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A long-term precision agriculture system sustains grain profitability

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A long-term precision agriculture system sustains grain profitability

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Abstract

After two decades of availability of grain yield-mapping technology, long-term trends in field-scale profitability for precision agriculture (PA) systems and conservation practices can now be assessed. Field-scale profitability of a conventional or 'business-as-usual' system with an annual corn (*Zea mays* L.)-soybean (*Glycine max* [L.]) rotation and annual tillage was assessed for 11 years on a 36 ha field in central Missouri during 1993 to 2003. Following this, a 'precision agriculture system' (PAS) with conservation practices was implemented for the next 11 years to address production, profit and environmental concerns. The PAS was multifaceted and temporally dynamic. It included no-till, cover crops, crop rotation changes, site-specific N and variable-rate or zonal P, K and lime. Following a recent evaluation of differences in yield and yield variability, this research compared profitability of the two systems. Results indicated that PAS sustained profits in the majority (97%) of the field without subsidies for cover crops or payments for enhanced environmental protection. Profit was only lower with PAS in a drainage channel where no-till sometimes hindered soybean stands and wet soils caused wheat (*Triticum aestivum* L.) disease. Although profit gains were not realized after 11 years of PA and conservation practices, this system sustained profits. These results should help growers gain confidence that PA and conservation practices will be successful.

Keywords Precision conservation · Precision nutrient management · Integrated precision practices · Crop production · No-till · Cover crops

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Introduction

Precision agriculture (PA) could be described as a suite of decision-support systems that seek to manage spatial and temporal variability in order to maximize crop yield, quality and profit, and improve input efficiency and environmental outcomes minimizing environmental harm on each unit of land (both managed farmland and land impacted by farmland)—be it hectare or sub-hectare. Precision conservation (PC) specifically addresses the concept of reducing environmental harm, such as decreasing soil erosion or nutrient losses (Berry et al. 2003; Delgado et al. 2011). In addition to minimizing harm, PC also seeks to restore or build soil health (Abit et al. 2018), which in turn will help improve the resiliency and sustainability of agricultural systems in future climates. Precision conservation can include variable-rate application of agrochemicals and irrigation, a hallmark of PA, but might also include targeted use of no or reduced tillage, cover crops, diversifying crop rotations for ecosystem services or other approaches.

As a relatively new farming system approach with rapidly evolving technologies, few long-term agronomic and economic evaluations of PA or PC systems exist in the United States or other parts of the world (Bullock and Bullock 2000; Bullock and Lowenberg-DeBoer 2007; Lal 2015). This lack of information is especially apparent at the field scale because grain yield monitoring systems were not available prior to the early 1990 s. The impacts of many major components of PA and PC on crop profitability have been tested in short-term trials at several scales ranging from small plots to whole farm fields. Results from over 200 studies on PA profitability were summarized by Griffin and Lowenberg-DeBoer (2005). This literature synthesis revealed that variable-rate applications of N were profitable in 72% and 20% of the studies for corn and wheat, respectively, and variable-rate P and K were profitable in 60% of studies for corn. It also showed that other PA practices such as yield mapping and global navigation satellite systems (GNSS) were generally profitable for most crops. Their review did acknowledge that profitability from PA practices was highly dependent on inherent variability in crop response to fertilizer application of a given field and farm as later confirmed by Lambert et al. (2006) and Liu et al. (2006).

More recent studies and reviews have confirmed that profitability at the field level is generally maintained or improved with variable-rate fertilizer applications, and that farm- and society level benefits will also need to be considered in the future (Schimmelpfennig 2016; Balafoutis et al. 2017; Griffin et al. 2018; Lowenberg-DeBoer 2018). Investigation of conservation practices has a much longer history than PA evaluations. The economics of conservation tillage systems including no-tillage, cover crops and diversified crop rotations have been studied for many decades. Ervin and Washburn (1981) estimated that conservation practices may only be economic on steeper soil areas in Missouri, but Triplett and Dick (2008) reviewed the economics of no-tillage studies in the literature and found that profitability was widely positive. Reviews of cover crop literature have found that they usually maintain or increase cash crop yield in water abundant cropping systems, but that their environmental services and profitability are highly site-specific (Snapp et al. 2005; Blanco-Canqui et al. 2015). Diversified crop rotations in North Dakota also improved profits over 12 years compared to systems with less diversity (Archer et al. 2018). While the aforementioned and many other practices have proven economic benefits, the cumulative impacts of PA and conservation practices together in a PA / PC system have seldom been investigated, especially at the field scale and over long time periods.

Shortly after some of the first grain yield-monitoring systems were commercialized, spatial data collection was initiated for a 36 ha field near Centralia, Missouri, USA.

Beginning in 1993, annual spatial crop yield and periodic spatial soil information were collected across the field under conventional or 'business-as-usual' management. A local grower owned and farmed the field with annual rotations of corn and soybean, annual tillage and uniform chemical inputs for the first 11 year. In 2004, a system termed a 'precision agriculture system' (PAS) was developed and initiated for another 11 year. The PAS was a combination of PA and PC and hereafter is referred to mainly as PAS. A slightly modified version of this system is still under investigation as an 'aspirational' system in the USDA Long-Term Agroecosystem Research (LTAR) network. Many of the other LTAR cropland sites across the USA are beginning to test aspirational systems that include PA and PC (Spiegal et al. 2018) and the present evaluation should help guide future LTAR efforts.

Management in PAS during 2004 to 2014 was targeted to soil and landscape characteristics varying within the field and included cover crops, no-tillage, crop rotation changes and variable-rate chemical inputs (Kitchen et al. 2005). As one of the few fields in the world with over two decades of spatial yield data, this site offered a unique opportunity to examine the long-term profitability of precision agriculture and conservation practices. Hypotheses were that PAS management would increase crop production and crop profitability, decrease crop production variability and improve soil and water quality over the conventional system. The production-related hypotheses have been tested previously (Yost et al. 2017). The objective of this article was to compare crop profitability between PAS and the conventional system (CONV).

Materials and methods

Site description and cropping system management

The study area was a 36 ha field in central Missouri (39°13′45″N, 92°7′2″W) (Fig. 1). Soils in the field were predominately Adco silt loam (fine, smectic, mesic Vertic Albaqualf) with 0 to 1% slopes and Mexico silt loam or silty clay loam (fine, smectic, mesic Vertic Epiaqualf) with 1 to 3% slopes. They are classified as claypan soils and contain abrupt clay-rich layers at shallow depths. Detailed elevation, depth to claypan (depth between soil surface and Bt_1 horizon) and soil physical and chemical characteristics of this site were measured in 1999 and have been reported previously (Kitchen et al. 1999; Drummond et al. 2003; Kitchen et al. 2005).

During 1993 to 2003, the field was conventionally managed with annual tillage, uniform fertilizer and herbicide rates, no cover crops and a 2-year crop rotation with corn in odd years and soybean in even years (Table 1). One exception to the crop rotation was sorghum instead of corn in 1995 due to extremely wet soil conditions in the spring that prevented corn planting. The PAS system was implemented during 2004 to 2014 (Kitchen et al. 2005). Management practices used across the entire field included: (i) no-tillage; (ii) cover crops in all years; (iii) variable-rate N fertilizer applied to cereal grain crops using commercial ground-based canopy reflectance technologies (USDA-NRCS 2009; Kitchen et al. 2010); and (iv) zonal or variable-rate P, K and lime fertilizer based on 30-m grid-sample soil-test results and University of Missouri fertilizer recommendations (Buchholz et al. 2004). Some practices in this system differed between management zones, which were created using profitability maps of the conventional system during 1993 to 2003 (Massey et al. 2008), coupled with local scientist and stakeholder expertise (Table 1). One zone encompassed the northern 21 ha of the field (Fig. 1) where corn production had not

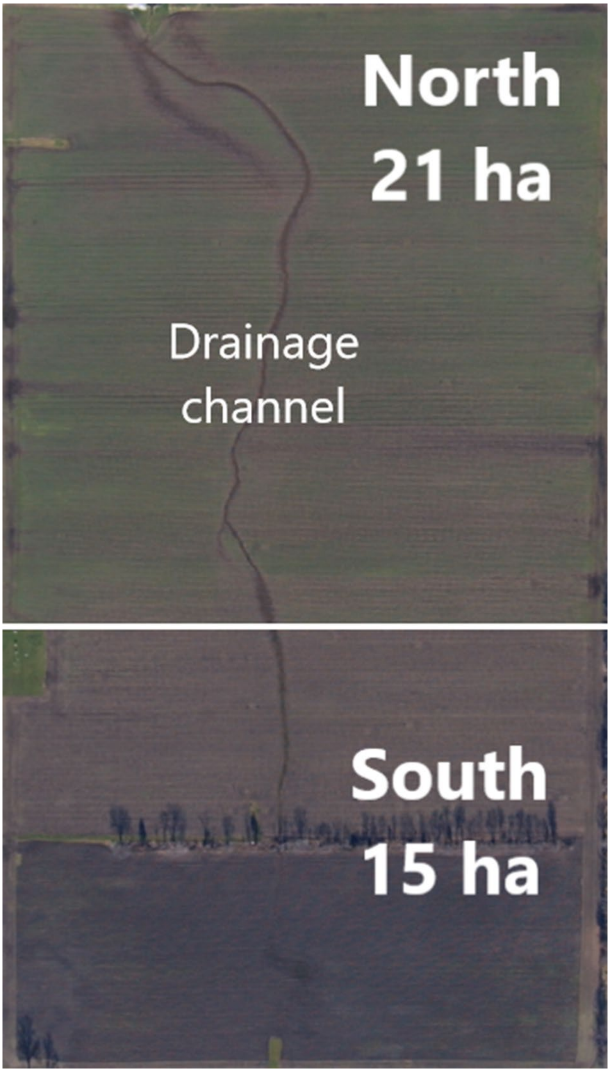

Fig. 1 Aerial photograph of 36 ha study field near Centralia, Missouri taken on 9 Dec. 2004 at the initiation of PAS

been profitable for much of the area. This zone included shoulder and backslope landscape positions that had historically experienced severe topsoil loss and exacerbated herbicide and nutrient losses (Lerch et al. 2005). In this zone, winter wheat replaced corn in PAS. Cover crops following wheat included medium red clover (*Trifolium pratense* L.), sudangrass (*Sorghum sudanense* P. Stapf) or mixtures of legumes and non-legumes.

The other zone comprised the southern 15 ha of the field (Fig. 1) and represented mainly summit and some shoulder landscape positions. Profitability generally had been positive in this zone during 1993 to 2003 for both corn and soybean. This zone had lower slope, less erosion, greater topsoil thickness and greater soil organic matter than the northern zone (Kitchen et al. 1999; Yost et al. 2017). The corn-soybean crop rotation was maintained in this zone for PAS. Cover crops following corn included cereal rye (*Secale cereals* L.) or mixtures of legumes and nonlegumes and covers following soybean included annual

Table 1 Generalized management description for the conventional system during 1993 to 2003 and the precision agriculture system (PAS) during 2004 to 2014

Practice	Conventional	PAS
Crop rotation	Annual corn/soybean	North: annual wheat/soybean South: annual corn/soybean
Tillage	Spring mulch tillage and one or two field cultivations	None
Cover crop[a]	None	North: Medium red clover, sudangrass, or legume and non-legume mix following winter wheat harvest. Winter wheat seeded after soybean harvest. South: Cereal rye or legume and non-legume mix after corn harvest. Annual ryegrass or legume and non-legume mix after soybean harvest.
Major herbicides[b]	Corn: atrazine, alachlor and metolachlor Soybean: alachlor, metolachlor, imazaquin	Corn: split-applied atrazine, other post-emerge plant-active herbicides as needed Soybean: split-applied glyphosate, other post-emergence as needed Wheat: rare except in few years to control ryegrass
N fertilization	Pre-plant broadcast, incorporated for corn and sorghum	Split-applied with 1/3 uniform rate at planting plus remainder as variable rate sidedress based on canopy sensors for corn and winter wheat
P, K fertilization	1993, 1995, 2001 at local cooperative rec. rates.	2004, 2006, 2008, 2013 at Univ. of MO rec. rates.
Lime	None	2004

[a] 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)

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

ryegrass (*Lolium multiflorum* Lam.) or mixtures of legumes and nonlegumes. For more specific management details see Yost et al. (2017).

Crop measurements

Grain yield was measured each year with a field-scale combine equipped with a commercial yield monitor. Grain moisture was adjusted to 155, 130 and 135 g kg^{-1} for corn, soybean and wheat, respectively. Yield data calibrations were checked using periodic grain mass measurements during harvest and adjusted if necessary. Yield monitor data were cleaned using Yield Editor software (Sudduth and Drummond 2007) to remove erroneous data. Cleaned yield monitor data were interpolated with the geostatistical technique of block kriging using GS+ (Gamma Design Software, LLC, Plainwell, MI, USA). Best-fitting semi-variograms developed by year and crop were used for kriging yield data to 10 m square grids. Kriged yield data for the east-west border between zones that received extra machinery traffic and herbicide drift, the weather station and the east-west tree line in the southern zone were omitted from analysis.

Input and output prices

Annual prices for inputs and outputs during 2007 to 2014 were considered in this analysis. This range of years was selected based on: (i) the ending date of the study; (ii) availability of prices; and (iii) and an attempt to capture a range in prices that may be realized in current and near-term future markets. A single U.S. dollar price was used for each input in the profitability calculation. This price was either the average price of each input during 2007 to 2014 or the average price during 2013 and 2014 if there was a linear increase in price over time according to linear regression results at $P \leq 0.10$ using the REG procedure of SAS (SAS Institute 2011).

Most herbicide and adjuvant prices were obtained from the North Dakota herbicide compendiums (Zollinger 2007–2014) and most fertilizer and fungicide prices were obtained from national prices paid by growers (USDA-NASS 2017). When prices could not be obtained from these two sources, they were obtained from local input suppliers or were actual prices paid for products used in the study. Custom rates for tillage, shredding, seeding, agrichemical, harvest and soil sampling operations were obtained from Iowa custom farming rate surveys (Edwards and Johanns 2007–2014). National grain crop seed prices were obtained from USDA-NASS surveys and separate prices were used for biotech and non-biotech corn and soybean seed (USDA-NASS 2017). When grain crops had to be replanted due to emergence failure, only 50% of the replant seed cost was charged. Seed prices for many of the most common cover crops were also obtained from USDA-NASS (2017), while those that were not available were obtained from Green Cover Seed in Lincoln, Nebraska. Crop insurance premiums and payouts were not included because detailed records of these payments were not kept. Land prices and the cost of yield mapping were considered fixed costs common among systems and not included.

Output prices for grain crops were obtained from the Center for Farm Financial Management (2018) for up to 2000 farms in nine Midwest states including Missouri. The same database was used to obtain forage prices for cover crops harvested and sold in 2007 and 2008. The minimum, mean and maximum selling price of grain crops during 2007 to 2014 were used to evaluate three profit scenarios.

Profitability comparison of systems

The first step in the analysis was to examine whether yields had increased over time. Field yields could not be used for this because management changed over time. Therefore, average yields from replicated large plots adjacent to the field (Yost et al. 2016) with consistent management over time were utilized. Linear regressions fit by crop for the average plot yield during 1991 to 2014 were not significant ($P=0.59$ for corn, $P=0.61$ for soybean and $P=0.97$ for wheat) indicating that yield did not need to be detrended (Delbridge et al. 2011). The independence of yield and grain price was also evaluated for each grain crop using linear regressions. No relationships existed between grain yield and price ($P=0.97$ for corn, $P=0.66$ for soybean and $P=0.83$ for wheat) indicating that the two variables could be combined to estimate gross returns that might account for risk and variability in markets that a grower might experience (Delbridge et al. 2011).

The costs of tillage or residue management operations that occurred in the fall after grain crop harvest were attributed to the grain crop in the subsequent year. Winter wheat costs were all applied to the year of harvest. Phosphorus, K and lime fertilizer and application costs were amortized over the 11 year of each system. Likewise, all cover crop costs (seed and herbicides) and outputs (cover crops harvested and sold in 2007 and 2008) were amortized over the 11 year of PAS. These inputs were amortized because they are long-term investments that influence the profit in more than the year of application.

Profit, or return to land and management, was calculated for each 10 m grid cell each year during 1993 to 2014 by summing up all variable input costs and subtracting them from the gross return. Fifteen profit comparisons were made between PAS and CONV. These included five profit comparisons at each of three grain price levels (minimum, mean and maximum during 2007 to 2014). The first profit comparison included all crops and all years. The additional four comparisons excluded sorghum in 1995 and soybean in the 2004 transition year and were (i) profit of all crops; (ii) profit of all crops in last 4 year of each system; (iii) soybean profit across the whole field; and (iv) corn profit in the southern zone and corn versus wheat in the northern zone. The comparison of the last 4 year of each system was included because the impacts of a new system such as PAS on crop profit may take time to realize.

Temporal and spatial variation in profit were compared between CONV and PAS. Temporal variation was calculated as the standard deviation (STDEV) in profit within each grid cell over time and was evaluated using the same 15 comparisons mentioned above for profit. Absolute values of differences $>25\%$ were chosen to examine large changes in temporal variation caused by PAS (Blackmore 2000; Yost et al. 2017). Spatial variation was the STDEV in profit across the field and was compared between systems. All differences in profit or profit STDEV by or across crops between CONV and PAS were evaluated using two-tailed *t*-tests at $\alpha \leq 0.10$.

Results and discussion

Weather conditions

Precipitation and air temperature were measured on site during the whole study period (Sadler et al. 2015). The mean cumulative precipitation and growing degree days were numerically greater during PAS than CONV, yet there were no differences ($P \geq 0.42$) in either measure between systems according to paired *t* tests (Table 2). Despite the lack of differences in average weather conditions among systems, there were significant annual variations in weather conditions in both systems and PAS had the largest weather deviations. In general, CONV had more years with low precipitation and growing degree days than PAS. Five PAS years (2005, 2008–2010 and 2012) had large deviations in semi-annual or annual cumulative growing degree days and/or precipitation from the average conditions during the 22 years of the study (Table 2). Shortly after PAS implementation in 2005, excessive precipitation occurred during January to March (74 mm more than any other year besides 2008). Three years later in 2008, annual cumulative precipitation was 241 mm greater than any other year of the study period and was 659 mm greater than the 22-year average. The two subsequent years also had more than 300 mm above the 22-year average. The drought and warm air temperatures (391 more °C -days than the 22-year average) of 2012 also occurred during PAS. Therefore, while both systems generally experienced similarities in weather conditions, PAS had larger deviations (warm or wet) from average conditions than CONV.

Expenses

Harvest and residue shredding costs were the only two expenses that were similar between CONV and PAS (Table 3). These costs were only slightly lower in PAS ($3 for harvest and $9 ha^{-1} year^{-1} for shredding) than CONV due to the inclusion of wheat instead of corn. Nitrogen fertilizer costs were $38 ha^{-1} year^{-1} lower in PAS than CONV due mainly to

Table 2 Cumulative precipitation and growing degree days with deviation from average conditions across the study period (1993–2014) in parenthesis for each year of the conventional (CONV) and precision agriculture system (PAS), along with the mean, standard deviation (STDEV) and coefficient of variation (CV) for each system

CONV			PAS		
Year	Cumulative precip. mm	Cumulative GDD °C-day	Year	Cumulative precip. mm	Cumulative GDD °C-day
1993	1340 (93)	2092 (−213)	2004	1138 (236)	2143 (−162)
1994	857 (−256)	2241 (−64)	2005	941 (8)	2469 (164)
1995	1150 (16)	2215 (−90)	2006	933 (72)	2369 (64)
1996	875 (−441)	2097 (−208)	2007	753 (−169)	2545 (240)
1997	941 (−361)	2145 (−160)	2008	1581 (659)	2090 (−215)
1998	1158 (−16)	2464 (159)	2009	1236 (338)	2059 (−246)
1999	824 (−350)	2398 (93)	2010	1283 (387)	2426 (121)
2000	926 (−248)	2397 (92)	2011	768 (−91)	2402 (97)
2001	1028 (−61)	2377 (72)	2012	838 (−39)	2696 (391)
2002	860 (−182)	2352 (47)	2013	936 (35)	2262 (−43)
2003	1076 (219)	2256 (−50)	2014	1045 (151)	2216 (−89)
Mean	1003	2276	Mean	1041	2334
STDEV	163	130	STDEV	251	200
CV	16%	6%	CV	24%	9%

Table 3 Average annual expense by and across expense categories and the difference in expenses between the weighted average of PAS (2004–2014) and CONV (1993–2003) systems

Year	Cover crops $\$\ \mathrm{ha}^{-1}$	Nitrogen	Other fertilizer	Tillage	Pesticides	Seed	Harvest	Shredding	Total
1993	0	381	48	68	123	196	84	0	901
1994	0	0	48	96	110	141	84	29	508
1995	0	281	48	137	90	66	84	0	706
1996	0	0	48	146	128	156	84	0	563
1997	0	281	48	68	118	208	84	0	809
1998	0	0	48	141	128	225	84	0	627
1999	0	281	48	103	197	196	84	0	910
2000	0	0	48	103	183	218	84	29	666
2001	0	368	48	68	198	270	84	0	1037
2002	0	0	48	36	126	221	84	40	556
2003	0	326	48	72	131	196	84	0	858
CONV avg.	0	174	48	94	139	190	84	9	740
2004 (north/south)	144/102	0/0	170/117	85/85	51/51	199/199	84/84	0/0	733/639
2005	144/102	217/337	170/117	0/0	0/147	129/301	74/84	0/0	733/1088
2006	144/102	0/0	170/117	0/0	60/93	225/225	84/84	0/0	684/622
2007	144/102	250/321	170/117	0/0	0/202	117/351	74/84	0/0	755/1177
2008	144/102	0/0	170/117	0/0	59/59	268/268	84/84	0/0	724/630
2009	144/102	325/408	170/117	0/0	64/173	129/319	74/84	0/0	905/1204
2010	144/102	0/0	170/117	0/0	94/66	220/220	84/84	0/0	712/590
2011	144/102	193/375	170/117	0/0	91/191	104/700	74/84	0/0	776/1571
2012	144/102	0/0	170/117	0/0	243/215	196/196	84/84	0/0	837/714
2013	144/102	244/399	170/117	0/0	91/156	129/319	74/84	0/0	851/1178
2014	144/102	39/0	170/117	0/0	239/259	178/178	84/84	0/0	855/740

Table 3 (continued)

Year	Cover crops $ ha^{-1}	Nitrogen	Other fertilizer	Tillage	Pesticides	Seed	Harvest	Shredding	Total
PAS avg.	144/102	115/167	170/117	8/8	90/146	172/298	79/84	0/0	778/923
PAS–CONV	127	− 38	100	− 86	− 26	34	− 3	− 9	97

Expenses for PAS are separated by the north 21 ha and south 15 ha zones less N application to wheat than corn in the northern zone. Variable-rate nitrogen to corn in the southern 15 ha only saved an average of \$7 ha^{-1} $year^{-1}$ in expenses. Phosphorus, K and lime costs were \$100 ha^{-1} $year^{-1}$ greater in PAS due to the need to elevate site-specific P and K levels in PAS following a drawdown of soil test P and K by the co-operating grower during the CONV system, but also included added costs associated with more intense soil sampling and variable-rate technology. Seed costs also increased by \$34 ha^{-1} $year^{-1}$ in PAS. This was mainly due to greater occurrence of crop replanting from extreme weather during PAS but also included greater use of more expensive biotech varieties during this period. Corn was replanted three times on the entire southern 15 ha and once on 4 ha during PAS versus only one occurrence of replanting during CONV (4 ha of soybean replanted). Biotech seed was used in all 11 year of PAS, but only 6 of 11 year of CONV. These added costs of PAS were partially offset by \$26 ha^{-1} $year^{-1}$ lower pesticide costs in PAS than CONV, due in large part to the inclusion of wheat. Cover crops added an additional \$127 ha^{-1} $year^{-1}$ in expenses during PAS, but were offset by \$86 ha^{-1} $year^{-1}$ less tillage costs in PAS. Overall, PAS had \$97 ha^{-1} $year^{-1}$ more expenses than the CONV system.

Soybean profit

Soybean profit comparisons excluded 2004 because it was the transition year and by excluding this year, each system had 5 year of soybean. On average, soybean was profitable every year across both the northern and southern zones of the field during the CONV system (Fig. 2; Table 4). In contrast, average soybean profit was negative in the northern zone during PAS in 2008 and 2012 due to the coupled effects of extreme weather conditions those years and more excessive cover crop residue than the southern zone (Table 2). Raw differences in mean profit between PAS and CONV showed that soybean profit was generally lower during PAS throughout most of the northern zone, but was equal or greater in PAS in the southern zone (Fig. 3). These trends were similar at all three grain price levels. However, few statistical differences occurred in profit between the two systems (Fig. 4). Soybean profit was significantly lower during PAS in a small section of the drainage channel in the northern zone, representing only 3% of total area of the field (Table 5). This reduction in profit was mainly due to decreased soybean stand densities and yield (Yost et al. 2017). Stand densities were not measured consistently throughout the study, but the farm manager's observations and notes indicate that densities were often reduced in the drainage channel during PAS. The compounding effects of no-tillage and cover crop residue in the drainage channel through the field where the soil is often saturated was interpreted to have made it more difficult to produce uniform stands in PAS. Prior studies have also shown that large amounts of cover crop biomass in no-till systems can negatively influence soybean emergence and growth (Williams et al. 2000). Given that PAS only reduced soybean profit in a small percentage of the field, no-tillage, cover crops and variable-rate fertilization should be viable for soybean grown in rotation with wheat or corn.

In all three grain price scenarios, temporal variability of soybean profit was equivalent (i.e., within $|<25\%|$ difference) for over half (56–67%) of the entire field and almost no areas of the field (1–3%) had reduced temporal variation (Table 5; Fig. 5). Temporal variation of soybean profit increased with PAS by 50 to 100% above CONV mainly in the northern half of the northern zone (Fig. 5). The spatial variation in soybean profit across zones at mean grain prices ranged from \$30–61 ha^{-1} in CONV and \$50–73 ha^{-1} in PAS (Table 4) and on average was \$23 ha^{-1} greater during PAS than CONV ($P = 0.015$). At minimum

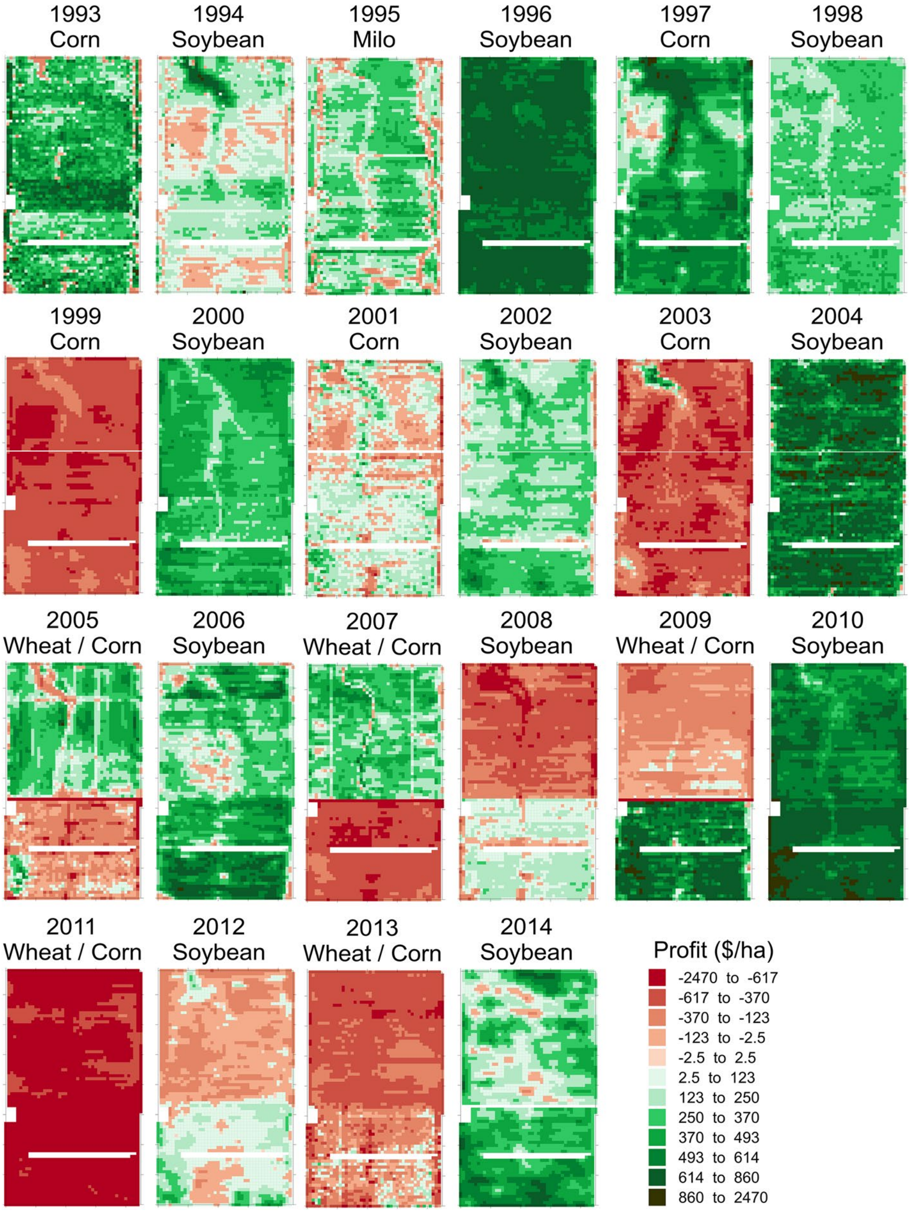

Fig. 2 Annual maps of crop profits during the conventional (CONV) system (1993–2003) and precision agriculture system (PAS) (2004–2014) (Color figure online)

and maximum grain prices, the increase in spatial variation with PAS was \$10 ha^{-1} ($P \leq 0.030$). Although PAS increased both temporal and spatial variation in soybean profit, it did not influence soybean profit for nearly all of the field. This indicates that more site-specific management of P, K and lime along with other aspects of PAS did not help reduce variability in or increase soybean profit. Contrasting results from a 5-year study in Minnesota

Table 4 Annual profit and spatial variation of profit (profit standard deviation (STDEV) across zones) by crop and zone using mean grain prices during 2007 to 2014

Year	Northern 21 ha zone			Southern 15 ha zone		
	Crop	Profit $ ha^{-1}	STDEV	Crop	Profit $ ha^{-1}	STDEV
1993	Corn	154	75	Corn	151	85
1994	Soybean	55	69	Soybean	45	46
1995	Sorghum	81	62	Sorghum	83	67
1996	Soybean	265	30	Soybean	269	34
1997	Corn	159	83	Corn	205	39
1998	Soybean	111	29	Soybean	120	31
1999	Corn	− 220	44	Corn	− 195	38
2000	Soybean	152	36	Soybean	149	38
2001	Corn	3	61	Corn	34	61
2002	Soybean	89	45	Soybean	113	49
2003	Corn	− 196	87	Corn	− 192	68
2004	Soybean	206	75	Soybean	225	60
2005	Wheat	86	69	Corn	− 100	86
2006	Soybean	144	64	Soybean	216	64
2007	Wheat	64	50	Corn	− 171	42
2008	Soybean	− 11	58	Soybean	97	45
2009	Wheat	− 179	47	Corn	211	70
2010	Soybean	203	39	Soybean	262	43
2011	Wheat	− 71	67	Corn	− 343	80
2012	Soybean	− 39	36	Soybean	46	45
2013	Wheat	− 227	31	Corn	− 53	84
2014	Soybean	90	61	Soybean	172	48

showed that variable-rate P alone provided profit advantages for soybean (Lambert et al. 2006). Differences among studies may be related to inherent variability in soil P levels, variation in crop response to applied P and other environmental conditions. It was not possible to isolate the impacts of weather on PAS performance in the present study, and more extreme weather conditions during PAS may have caused much of the increased variation. This may be especially apparent because soybean was grown in PAS during the extreme 2012 drought. It was encouraging, however, that PAS did not increase temporal variability in soybean profit in over half of the field despite more extreme weather, suggesting greater resiliency.

Corn profit

By excluding sorghum in 1995, comparisons in corn profit for 5 year of each system could be made for the southern zone of the field. Average corn profit across this zone was positive for 3 year in CONV but only 1 year in PAS (Table 4; Fig. 2). Thus, without crop insurance payments applied in this analysis, corn was often not profitable in either system, reinforcing results from Massey et al. (2008) for prior analysis of the CONV system. The more extreme weather conditions experienced during PAS caused delayed planting or stand failure more frequently than during CONV, which was likely

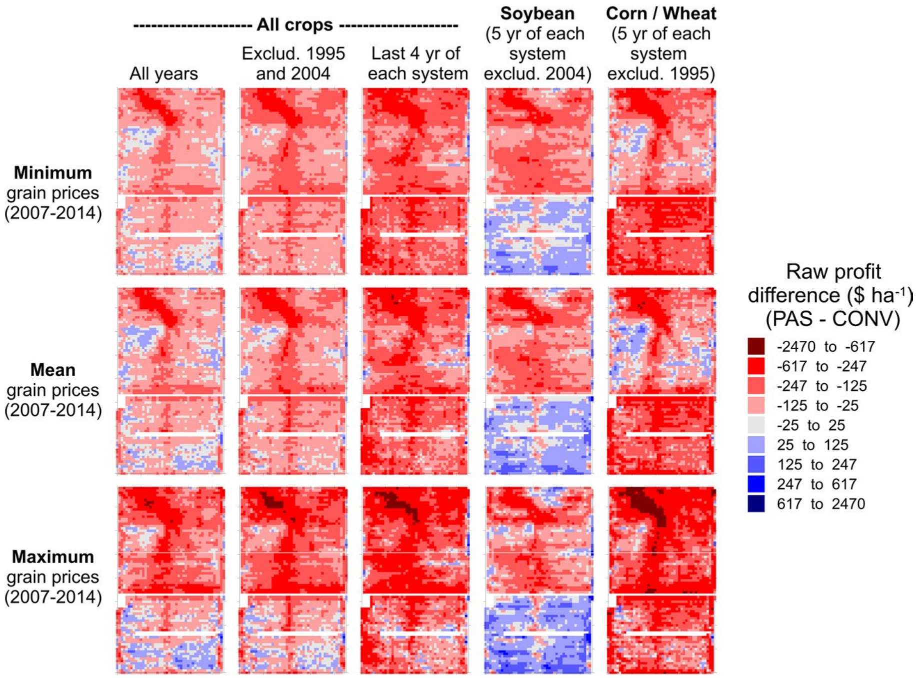

Fig. 3 Mean differences in profits between the precision agriculture system (PAS) and the conventional (CONV) system for five crop and three grain price scenarios (Color figure online)

a main contributor to lower profits. Subsequently, raw differences in the mean corn profit over 5 yr showed that it was lower in PAS than CONV in nearly all of the southern zone (Fig. 3). However, almost none ($<1\%$) of the area in the southern zone had significantly ($P>0.10$) lower profit in PAS than CONV (Fig. 4). Thus, PAS sustained corn profit despite greater expenses (Table 2) than CONV, and despite the lack of subsidies for cover crops or other potential environmental services. Growers should be able to sustain corn and soybean profit when incorporating both cover crops and no-tillage into their cropping systems. Further, no-tillage helped offset the cost of cover crops and may be essential in making cover crops feasible and profitable on commercial operations.

As was the case with soybean, the differences in temporal variation of corn profit between PAS and CONV generally diminished slightly as grain prices increased (Fig. 5). At all three grain prices, temporal variation in corn profit was equivalent for a majority (75%) of the southern zone in PAS compared to CONV (Table 5). Temporal variation in corn profit increased with PAS in about one-fifth of the area in the southern zone, mainly along the edges of the field and in the center of the northern half of the southern 15 ha (Fig. 5). Spatial variation of corn profit was equivalent in CONV and PAS ($P>0.19$) at all three grain price scenarios. Thus, cover crops and no-tillage did not increase spatial variability of corn profit, and variable-rate N did not reduce spatial variability in corn profit. Other shorter-term studies have generally found profit advantages to variable N applications for corn if spatial variation is great and variation is appropriately accounted for (Mamo et al. 2003; Griffin and Lowenberg-DeBoer, 2005;

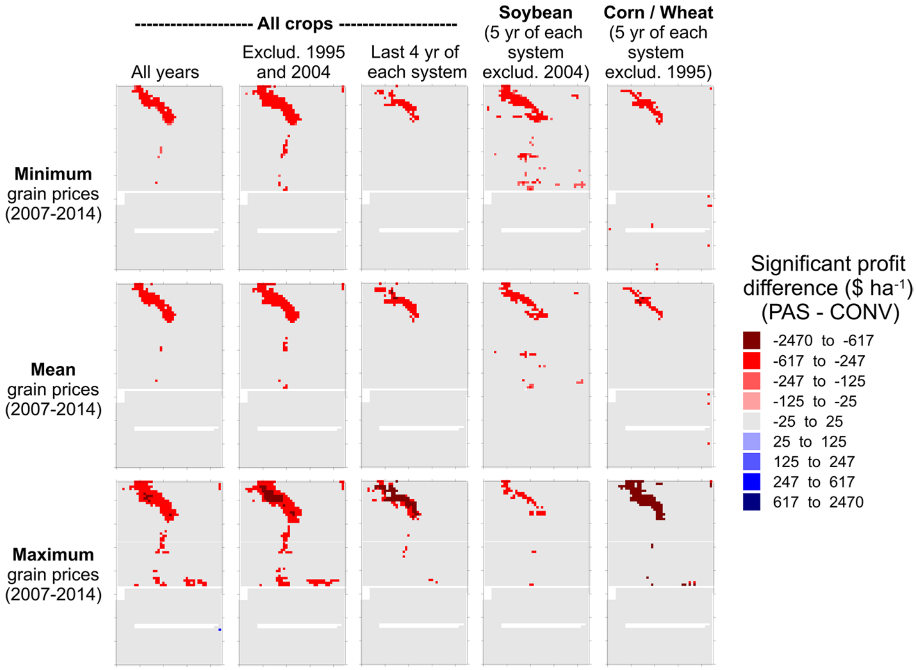

Fig. 4 Maps of the significant differences ($P < 0.10$) in profits between the precision agriculture system (PAS) and the conventional (CONV) system for five crop and three grain price scenarios (Color figure online)

Table 5 The percentage of a zone or zones where profit or temporal variation in profit (standard deviation (STDEV) in profit within a grid-cell over time) was influenced by the precision agriculture system (PAS), as summarized from the difference maps in Figs. 3 and 4

Attribute	Profit or Profit STDEV with PAS was…	Corn/wheat (north)	Corn (south)	Soybean (north/south)	All crops (north/south)
		Percentage of zone(s) (%)			
Profit	Reduced	2	< 1	3	3
	Increased	0	0	0	0
	Same	98	99	97	97
Profit STDEV[a]	Reduced	44	4	2	3
	Increased	2	21	62	66
	Same	53	75	36	31

These data are only for the scenarios with mean grain prices used in profit calculations

[a] Reduced and increased was based on significant (*t*-tests at $P = 0.10$) profit change and |> 25%| change in STDEV from the conventional system to PAS

Lambert et al. 2006). While variable-rate application of N had no apparent benefit on corn profit in this field, the water and air quality impacts of this practice within a PAS system have yet to be examined.

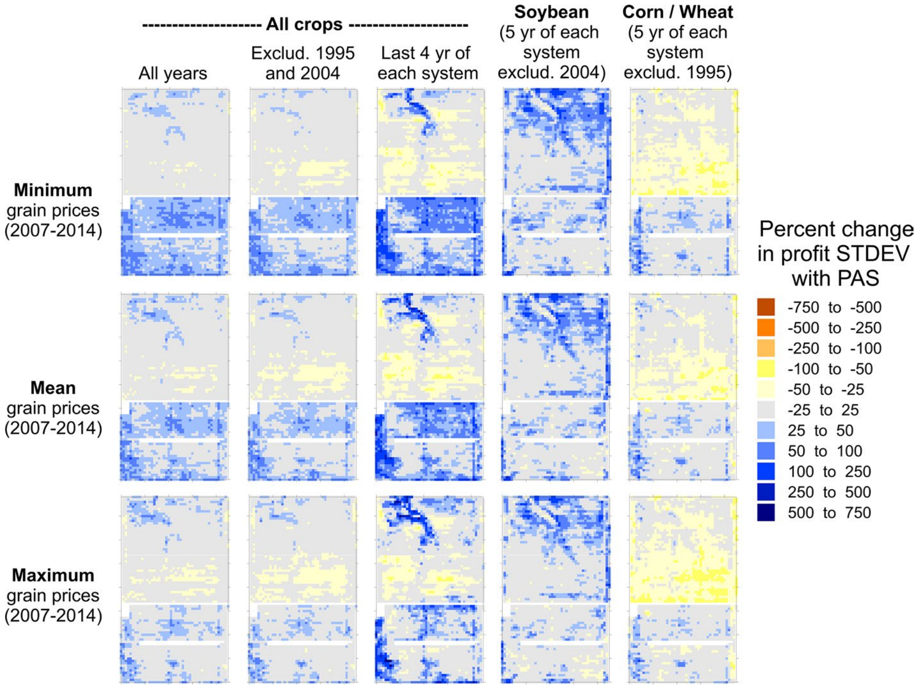

Fig. 5 Maps of the percent changes |> 25%| in crop profit temporal variation [measured by standard deviation (STDEV)] with the precision agriculture system (PAS) compared to the conventional system (CONV) for five crop and three grain price scenarios. Mapped areas in yellow and orange indicate PAS reduced within-grid cell STDEV in crop profit (Color figure online)

Corn and wheat profit

Wheat replaced corn during PAS in the northern 21 ha of the field and 5 years of profit for each crop were compared. Averaged across this zone, corn was profitable in 3 of 5 year during CONV and wheat was profitable only during the first two cycles of the crop rotation of PAS (Table 4). Annual maps revealed that corn profit was usually enhanced in the drainage channel during CONV and wheat profit was hindered in the channel during PAS (Fig. 2). Raw differences in mean profit by grid cell showed that wheat in PAS reduced profit compared to corn in CONV for nearly all of the northern zone (Fig. 3). The exceptions to this were increased profit on the eroded side slope portions of the field when mean or minimum grain prices were considered. The cause of greater raw profits on side slopes was mainly due to yield improvements of wheat relative to corn on these landscape positions (Yost et al. 2017). However, similar to soybean results, wheat profit in PAS was only statistically lower ($P < 0.10$) than CONV in a small section (2%) of the northern part of the drainage channel (Table 5; Fig. 4). Thus, wheat profit in PAS was equivalent to corn profit in CONV for nearly all of the northern zone.

Wheat profit in PAS was less temporally variable than corn in CONV for nearly one-half (44%) of the northern 21 ha and was only more variable in a small portion of that zone (2%) at the mean grain price scenario (Table 5). Trends in profit variation were similar at the minimum and maximum grain price, but with greater expansion of areas with less temporal variation in wheat profit in PAS than corn profit in CONV (Fig. 5). A similar trend was observed for temporal variability in crop yields between PAS and CONV and, as noted in Yost et al. (2017), the reductions in temporal variability of wheat were likely related to less impact of weather conditions on wheat than corn due to the difference in growing seasons. Wheat spatial variation in PAS did not differ from the spatial variation of corn during CONV ($P = 0.14$) at the mean grain price scenario, but decreased the STDEV in wheat profit by \$34 or \$18 ha^{-1} in the minimum or maximum grain price scenario, respectively ($P \leq 0.048$).

The results in the northern zone indicate that wheat may be a suitable alternative to corn in Missouri, especially on sloping soils, despite disease (e.g., deoxynivalenol or vomitoxin) pressure challenges in wheat production in humid climates. The inclusion of winter wheat also created the opportunity for summer cover crops that have more time to grow, retain nutrients and contribute to soil health improvements. These summer cover crop mixes typically cost more than cover crops following corn or soybean (Table 3), but they had no negative impacts on soybean or wheat profit.

Profit of all crops

Comparisons of profit among all crop types allowed for additional assessments of the overall performance of the PAS. Three profit comparisons were evaluated: (i) all years; (ii) all years except 1995 (unplanned sorghum crop) and 2004 (transition year between systems); and (iii) only the last four years of each system to test possible cumulative impacts of PAS over time.

All years

Raw differences in the mean profit of all crops showed that PAS decreased profit for major areas of the field in both zones (Fig. 3). Mean profit did increase in small clusters on the eroded side slopes in the northern zone and in much of the southern half of the southern zone at maximum grain prices. Similar to results from single crop comparisons, PAS only significantly decreased ($P < 0.10$) profit in a small area of the field (3%; Table 5) almost exclusively within the drainage channel. Reductions in profit worsened and expanded slightly as grain prices increased. This agreed with Lowenberg-DeBoer and Aghib (1999) and Mallarino et al. (1999) who found that variable-rate P and K (one component of PAS system) did not improve corn, soybean or wheat net returns.

As was the case with individual crop comparisons, temporal variation of all crops was not drastically influenced by grain price. In all three grain price scenarios, PAS had equal temporal variation in the profit of all crops for 60 to 78% of the area of the whole field (Table 5). Most of this occurred in the northern 21 ha of the field where few differences occurred. In large portions of the southern 15 ha of the field, temporal variation in the profit of all crops was greater with PAS (16 to 39% of the entire field) than CONV (Fig. 5). Increased temporal variation with PAS in the southern zone was caused by increased variation in both corn and soybean. Profit spatial variation of all crops was 38–47% greater in PAS than CONV ($P < 0.064$) across grain price scenarios.

Precision agriculture is sometimes marketed as a way to simultaneously intensify management and increase crop yield and profit. Data from this study indicates that in some cases it may only maintain profits. This aligns with studies conducted in Nebraska where panel data analysis of a sample of their growers showed that greater use of precision agriculture technology did not statistically impact farm profitability (Castle 2016). Once more complete data on environmental impacts of PAS can be assessed, results may indicate that longer-term profits can be improved. For example, value obtained from improvements in soil health and reduction of erosion or potential ecosystem service payments for improvements in air and water quality could cause future enhancements in the profitability of PAS. Other indicators in research plots adjacent to the field used in the present study (Yost et al. 2016) also point to greater yields over time (17 year) on sloping soils when no-tillage and cover crops are incorporated into cropping systems.

All years except 1995 and 2004

The exclusion of 1995 and 2004 did not cause major changes in profit or profit variation trends. The area around the drainage channel with significantly less profit in PAS expanded slightly (Fig. 4) and a greater amount of area had less profit temporal variation with PAS compared to CONV (Fig. 5). Spatial variation remained consistently greater in PAS (47% vs. 43% increase with PAS when 1995 and 2004 were included or excluded, respectively) among grain price scenarios ($P \leq 0.062$). These results confirm that the inclusion of sorghum in 1995 and the transition year in 2004 had minimal impacts on the profit comparisons.

Last 4 years of each system

Examination of the last 4 years of each system produced some similar results as considering all years. Notable exceptions were reductions in the area around the drainage channel with decreased profit during PAS (Fig. 4). The reductions in profit were concentrated mainly in the most northerly part of the drainage channel. Large changes in the extent and magnitude of differences in temporal variation of crop profit between PAS and CONV occurred when the last 4 years of each system were considered relative to the whole study period (Fig. 5). The reductions in temporal variation on eroded side slopes due to wheat in the northern 21 ha expanded. Increases in temporal variation intensified in the drainage channel and much of the area in the southern 15 ha. These differences were likely magnified in PAS because with fewer years considered, extreme weather years like 2012 had more influence on comparisons. Using only the last 4 year of the systems also further highlighted some of the advantages of wheat in PAS over corn in CONV in terms of reduced temporal variability in profit. Spatial variation did not differ ($P > 0.13$) among PAS and CONV for any of the three grain price scenarios. Although profit temporal and spatial variation trends changed when only the last 4 years were considered, profit differences were similar whether the last four or all years were considered. These results indicate that the year of evaluation likely did not cause large changes in profit comparisons between CONV and PAS, and that profit advantages of PAS did not accrue during this 11-year evaluation.

Conclusions and Implications

The PAS that was implemented on a 36 ha field in Missouri for 11 year following a CONV system had less pesticide and tillage expenses than CONV, but with added cover crop, fertilizer and seed expenses, overall inputs were \$97 ha^{-1} year^{-1} more expensive than CONV.

Despite greater expenses and nearly equivalent yield with PAS (previous analysis by Yost et al. 2017), few statistical differences in profit were detected. Results indicated that:

- Corn profit was not influenced by PAS, despite greater seeding expenses due to weather-induced corn replanting in PAS.
- Soybean and wheat were less profitable with PAS only in 3% of the entire field.
- Changes in soybean and wheat profit were concentrated within the drainage channel where no-till inhibited soybean and wheat stands.
- The lack of profit difference was consistent regardless of whether all or only the last 4 years were considered, or the three grain price levels.
- Temporal variation in profit was reduced for wheat in PAS, but increased for corn and soybean.
- Spatial variation in profit of corn and wheat was not influenced by PAS, but soybean profit was $23 ha^{-1} more variable in PAS.

As one of the first long-term evaluations of PA that also encompasses PC practices at a field scale, this analysis revealed that these practices can sustain profitability of grain-based cropping systems. This indicates that in environments similar to those studied in this work, growers who implement systems like PAS may not see profit gains after 11 yr, but they should be able to invest in cover crops, no-tillage and precision technologies to help enhance environmental protection and build soil health without forgoing profit. The financial incentives and subsidies that some U.S. states already offer for implementing some of the practices utilized in PAS may help improve profitability.

Sustained profit with PAS is especially important for the claypan soils studied in this work because they are among some of the most variable and vulnerable soils. Although the long-term profitability of PA and PC systems will probably be highly site-specific, it is unlikely that environments with less variability or vulnerability than the present study would see additional profit gains. To this end, other long-term field-scale studies of PA/PC systems are needed to confirm that the results of this work apply in other environments.

Few profit enhancements with PAS may dissuade some growers from making investments in PA and PC. However, some of these investments will likely be necessary in many environments to provide desired and sustained ecosystem services for decades and centuries to come. Environmental impacts of PAS, such as water quality and soil health, are still being assessed and may indicate that profit will be enhanced with PAS going forward if soil erosion and offsite nutrient losses decrease. These critical additional assessments will provide a more comprehensive view of how systems like PAS may lead to more sustainable cropping systems. Other potential ecosystem services of PAS such as impacts on air quality and greenhouse gas emissions, and implications of PAS systems at farm, community and society scales will also need to be assessed.

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