C)	Soybean (zones A,B,C)	All crops (zones A,B,C)
		----------------- percentage of zone(s) (%)-----------------			
Relative yield	Reduced	11	4	4	9
	Increased	22	7	5	13
	Same	68	89	90	78
Yield	Reduced	.	0	0	.
	Increased	.	0	1	.
	Same	.	100	99	.
Relative Yield CV[a]	Reduced	31	51	21	32
	Increased	36	19	45	28
	Same	34	30	35	41
Yield CV[a]	Reduced	.	24	30	.
	Increased	.	4	10	.
	Same	.	72	60	.

[a] Reduced and increased was based on significant (*t*-tests at P = 0.10) yield change and |>25%| change in CV from pre-PAS to PAS

Conclusions

Though PAS has been in place for only a decade, significant productivity changes have been documented. Most drastic has been improved relative grain yield on vulnerable, eroded backslope positions from wheat instead of corn, and reductions in temporal variability of corn grain yield. These improvements occurred in PAS despite its having larger and more frequent weather deviations from the 30 year average than the decade of pre-PAS, and added challenges associated with managing cover crops on claypan soils. Therefore, this PAS should improve grain yield stability and resilience to changing climate. A decade of PAS was not able to increase soybean or corn grain yield or reduce spatial grain yield variability of any crop in most of the field, which suggests that more time is needed before these potential benefits are realized. Future analysis will be conducted to evaluate the profitability, soil quality, and water quality impacts of PAS.

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