PRODUCTION AND CONSERVATION RESULTS FROM A DECADE-LONG FIELD-SCALE PRECISION AGRICULTURE SYSTEM

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ABSTRACT

Research is needed that simultaneously evaluates production and conservation outcomes of precision agriculture practices. From over a decade (1993-2003) of yield and soil mapping and water quality assessment, a multi-faceted, “precision agriculture system” (PAS) was developed and initiated in 2004 on a 36-ha field in Central Missouri. The PAS assessment was accomplished by comparing it to the previous decade of conventional, whole-field corn-soybean mulch-tillage management. The employed PAS plan takes advantage of targeted management that addresses crop production and environmental issues. The PAS plan included no-till, cover crops, growing wheat instead of corn for field areas where depth to the argillic horizon was shallow, site-specific N for wheat and corn using canopy reflectance sensing, variable-rate P, K, and lime using intensively grid sampled data, and targeting of herbicides based on weed pressure. Yield slightly improved for corn (5%) and soybean (9%) with PAS over pre-PAS management. Risk as measured by grid cell year-to-year yield coefficient of variation decreased 57% when comparing where wheat replaced corn with PAS, but has remained unchanged for soybeans. Removing corn from the northern portion of the field for the PAS years resulted in within-year corn CV of 16.6%. Using soil quality measurements on research plots adjacent to PAS, we can estimate that PAS soil quality has increased at the rate of one point per year on a 0-100 scaled index. Surface runoff has not been found to be significantly different between PAS and pre-PAS. Sediment loss with PAS has been reduced 80% compared to pre-PAS years.

Keywords: precision conservation, integrated precision practices

INTRODUCTION

Most producers’ primary justification for employing precision agriculture is to improve profitability. In some cases gains that have resulted from yield increases more than balanced increased input costs, while in other cases net gains were primarily from reduced 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.

Field and simulation studies conducted to determine the benefits of precision agriculture 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 spatial field variability; thus temporal information may dictate the optimal management (Dinnes et al., 2002).

We have found that for claypan soil fields in Missouri, significant spatial variability exists in many important soil and crop measurements (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., climate), 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 1991-2003 a 36-ha claypan soil field in north-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 in 2004 where management was targeted to soil and slope characteristics, varying within the field. 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). The objective of this paper is to compare the production and environmental performance of PAS with the uniform pre-PAS management.

MATERIALS AND METHODS

PAS Priorities

The field site for the PAS investigation is a 36-ha claypan soil field in central Missouri. From 1991 to 2003, the field was under conventional uniform management 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). 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 (Table 1).

Table 1. Priorities for PAS established in 2004.

Priority	Category	Intended PAS Outcomes
1	Production	1. Reduce production costs
		2. Achieve stable yield
		3. Improve crop water-use efficiency
2	Surface Water Quality	1. Reduce sediment
		2. Reduce herbicide loss
		3. Reduce nutrient loss
3	Soil Quality	1. Greatly reduce topsoil loss
		2. Improve soil structure and infiltration
		3. Build organic matter
4	Ground Water Quality	1. Decrease nitrates

Using the pre-PAS 10-year averaged profitability map (Massey et al., 2008) as a starting point, three major sub-field areas were delineated (Fig. 1). PAS management was targeted to these areas to address specific priorities listed in Table 1. Management zone A encompasses the north half of the field, where crop production had not been profitable for much of the area (yellow and brown in Fig.1). This zone is associated with shoulder and side-slope landscape positions

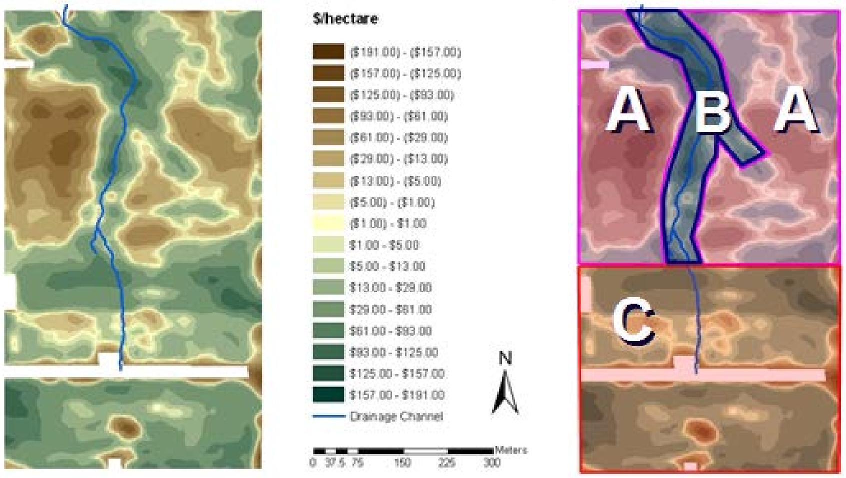

Figure 1. Three crop management zones, shown overlaid on average long-term profitability map, identified to target production and conservation priorities of the Precision Agriculture System (PAS). Detailed description of these management zones is found in Kitchen et al. (2005).

that historically have experienced severe topsoil loss and has been most prone to higher herbicide and nutrient losses (Lerch et al., 2005). Management zone B encompasses both the drainage channel and the foot slope 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 has generally been positive. Because this zone has very little slope, erosion has been less evident and topsoil thickness is greater than in zone A.

Management Details of PAS

The PAS plan was developed on the premise that this mapped crop and soil information was fundamental to understanding what crops should be grown and what other management and conservation practices should be adopted. A team of experts, including project scientists, producers, and crop advisors, reviewed the assessment results, considered crop and management options and projected their likely future impact, integrated other non-quantitative factors (e.g., adoptability of a particular practice), and reached a consensus decision on those management components to include in the PAS. We considered this to be the best available approach to the PAS development, a process which cannot currently be (and may never be) undertaken by numerical analysis.

The plan adopted a soybean-wheat-cover crop/hay crop rotation (three crops in two years if hay harvested) for management zones A and B, and a soybean-corn crop rotation for management zone C. Thus for PAS, corn would not be grown on that portion of the field where it had been least profitable (management zone A). Corn had generally been profitable in management zone B, but more aggressive conservation management was needed there than growing corn would allow. The size and shape of zone B would also make it difficult to manage it differently from zone A.

Significant measures were needed to minimize erosion for this field, especially for management zones A and B. No-till was employed for the entire field, but modified for zone C to allow, as needed, light incorporation of soil herbicides for weed control in corn. This helps protect surface water by reducing desorption of soil-active herbicides, identified as a risk on this field (Lerch et al., 2005). Cover crops were employed for zones A and B to maintain ground cover each year during winter and spring runoff events. Wheat acted as the cover crop following soybean. Using the cover crop as a hay crop was left as an option. Cover crops would also be employed for zone C if a suitable window for planting such was available. In addition to erosion prevention, we expected cover crops to promote soil organic matter and aggregate stability leading to subsequent improvement in infiltration and reduced runoff.

Initially consideration was given to establishing a permanent grassed waterway along the drainage channel of this field along zone B. However, when we applied a 15 to 30 m grass waterway to the spatial analysis database, average profitability decreased by \$10 to 13 ha^{-1} (\$4 to 5 acre^{-1}), excluding costs of establishment. In lieu of a grassed waterway, permanent stiff-stem grass strips of switchgrass were established in several critical areas of the waterway within management zone B. By 2008 the switchgrass had effectively been eliminated because herbicide applications for the grain crop required spraying sections of the grass strips. However, by this time erosion control from no-till and cover crops were so successful, further targeted management for zone B was not required. No soil-applied herbicides were used for the soil sensitive areas of the field represented by zones A and B.

Nitrogen for corn and wheat was applied variably, relying on ground-based reflectance technologies that have been proven viable (Kitchen et al., 2010) and commercialized and promoted in recent years (USDA-NRCS. 2009). Variable-rate applications of lime, and P and K fertilization were based on 30-m grid-sample soil-test results and University of Missouri fertilizer recommendations. For P and K applications, the fertilizer recommendation was altered to include a site-specific soil nutrient buffer (Kitchen et al., 2005).

Following initiation of the PAS plan in 2004, variable-rate lime, P, and K were applied. Wheat was established 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 was initiated in 2005.

A summary is provided of pre-PAS (Table 2) and PAS (Table 3) management operations. Photo 1 shows the field shortly after initiating PAS.

Table 2. Management description for pre-Precision Agriculture System (PAS) years (1991-2003).

Practice	Years	Description
Crop Rotation	odd	corn (grain sorghum in 1995 because of delayed planting caused by rain)
	even	soybean
Tillage	all	Spring mulch tillage and 1 or 2 field cultivations
Herbicides	odd	corn: 2.24 kg ha^{-1} of both atrazine and alachlor from 1991 to 1995; and 2.24 kg ha^{-1} of both atrazine and of metolachlor from 1997 to 2003
	even	soybean: 2.24 kg ha-1 of alachlor from 1991 to 1995, and 2.24 kg ha-1 metolachlor from 1996 to 2003. Also, 0.13 L ha-1 of imazaquin, all years
N fertilization	odd	190 kg N ha^{-1}, pre-plant broadcast, usually as UAN solution, , incorporated (123 kg N ha^{-1} for grain sorghum).
P, K fertilization	1993	90 kg P_2O_5 ha^{-1} and 67 kg K_2O ha^{-1},
pre-plant broadcast,	1995	56 kg P_2O_5 ha^{-1} and 56 kg K_2O ha^{-1}
incorporated	2001	90 kg P_2O_5 ha^{-1} and 90 kg K_2O ha^{-1}
Lime	1999	6.7 Mg ha^{-1}, December

Table 3. Management description for Precision Agriculture System (PAS) years (2004-2013).

Practice	Years	Sub-field	Description
Crop Rotation	odd	north	wheat (planted in fall of even years)
		south	corn
	even	all	soybean
Cover Crop	odd	north	
		south	
	even	north	
		south	
Tillage	all	all	No-till (some grading work to shape the central water-way, spring 2007)
Herbicides	odd	north	wheat: most years none, otherwise as needed to control ryegrass
		south	corn: generally 2.24 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	north/ south	soybean: burn-down and within-season applications using glyphosate, other post-emergence as needed for glyphosate-resistant weeds
N fertilization	odd	north	wheat: 30-40 kg N ha^{-1} at planting; 50-110 N ha^{-1} variable rate, top-dress, using canopy reflectance sensors, early April
		south	corn: 30-40 kg N ha^{-1} at planting; 80-160 N ha^{-1} variable rate, top-dress, using canopy reflectance sensors, early late June/early July
	even	all	none
P, K fertilization	2004	all	0 to 175 kg P_2O_5 ha^{-1} and 0 to 190 kg K_2O ha^{-1} variable rate
	2006	north	179 kg P_2O_5 ha^{-1} and 224 kg K_2O ha^{-1}
		south	90 kg P_2O_5 ha^{-1} and 224 kg K_2O ha^{-1}
		south of treeline	70 kg K_2O ha^{-1}
	2008	north	90 kg P_2O_5 ha^{-1} and 90 kg K_2O ha^{-1}
		south	45 kg P_2O_5 ha^{-1} and 90 kg K_2O ha^{-1}
		south of treeline	none
	2013	all	X to X kg P_2O_5 ha^{-1} and X to X kg K_2O ha^{-1}
Lime	2004	all	0-9.4 Mg ha^{-1}, variable rate

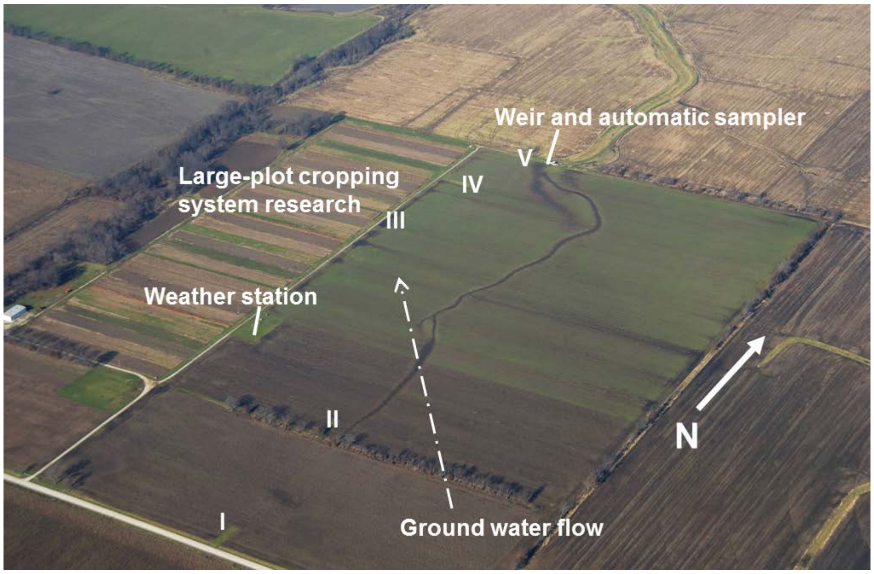

Photo 1. Photograph of the PAS study field and adjacent research plots, taken on December 9, 2004, showing wheat growing in zones A and B. Also shown aregroundwater flow direction and the location of the weir, weather station, and ground water well nests (I-V).

PAS Compared to Pre-PAS

The PAS assessment is like a paired watershed design in 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 soil, water, and crop measurements to compare PAS (2004-2013) to pre-PAS (1991-2003).

For grain production, combines equipped with commercially available yield sensing systems were used to collect data for 1993-2013 yield maps. Individual points where yield data were unreliable due to combine operation or yield sensor issues were removed so that the resulting yield map represented the actual yield as closely as possible. Yield data points were removed for reasons such as GPS positional error, abrupt combine speed changes, significant ramping of grain flow during entering or leaving the crop, unknown or variable crop swath width, and other outlying values (Sudduth and Drummond, 2007). Cleaned yield monitor data was interpolated with the geostatistical technique of block kriging. The best-fitting semivariogram interpolation function was determined separately for each year and applied to estimate yield for each 10-m square grid within the field.

For soil nutrients, composite soil samples (8 15-cm cores per point) were taken on a 30-m grid every odd year (from 1995 to 2007) and also in 2013. The samples were analyzed at the University of Missouri Soil and Plant Laboratory. Additional details have been previously documented (Drummond et al., 2003).

For soil quality evaluation, surface (0-5 cm) soil samples were obtained in 2008 from over 10 different perennial and annual cropping systems in the claypan soil region around the PAS field. Included in this sampling campaign were samples from the PAS field and large-plot cropping system research adjacent to PAS (plots seen in Photo 1). One of the plot cropping systems has been managed (1991-2013) the same as the pre-PAS management. Another plot management system has been managed (1996-2013) in no-till and with cover crops, similar to PAS management. Samples were analyzed for biological, physical, and chemical soil quality indicators using standard procedures. These indicators were then combined within the Soil Management Assessment Framework (SMAF) to obtain a soil quality index (Wienhold et. al., 2009; Stott et al. 2010). From this pool of multiple sites the current soil quality status for PAS was inferred and compared to the management similar to pre-PAS.

For water quantity and quality, monitoring was installed in 1992 and became fully operational in 1993. Flow was continuously monitored on a 5-min basis (Baffaut et al., 2014) and flow-proportioned water samples were collected during events (Baffaut et al., 2013). Sub-daily data were then aggregated to the daily and monthly time step. For this analysis, monthly volumetric flow depths were divided by the corresponding precipitation amount to calculate monthly runoff coefficients, which quantify runoff as a fraction of precipitation and vary as a function of soils, management, precipitation, and temperature. Runoff coefficients were then averaged by month for PAS (2005-2012) and pre-PAS (1993-2002). Reduced periods were considered because of the availability of monitoring data and the need to have an even number of years in each period so that corn or soybean years would not dominate the data set. To consider the possible effects of weather on these runoff coefficients, similar monthly coefficients were calculated using flow and precipitation data from the 72-km^2 watershed in which this field is located. Significant differences between average monthly runoff coefficients during the PAS and pre-PAS periods were assessed using the Student t-test. Differences in sediment transport were assessed with the Student t-test applied to monthly averages of transport per unit area.

RESULTS AND DISCUSSION

Grain Production and Yield Stability

Yield and yield stability from PAS (2004-2013) were compared to uniform management (pre-PAS; 1993-2003). The areas in the maps (Fig. 2) separated by a blanked-out horizontal white strip on the figure maps represent a tree line that runs east-west across much of the field. Average corn grain yield in the northern portion of the field during the pre-PAS years was much more variable than the southern portion of the field for the same period (Fig. 2; left map). For these years, both the highest producing areas (from over-washed alluvium footslope areas) as well as the lowest producing areas (from eroded side-slopes with surface-exposed argillic subsoil) are seen adjacent to each other on the northern end of the field. The high level of spatial variability observed in Fig. 1 represented an average within-year CV for pre-PAS years of 23.8%. Removing corn from the northern portion of the field for the PAS years resulted in within-year corn CV of 16.6%. The major factor in discontinuing corn production for the northern 21 ha of the field with PAS was the chronic low-producing areas represented by the eroded topsoil (Kitchen et al., 2005) that translated into negative profits (Massey

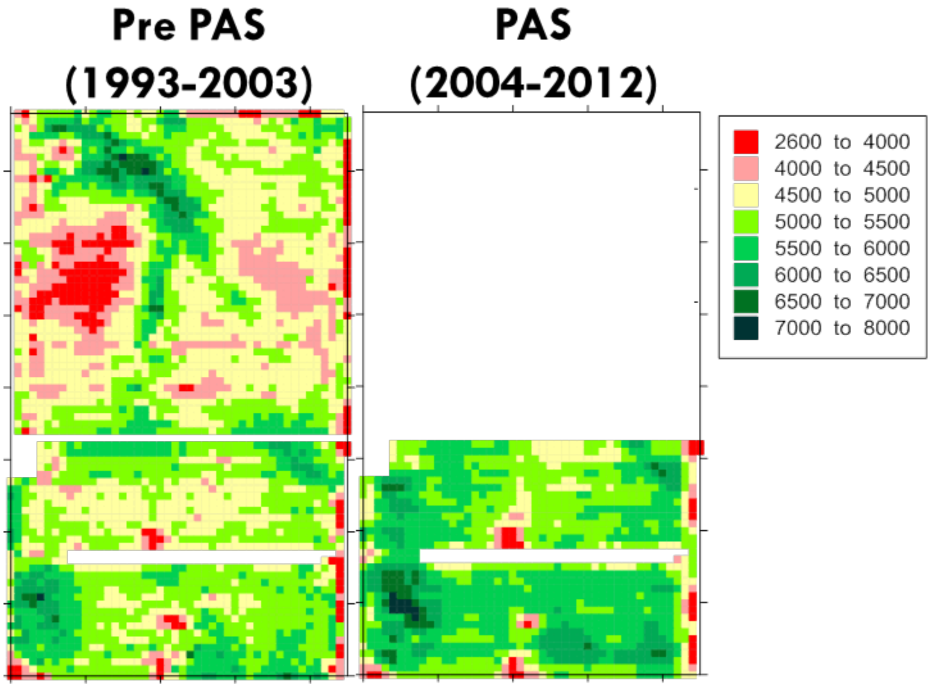

Figure 2 Maps of corn yield (kg/ha) averaged across years during pre-PAS and PAS management.

et al., 2008). Only on the southern 15 ha can corn production from PAS years be compared to pre-PAS years. For PAS, corn grain production averaged 5.49 Mg ha^{-1} and was 0.31 Mg ha^{-1} greater than pre-PAS (a 5% yield increase). We recognize that this type of comparison between two different time periods is confounded by differences in weather years and in improving genetics over time. A more rigorous evaluation will be done in the future that employs calibrated crop

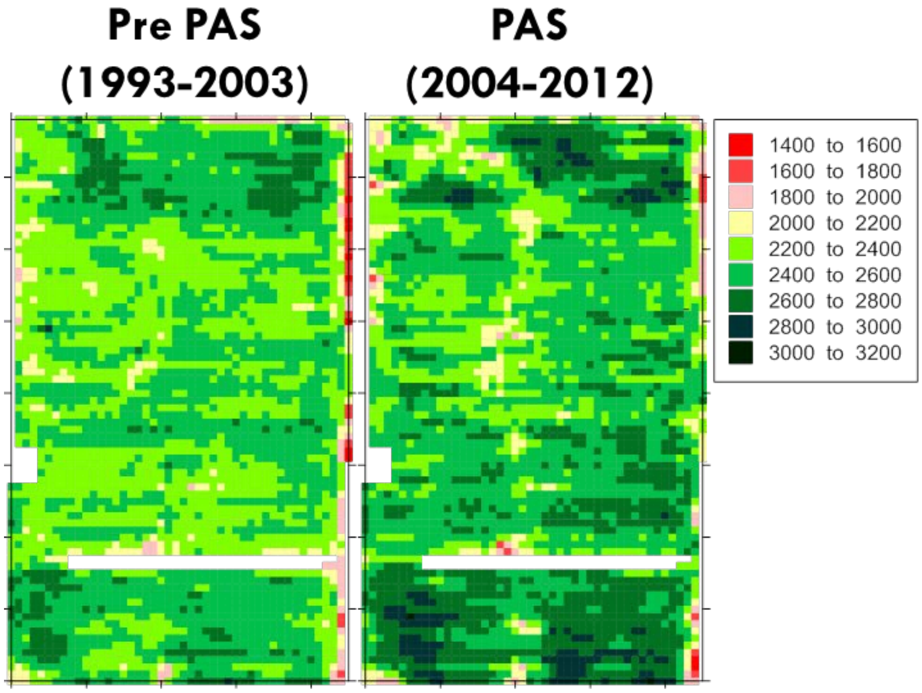

Figure 3. Maps of soybean yield (kg/ha) averaged across years during pre-PAS and PAS management.

modeling to validate production outcomes from both systems under a wide-array of genetic and weather scenarios. We know that weather is the most significant factor affecting yield on these soils, as evidenced by the year-to-year variability. The calculated CV of corn yield within grid cells across multiple years, was similar between the two periods [52.1% for pre-PAS (whole field) and 50.5% for PAS (southern portion)].

Soybean production during pre-PAS years averaged 2.28 Mg ha^{-1}; averaged 2.49 Mg ha^{-1} for PAS years (a 9% increase with PAS) (Fig 3.). Again, weather and genetics could also explain part of this difference. Yield improvement was generally seen over the whole 36-ha field. An exception was a slight yield reduction during PAS years in the alluvial soils where water accumulates in the central portion and flows north off the field (seen in photo 1). This feature was one reason the within-year CV average across years was slightly higher for PAS than pre-PAS (14.3% and 12.2%, respectively). As with corn, the variability within grid cell changed little when comparing the two systems with CVs of 26.9% for pre-PAS and 26.5% for PAS. Note, this grid-cell CV was half that of corn, showing greater yield-stability in soybean.

Wheat yield during the PAS years was generally uniform over the northern 21 ha of the field (Fig. 4). One small area (~1 ha) on the north end of the field where runoff exists the field had significantly lower yield. Extended wet soils in this area of the field negatively affected wheat stand and vigor, causing this yield depression. Within-year yield CV averaged 21.4% and across-year grid-cell CV averaged 38.1%.

To assess spatial changes in yield stability from implementing PAS, pre-PAS within grid-cell CV was divided by PAS grid-cell CV, and the ratio mapped by crop (Fig. 5). Using CV's allows for assessing production across crop types. For the maps in Fig. 5 the color red is interpreted as lower within-cell year-to-year variability with PAS production when compared to pre-PAS years. Map areas in blue are interpreted as higher year-to-year production variability with PAS years than with pre-PAS years. Yellow represents areas where variability was approximately the same (± 5%) between the two management systems.

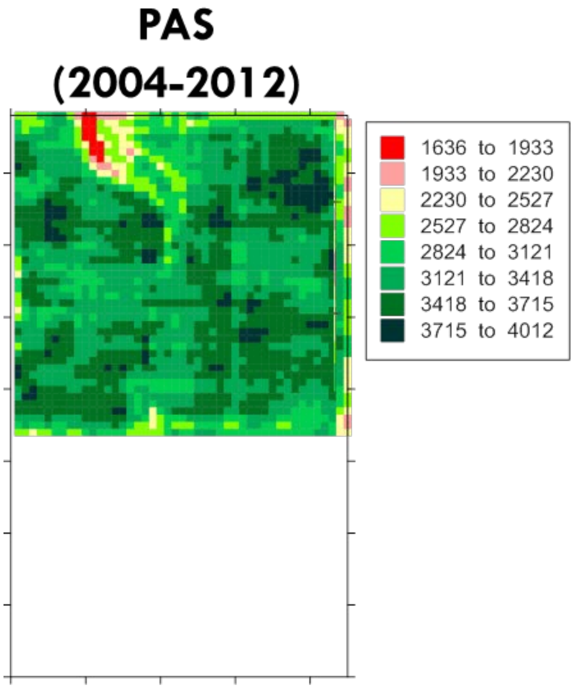

Figure 2. Maps of wheat yield (kg/ha) averaged across years during PAS management.

For corn on the south 15 ha of the field, one half mostly increased in variability with PAS and the other half mostly decreased in variability. No plausible explanation is available for this difference. Over the total corn area the average CV ratio was 1.03.

For soybean, average variability across years for the whole field was slightly

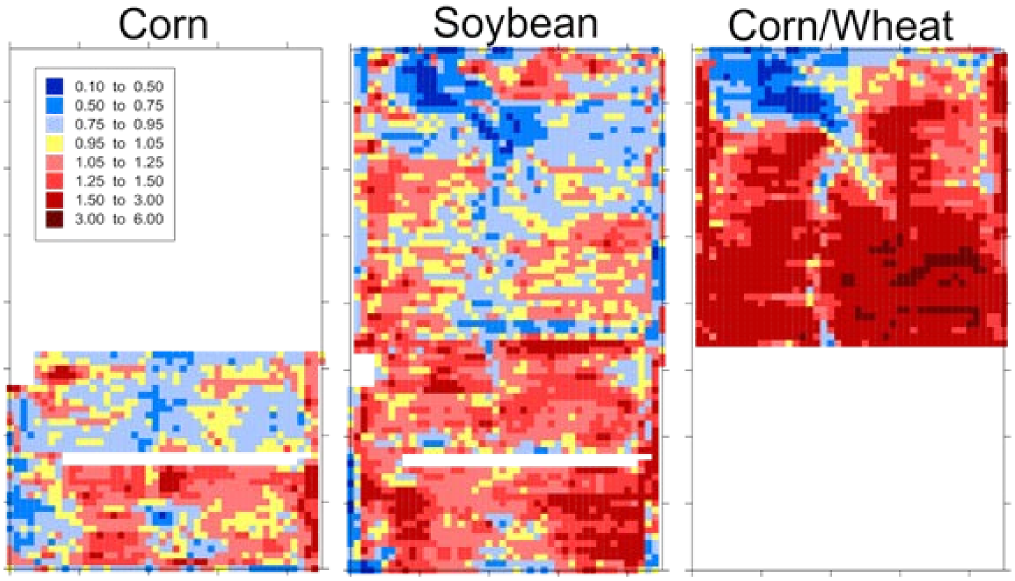

Figure 3. Ratio maps of yield CV across years. Areas in red are where variability across year was less with PAS production when compared to pre-PAS years. Mapped areas in blue are interpreted as where PAS gave higher year-to-year production variability.

lower as a result of PAS than pre-PAS (CV ratio=1.10), however there were spatial differences. On the north 21 ha variability slightly increased with PAS (CV ratio=0.96) but on the southern 15 ha variability with PAS was notably less (CV ratio=1.29). Cover crop type/growth and crop rotation are the main differences between these two field areas.

For the north portion of the field that was in corn for pre-PAS and wheat for PAS, average variability across years was notably less as a result of PAS (CV ratio=1.57), indicating 57% less variability across years with wheat grown in PAS management than with corn grown in pre-PAS management.

Variability in Soil Nutrient

This research field has been grid soil sampled for fertility analysis regularly over the past 20 years. With the inception of PAS management in 2004, fertilizer and lime have been variably applied on the field and one could hypothesize that the variability within the field would decrease. Within-field variability of P, K, and pH by the year sampled were examined by assessing the within-sampling year spatial CVs (Fig. 6). There was a slight downward trend in soil-test P and K CVs after 2004 when PAS began. This was primarily because of an increase in soil test P and K with a significant application of fertilizer material (see Table 2). However CVs increased between the 2007 and 2013 sampling giving a similar range of CVs when comparing before and after PAS management. This initial analysis of soil test P and K results challenges the assumption that variable rate applications can decrease within-field variability of nutrient availability.

Soil pH CVs have decreased slightly because of PAS. Prior to PAS pH CVs ranged from 9.7 to 8.2, compared to 5.8 to 6.8 after PAS.

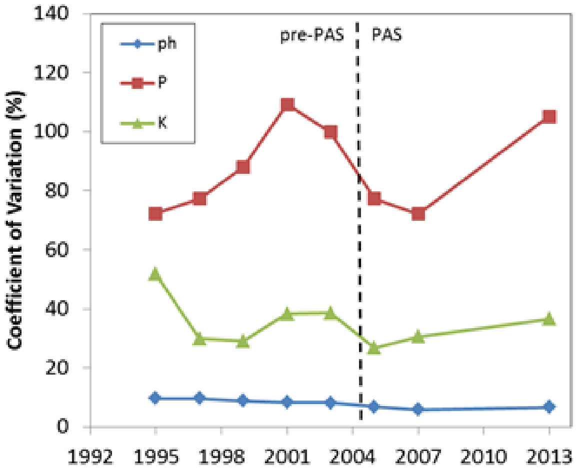

Figure 4. Coefficient of variation within sampling year of soil test pH, P, and K over two decades of grid soil sampling (n=358).

Soil Quality

Soil quality rankings for surface soil are shown for contrasting grain and perennial management systems typical for this region (Fig.7). Grass and pasture systems generated the greatest SMAF scores. Within the grain cropping systems, those in no-till with or without cover crops produced the greatest soil quality scores. As shown on Fig. 7, the system most like the current PAS had a SMAF score of 87 while the system most like the pre-PAS had a score of 76. PAS in 2008 is also shown on Fig. 7. Using the PAS 2008 sampling and the management systems to represent pre-PAS and PAS, and for the length of time these systems have been in place, it is estimated that PAS soil quality using this SMAF metric

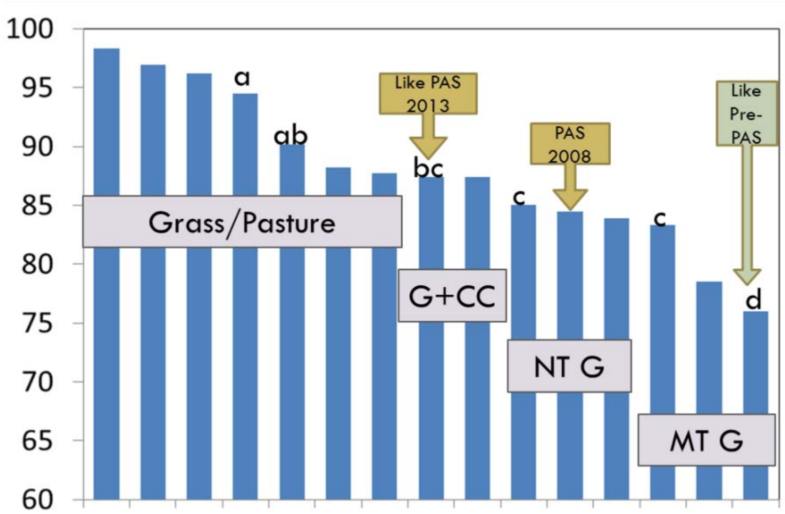

Figure 5. Soil quality rankings of surface soil for 15 contrasting grain (G) and perennial management (Grass/Pasture) systems assessed in 2008 on claypan soil sites near the PAS field. Comparable practices would indicate soil quality scores for pre-PAS and PAS as shown on the graph (CC, cover crop; NT, no-till; MT, mulch till).

has increased annually about one SMAF point over the decade it has been in place. Examining individual soil quality indicators shows the greatest impact on the SMAF score for these claypan soil landscapes comes from the physical and biological categories, and not chemical and nutrient categories. This would suggest that implementation of no-till and cover crops with the PAS system have been the most important management changes that have improved soil quality.

Water Quantity and Quality

Comparison of average monthly runoff coefficients during the two periods for the field (fig.8a) and the watershed (fig. 8b) showed no significant differences. The fact that January and February runoff coefficients for PAS and pre-PAS are similar in the field but higher during PAS for the watershed may indicate an impact of cover crops but the data set and the methodology are not powerful enough to definitely conclude. Further modeling will attempt to ascertain whether we can identify an effect.

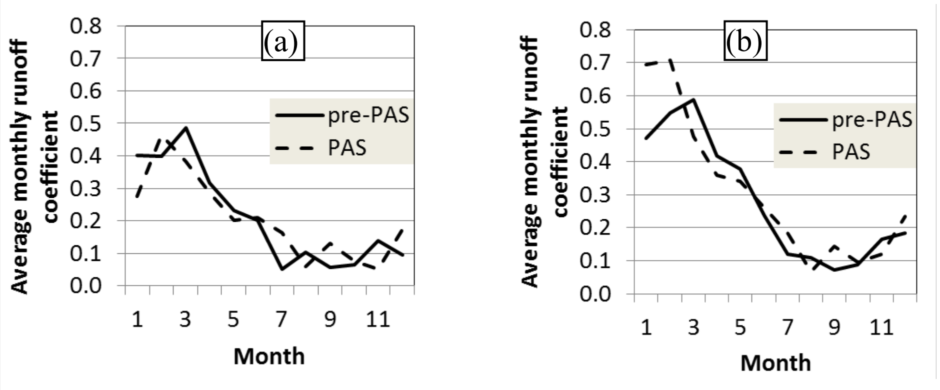

Figure 6. Average monthly field runoff coefficients during the pre-PAS (1993-2002) and PAS (2005-2012) periods, a) for the field, and b) for the watershed.

Comparison of sediment transport showed significant and important (>80%) reductions from PAS (fig. 9). During the pre-PAS period, the higher transport during odd years corresponds to erosion following tillage and planting of corn in soybean residues. Soil loss during soybean years was less because of the larger amounts of corn residues. During the PAS period, there was minimal

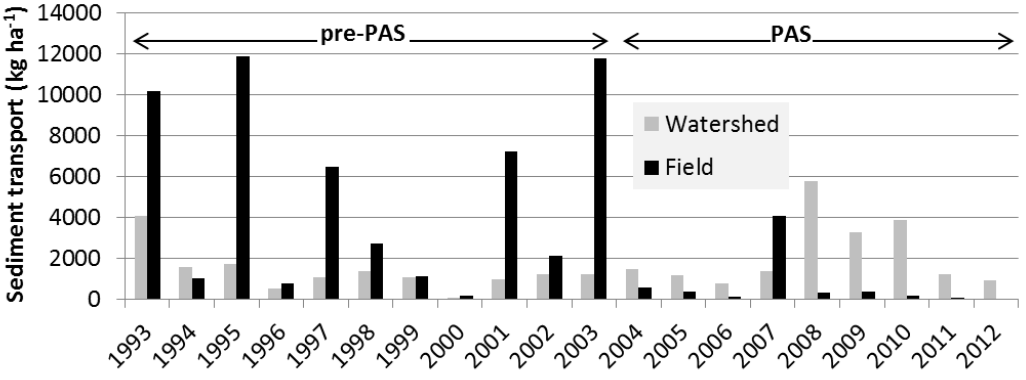

Figure 9. Sediment transport from 1993 to 2012 from the field and the watershed.

sediment transport from the field even though transport out of the watershed remained similar. Even the high precipitation years (2008-2010) did not increase sediment transport from the field. The 2007 spike in sediment transport corresponded to localized tillage just upstream of the weir to remove accumulated sediment.

CONCLUSIONS

Though PAS has only been in place for a decade, significant changes have been documented. Most drastic has been improved water and soil quality factors, especially reduction in sediment loss. Undoubtedly, incorporating no-till and cover crops alone can be attributed to many of these improvements. Yield variability both within-field and across years has been reduced, and there has been a slight improvement in overall corn and soybean yields. Additional analysis will be conducted in the future to use crop and water quality modeling to predict how PAS and pre-PAS perform under the same weather years.

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REFERENCES

Baffaut, C., F. Ghidey, K.A. Sudduth, R.N Lerch, and E.J. Sadler, Long-term suspended sediment transport in the Goodwater Creek Experimental Watershed and Salt River Basin, Missouri, USA, Water Resources Research*,* 49: 7827-2830, doi: 10.1002/wrcr.20511.

Baffaut, C., E.J. Sadler, and F. Ghidey. 2014 Long-term agro-ecosystem research in the central Mississippi river basin, USA – Goodwater Creek Experimental Watershed flow data. J. Env. Qual. In press.

Berry, J.K., J.A. Delgado, R. Khosla and F.J. Pierce. 2003. Precision conservation for environmental sustainability. J. Soil and Water Cons. 58:332-339.

Bianchini, A.A. and A.P. Mallarino. 2002. Soil-sampling alternatives and variable-rate liming for a soybean–corn rotation. Agron. J. 94:1355-1366.

Bongiovanni, R. and J.Lowenberg-Deboer. 2000. Economics of variable rate lime in Indiana. Precision Agric. 2:55-70.

Dinnes, D.L., D.L. Karlen, D.B. Jaynes, T.C. Kaspar, J.L. Hatfield, T.S. Colvin, and C.A. Cambardella. 2002. Nitrogen management strategies to reduce nitrate leaching in tile-drained Midwestern soils. Agron. J. 94:153-171.

Drummond, S.T., K.A. Sudduth, A. Joshi, S.J. Birrell, and N.R. Kitchen. 2003. Statistical and neural methods for site-specific yield prediction. Trans. ASAE 46(1): 5-14.

Kitchen, N. R., K.A. Sudduth, D.B. Myers, R.E. Massey, E.J. Sadler, R.N. Lerch, J.W. Hummel, and H.L. Palm. 2005. Development of a conservation-oriented precision agriculture system: Crop production assessment and plan implementation. J. Soil Water Cons. 60(6): 421-430.

Kitchen, N.R., K.A. Sudduth and S.T. Drummond. 1999. Electrical conductivity as a crop productivity measure for claypan soils. J. Prod. Agric. 12(4): 607-617.

Kitchen, N.R., K.A. Sudduth, S.T. Drummond, P.C. Scharf, H.L. Palm, D.F. Roberts, and E.D. Vories. 2010. Ground-based canopy reflectance sensing for variable-rate nitrogen corn fertilization. Agron. J. 102: 71-84.

Larson, W.E., J.A. Lamb, B.R. Khakural, R.B. Ferguson, and G.W. Rehm. 1997. Potential of site-specific management for nonpoint environmental protection. p. 337-367. In The State of Site-Specific Management for Agriculture (ch. 15). ASA, CSSA, SSSA, Madison, WI.

Lerch, R.N., N.R. Kitchen, R.J. Kremer, W.W. Donald, E.E. Alberts, E.J. Sadler, K.A. Sudduth, D.B. Myers, and F. Ghidey. 2005. Development of a conservation-oriented precision agriculture system: Water and soil quality assessment. J. Soil Water Cons. 60(6): 411-421.

Massey, R.E., D.B. Myers, N.R. Kitchen, and K.A. Sudduth. 2008. Profitability maps as input for site-specific management decision making. Agron. J. 100:52-59.

Pierce F.J., and P. Nowak. 1999. Aspects of precision agriculture. Advances in Agron. 67:1-85.

Sadler, E.J., C.R. Camp, D.E. Evans, and J.A. Millen. 2002. Spatial variation of corn response to irrigation. Trans. ASAE 45(6): 1869-1881.

Scharf, P.C., D.K. Shannon, H.L. Palm, K.A. Sudduth, S.T. Drummond, N.R. Kitchen, L.J. Mueller, V.C. Hubbard, and L.F. Oliveira. 2011. Sensor-based nitrogen applications out-performed producer-chosen rates for corn in on-farm demonstrations. Agron. J. 103:1683–1691.

Stott, D.E., C.A. Cambardella, M.D. Tomer, D.L. Karlen, and R. Wolf. 2011. A soil quality assessment within the Iowa River South Fork watershed. Soil Science Society of America Journal 75(6):2271-2282.

Sudduth, K.A., and S.T. Drummond. 2007. Yield editor: Software for removing errors from crop yield maps. Agron. J. 99:1471-1482.

Sudduth, K.A., D.B. Myers, N.R. Kitchen, and S.T. Drummond. 2013. Modeling soil electrical conductivity-depth relationships with data from proximal and penetrating ECa sensors. Geoderma. 199:12-21.

USDA-NRCS. 2009. Variable-Rate Nitrogen Fertilizer Application in Corn Using In-field Sensing of Leaves or Canopy. Missouri NRCS Agronomy Tech Note 35. Available online at: http://www.mo.nrcs.usda.gov/technical/agronomy/out/Agronomy%20Technical%20Note%20MO-35.pdf.

Wienhold, B.J., D.L. Karlen, S.S. Andrews, and D.E. Stott. 2009. Protocol for indicator scoring in the soil management assessment framework (SMAF). Renew. Agric. Food Syst. 24:260–266.