A Long-Term Precision Agriculture System Maintains 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 dynamic and included no-till, cover crops, growing winter wheat (Triticum aestivum L.) instead of corn in a section of the field where corn was often not profitable, site-specific N for wheat and corn using canopy reflectance sensing, variable-rate or zonal P, K and lime using intensively grid-sampled data, and targeting of herbicides based on weed pressure. Differences in yield and yield variability between the two systems were recently evaluated, but profitability comparisons have not been made. Results indicated that PAS maintained profits in the majority (97%) of the field without subsidies for cover crops or payments for enhanced environmental protection. Profit or net returns were only lower with PAS in the drainage channel where no-till sometimes hindered soybean stands and wet soils caused wheat disease. Although profit gains were not realized after 11 years of PA and conservation practices, results indicate this type of system can maintain profits. Furthermore, this information 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 while 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) is a similar concept but with added emphasis on reducing environmental harm, such as decreasing soil erosion or degradation (Berry et al. 2003; Delgado et al. 2011). 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. In additional to minimizing harm, PC also seeks to restore or build soil health, which in turn will help improve the resiliency and sustainability or agricultural systems in future climates.

As a relatively new farming system approach with rapidly evolving technologies, few long-term evaluations of PA or PC systems exist in the United States or other parts of the world. This lack of information is especially apparent at the field-scale because grain yield monitoring systems were not available prior to the early 1990s. 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 most other PA practices such as variable-rate technology, yield mapping, and global positioning systems 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). Investigation of conservation practices has a much longer history than PA evaluations. No-tillage, cover crops, and diversified crop rotations have been studied for several decades. Ervin and Washborn (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. While these and many other practices have proven economic benefits, the cumulative impacts of PA and conservation practices together in a PA / PC system have not been investigated, especially at the field scale and over long time periods.

Shortly after some of the first grain yield-monitoring systems were commercialized, a long-term trial with PA and conservation practices was established across 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 yr. In 2004, a system termed a ‘precision agriculture system’ (PAS) was developed and initiated for another 11 yr. A slightly modified version of this system is still under investigation as an ‘aspirational’ system treatment in the USDA Long-Term Agroecosystem Research (LTAR) network.

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 offers 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 yield hypothesis and a few others have been tested previously (Yost et al. 2017). The objective of this article was to compare crop profitability between PAS and the conventional system. Environmental assessments of PAS will be forthcoming.

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). 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; Kitchen et al. 2005).

Precipitation and air temperature were measured on site during the whole study period (Sadler et al. 2015). The range in annual cumulative growing degree days with base of 10°C and precipitation was similar between the CONV and PAS systems. Exceptions were that three PAS years (2005, 2008 and 2012) had the greatest deviations in annual cumulative growing degree days and/or precipitation from the 30-year normal (Table 1). Shortly after PAS implementation in 2005, excessive precipitation occurred in the later winter and early spring. This deviation from normal was not reflected in annual values, but 2005 had the greatest deviation from normal in the early spring among all other years. Three years later in 2008, precipitation was 532 mm greater than normal. This was the wettest year of the whole study period. The widespread drought and warm air temperatures (498 more °C-days than normal) of 2012 also occurred during PAS. Therefore, while both systems experienced some similarities in weather conditions, PAS had more frequent large deviations (warm or wet) from average than CONV.

Table 1 Cumulative precipitation and growing degree days with deviation from the 30-yr normal (1981-2010) in parenthesis for each year of the conventional (CONV) and precision agriculture system (PAS)

CONV			PAS		
Year	Cumulative precip.	Cumulative GDD	Year	Cumulative precip.	Cumulative GDD
	mm	°C-day		mm	°C-day
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)

During 1993 to 2003, the field was conventionally managed with annual tillage, uniform fertilizer and herbicide rates, no cover crops, and a two-year crop rotation with corn in odd years and soybean in even years (Table 2). 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. An "aspirational" or 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 2). One zone encompassed the north 21 ha of the field where corn production had not 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 production replaced corn in PAS. Cover crops following wheat included medium red clover, sudangrass, or mixtures of legumes and nonlegumes.

Table 2 Generalized management description for the conventional system during 1993 to 2003 and the precision agriculture system (PAS) during 2004 to 2014

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

The other zone comprised the southern 36 ha of the field 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 (Fig. 1). 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 or mixtures of legumes and nonlegumes and covers following soybean included annual ryegrass or mixtures of legumes and nonlegumes. For 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. Data were cleaned using Yield Editor software (Sudduth and Drummond, 2007) to remove erroneous data. Cleaned yield monitor data was 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. Yield data kriged 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.

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 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). Prices were obtained from local input suppliers or were actual prices paid for products used in the study when they could not be obtained from the two sources mentioned above. 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 obtained from USDA-NASS, while those that were not available were obtained from Green Cover Seed in Lincoln, Nebraska. Land prices were not included in this analysis. Crop insurance premiums and payouts also were not included because detailed records of these payments were not kept. The cost of yield mapping also was not included because it was used every year and did not differ among systems.

Output prices for grain crops were obtained from the Center for Farm Financial Management (2014) for up to 2,000 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 evaluate possible profits scenarios that might account for risk and variability in markets that a grower might experience (Delbridge et al. 2011).

Profit was calculated for each 10-m grid cell by summing up all inputs costs and subtracting them from the gross return. The cost 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 yr 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 yr of PAS. These inputs were amortized because they are long-term investments that influence the profit in more than the year of application.

Profit was calculated for each grid cell in each year during 1993 to 2014 and 15 profit comparisons between PAS and the conventional were made. 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 yr of each system; iii) soybean profit across the whole field; and iv) corn profit in the southern zone and corn vs. wheat in the northern zone. The comparison of the last 4 yr of each system was included because the impacts of a new system such as PAS on crop profit may take time to realize. All differences in within-grid cell profit by or across crops between the conventional system and PAS were determined using two-tailed t-tests at $\alpha \leq 0.10$.

The temporal and spatial variation in profit was also compared between the conventional system and PAS. Temporal variation was calculated as the coefficient of variation (CV) in profit within each grid cell over time and was evaluated using the same 15 comparisons mentioned above for profit. Spatial variation was the CV in profit across the field and was compared between systems. Absolute differences in CV greater than 25% were evaluated.

Results and Discussion

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 (\$2-9 ha^{-1} yr^{-1}) than CONV due to the incorporation of wheat instead of corn. Fertilizer costs were \$62 ha^{-1} yr^{-1} greater in PAS than CONV. This was mainly 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 cooperating 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 \$45 ha^{-1} yr^{-1} in PAS. This was mainly due to greater occurrence of re-planting from extreme weather during PAS but also included greater use of more expensive biotech varieties during this period. These added costs of PAS were partially offset by \$21 ha^{-1} yr^{-1} lower pesticide costs in PAS than CONV. Cover crops added an additional \$123 ha^{-1} yr^{-1} in expenses during PAS, but were offset by \$87 ha^{-1} yr^{-1} less tillage costs in PAS. Overall, PAS had \$111 ha^{-1} yr^{-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 yr of soybean. On average, soybean was profitable every year in both systems across both the northern and southern zones of the field during the CONV system (Fig. 1). In contrast, average soybean profit was negative in both zones during PAS in 2008 and 2012 due to extreme weather conditions those years (Table 1). Mean differences in 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. 2). These trends were similar at all three grain price levels. Few statistical differences occurred in profit between the two systems (Fig. 3). Soybean profit was only lower during PAS in a small section of the drainage channel in the northern zone. This reduction in profit was mainly due to decreased soybean stand densities resulting from no-tillage on wet soils.

Temporal variability in soybean profit was influenced by grain prices and the zone of the field. At minimum grain prices, about half of the northern zone had lower temporal profit CV and half had greater CV (Fig. 4). Most of the area in the northern zone with lower temporal CV with PAS was concentrated in the drainage channel. Therefore, although PAS had lower profit in the drainage channel, it had less variability from year to year. This low temporal variability may indicate better resiliency in PAS to weather conditions, but it came at the cost of less overall profit. At mean and maximum grain prices, there were few differences in temporal variation of soybean profit, with most small differences being increases in CV with PAS. Grain prices likely had strong influence on temporal variation trends due to the large influence of yield on profit. The spatial CV in soybean profit at mean grain prices ranged from 11 to 130% among years and was not different between the two systems in either zone or across zones ($P > 0.25$) (Table 4).

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

Year	Cover crops	Fertilizer	Tillage	Pesticides	Seed	Harvest	Shredding	Total
				$ ha^{-1}				
1993	0	429	68	123	196	84	0	901
1994	0	48	96	110	141	84	29	508
1995	0	329	137	90	66	84	0	706
1996	0	48	146	128	156	84	0	563
1997	0	329	68	118	208	84	0	809
1998	0	48	141	128	225	84	0	627
1999	0	329	103	197	196	84	0	910
2000	0	48	103	183	218	84	29	666
2001	0	416	68	198	270	84	0	1037
2002	0	48	36	126	221	84	40	556
2003	0	374	72	131	196	84	0	858
2004	123	144	85	51	199	84	0	686
2005	123	420	0	73	215	79	0	911
2006	123	144	0	76	225	84	0	653
2007	123	429	0	101	234	79	0	966
2008	123	144	0	59	268	84	0	677
2009	123	510	0	118	224	79	0	1055
2010	123	144	0	80	220	84	0	651
2011	123	427	0	141	402	79	0	1173
2012	123	144	0	229	196	84	0	776
2013	123	465	0	123	224	79	0	1014
2014	123	163	0	249	178	84	0	797
Difference (04-14) – (93-03)	123	62	-87	-21	45	-2	-9	111

Table 4 Annual profit and spatial variation of profit (profit coefficient of variation (CV) across cells) by crop and zone(s) using mean grain prices during 2007 to 2014

	Northern 52 ha zone			Southern 36 ha zone		
Year	Crop	Profit	CV	Crop	Profit	CV
		$ ha^{-1}	%		$ ha^{-1}	%
1993	Corn	156	49	Corn	151	56
1994	Soybean	56	123	Soybean	45	102
1995	Sorghum	81	76	Sorghum	83	80
1996	Soybean	265	11	Soybean	269	13
1997	Corn	159	52	Corn	205	19
1998	Soybean	111	27	Soybean	120	26
1999	Corn	-220	-20	Corn	-195	-19
2000	Soybean	153	23	Soybean	149	26
2001	Corn	4	1374	Corn	34	181
2002	Soybean	89	51	Soybean	113	43
2003	Corn	-196	-44	Corn	-192	-35
2004	Soybean	252	30	Soybean	251	24
2005	Wheat	98	107	Corn	-73	-118
2006	Soybean	107	60	Soybean	193	34
2007	Wheat	100	104	Corn	-210	-20
2008	Soybean	-176	-38	Soybean	35	130
2009	Wheat	-76	-96	Corn	243	29
2010	Soybean	223	18	Soybean	285	16
2011	Wheat	-315	-26	Corn	-388	-21
2012	Soybean	-39	-97	Soybean	39	115
2013	Wheat	-180	-20	Corn	-77	-109
2014	Soybean	73	83	Soybean	168	28

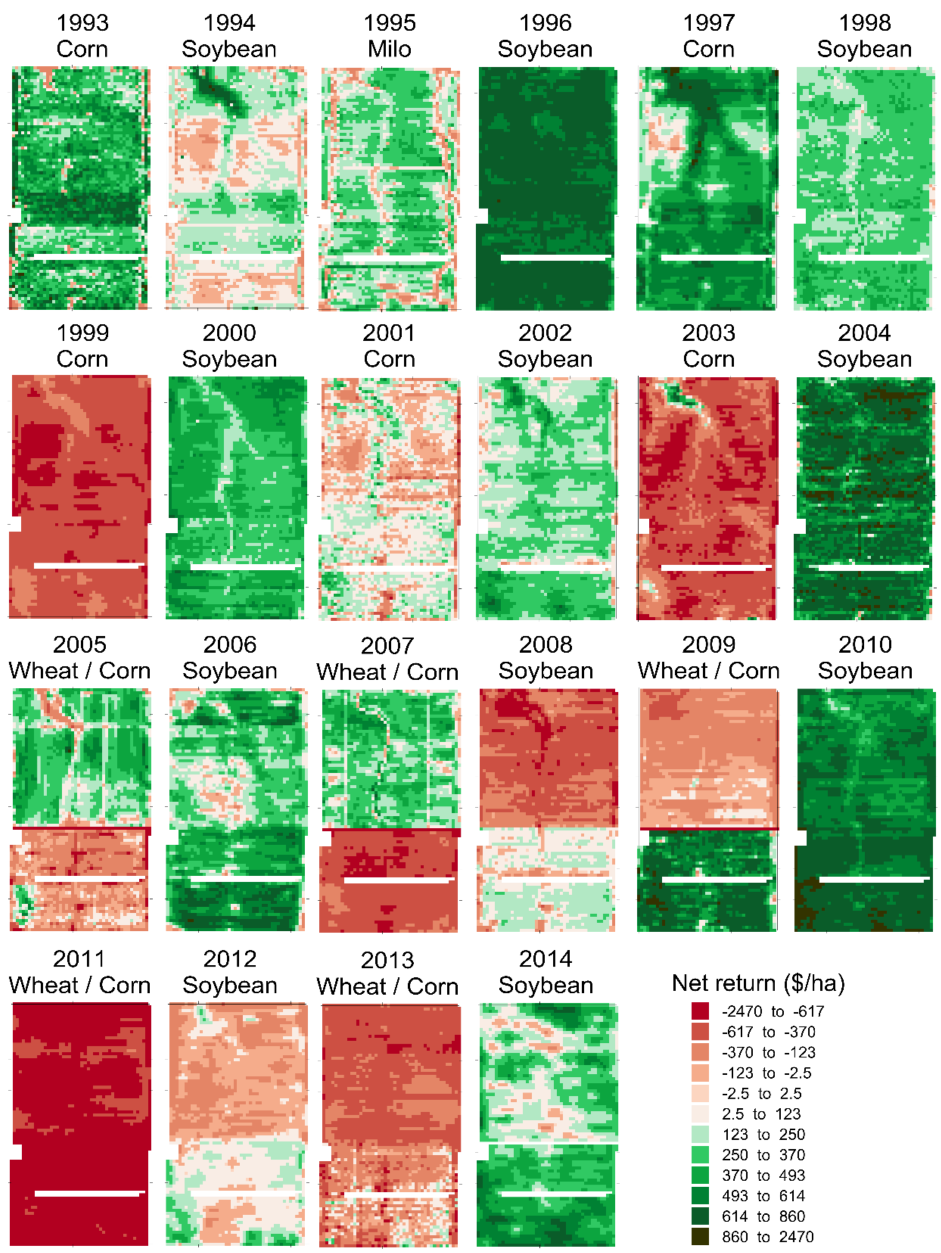
Corn Profit

By excluding sorghum in 1995, comparisons in corn profit for 5 yr of each system could be made for the southern zone of the field. Average corn profit across the southern zone was positive for 3 yr in CONV but only 1 yr in PAS (Fig. 1). The more extreme weather conditions experienced during PAS caused delayed planting or stand failure more frequently than during CONV, which was likely a main contributor to lower profits. Subsequently, the mean differences in corn profit showed that corn profit was lower in PAS than CONV in nearly all of the southern zone (Fig. 2). However, almost none of the area in the southern zone had significantly ($P > 0.10$) lower profit in

PAS than CONV (Fig. 3). These results indicate that corn is often not profitable in many years on claypan soils, as noted by Massey et al. (2008) for the CONV years in this same field, and that PAS maintained corn profits.

Temporal variation in corn profit was also influenced by grain price scenario. At minimum grain prices, temporal variation in corn profit was lower for nearly all of the southern zone in PAS compared to CONV (Fig. 3). Similar results were obtained when mean grain prices were considered, with the exception of greater reductions in corn profit CV around the borders of the southern zone and in much of the southern half of the southern zone. The other exception was greater temporal variation in a small cluster on the southwest corner of the zone. At maximum grain prices, the trend reversed and much of the zone had greater temporal variation in corn profit with PAS. The range in spatial variation in corn profit (CV = 19-81%) was similar to the range in soybean profit variation and system likewise had no impact on spatial variation (*P* = 0.35).

Fig 1. Annual maps of crop profits during the conventional (CONV) system (1993-2003) and precision agriculture system (PAS) (2004-2014)



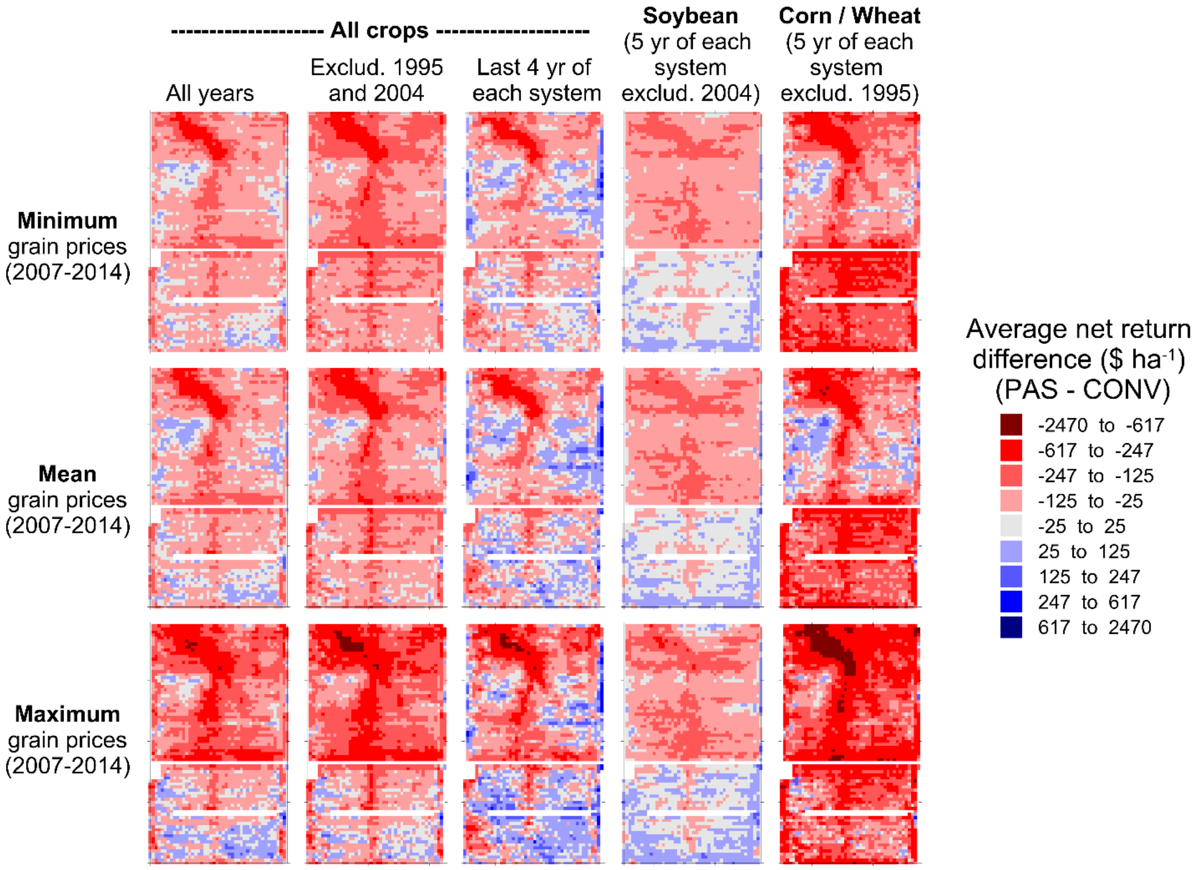


Fig 2. Mean differences in profits between the precision agriculture system (PAS) and the conventional (CONV) system for five crop and three grain price scenarios

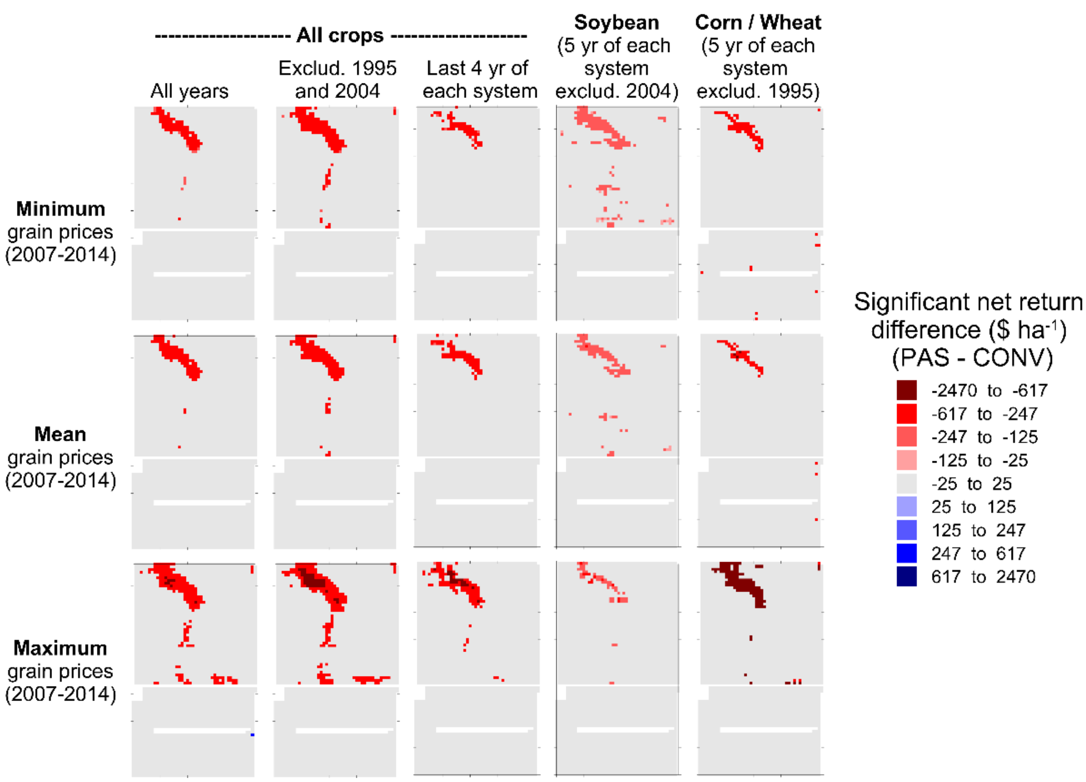


Fig 3. Significant differences (*P* = 0.10) in profits between the precision agriculture system (PAS) and the conventional (CONV) system for five crop and three grain price scenarios

Corn and Wheat Profit

Wheat replaced corn during PAS in the northern 21 ha of the field. Five years of profit for each crop were compared. Averaged across this zone, corn was profitable in 3 of 5 yr during CONV and wheat was profitable only during the first 2 yr of PAS. Annual spatial profit 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. 1). Mean profit differences by grid cell showed that wheat in PAS reduced profit compared to corn in CONV for nearly all of the northern zone (Fig. 2). The exceptions to this were increased profit outside the drainage channel on the eroded sideslopes at mean or minimum grain prices. The cause of greater profit on sideslopes 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 of the northern part of the drainage channel (Fig. 3). Thus, wheat profit in PAS was equivalent to corn profit in CONV for the vast majority of the northern zone.

Wheat profit was more temporally variable outside the drainage channel when maximum wheat prices were considered (Fig. 4). Otherwise, wheat profit in PAS was less temporally variable than corn profit in CONV, especially in the drainage channel at mean to maximum grain prices. Spatial variation in corn profit was exceptionally high in 2001 (CV = 1374%) compared to 20 to 50% in other years. Wheat spatial variation ranged from 20 to 107% and did not differ from the spatial variation during CONV ($P > 0.39$).

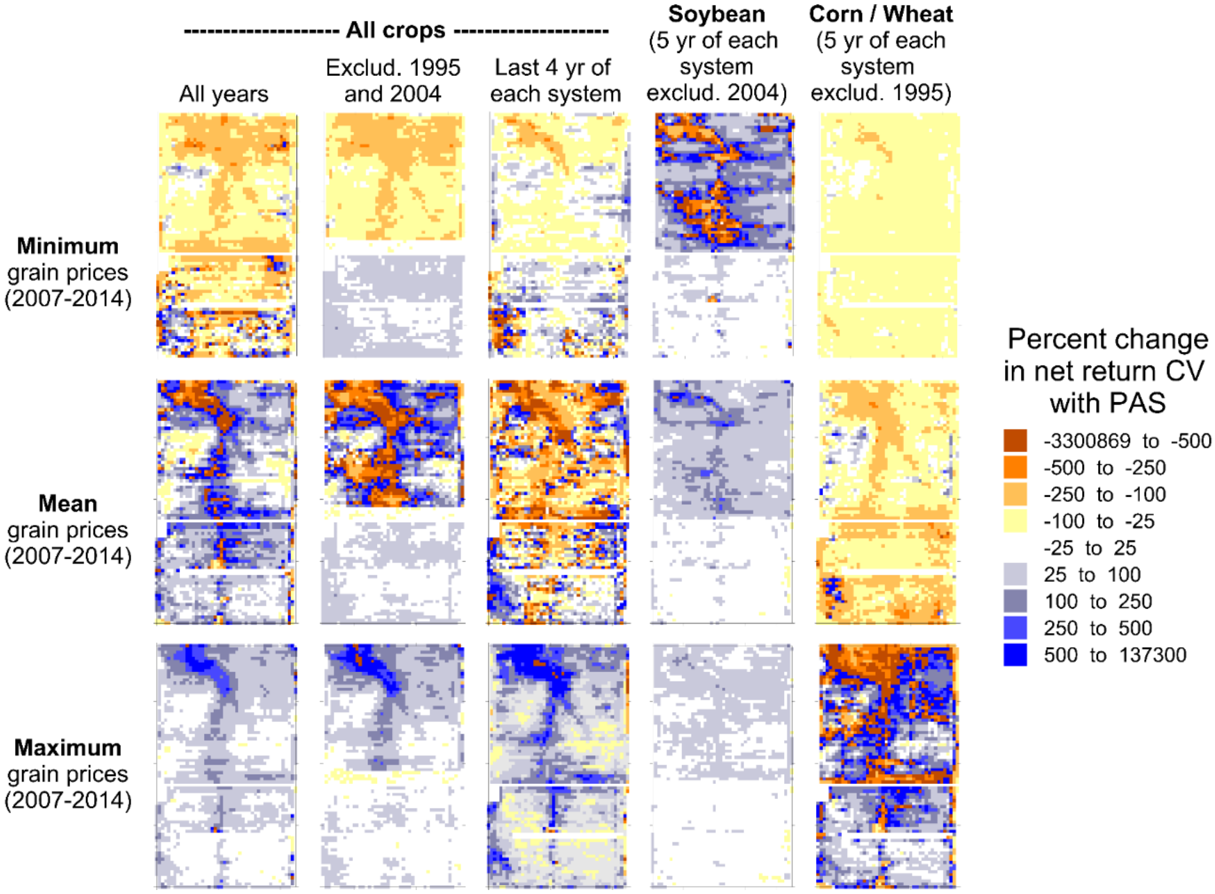


Fig 4. Percent changes in profit coefficient of variation (CV) with the implementation of the precision agriculture system (PAS) in relation to the conventional (CONV) system for five crop and three grain price scenarios

Profit of All Crops

Comparisons of profit among crop types allows for more complete assessment of how PAS performs. 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

Mean differences in the profit of all crops showed that PAS decreased profit for major areas of the field in both zones (Fig. 2). Mean profit did increase in small clusters on the eroded sideslopes 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 almost exclusively within the drainage channel. This agreed with Lowenberg and Aghib (1999) and Mallarino et al. (1999) who found that variable-rate P and K (one component or PAS system) did not improve corn, soybean, or wheat net returns. Reductions in profit worsened and expanded as grain prices increased. As was the case with individual crop comparisons, temporal variation of all crops was strongly influenced by grain price. At minimum prices, PAS reduced temporal variation for most of northern zone and the northern half of the southern zone. At mean grain prices, PAS increased temporal variation in most of the field except on the eroded sideslopes and drainage channel. Differences in profit temporal CV were minor at maximum grain prices with the exception of greater temporal CV in the drainage channel. Profit spatial variation of all crops did not differ between PAS and CONV ($P > 0.25$).

All Years except 1995 and 2004

The exclusion of 1995 and 2004 did not cause major changes in profit or profit variation trends (Fig. 2, 3, 4). The area around the drainage channel with significantly less profit in PAS expanded slightly and differences in temporal variation between PAS and CONV in the southern zone were reduced. Spatial variation remained consistent between systems.

Last Four Years of Each System

Examination of the last four years of each system produced similar results as considering all years. Notable exceptions were reductions in the area around the drainage channel with decreased profit during PAS (Fig. 3). The reductions in profit were concentrated in only the most northern part of the drainage channel. At mean grain prices, temporal variation of profit was lower in PAS than CONV for most of the northern zone and much of the northern half of the southern section.

Conclusions

The PAS that was implemented on a 36-ha field in Missouri for 11 years following a CONV system had less pesticide and tillage expenses than CONV, but overall with added cover crop, fertilizer, and seed expenses was \$111 ha^{-1} yr^{-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. Soybean and wheat were less profitable with PAS only in about 3% of the field, mainly the part within the drainage channel. Corn profit was not influenced by PAS in the southern 15 ha of the field. As one of the first long-term evaluations of PA and conservation practices at the field scale, this analysis revealed that these practices can maintain profitability of grain-based cropping systems. This indicates that growers who implement PA and conservation practices may not see profit gains after 11 yr, but they should be able to invest in cover crops, no-tillage and precision technologies to enhance environmental protection and build soil health without forgoing profit. Environmental impacts of PAS are still being assessed and may indicate that profit will be enhanced with PAS going forward if soil erosion and offsite nutrient losses decrease.

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References

Berry, J. K., Delgado, J. A., Khosla, R., & Pierce, F. J. (2003). Precision conservation for environmental sustainability. *Journal of Soil and Water Conservation*, *58*(6), 332–339.

Buchholz, D. D., Brown, J. R., Garret, J., Hanson, R. & Wheaton, H. (2004). Soil test interpretations and recommendations handbook. University of Missouri-College of Agriculture, Division of Plant Sciences, Columbia, MO, USA.

Center for Farm Financial Management. (2017). FINBIN Farm financial database. Univ. of Minnesota, St. Paul. www.finbin.umn.edu/CropEnterpriseAnalysis/Default.aspz (accessed 1 Jul. 2017)

Delbridge, T. A., Coulter, J. A., King, R. P., Sheaffer, C. C., & Wyse, D. L. (2011). Economic Performance of Long-Term Organic and Conventional Cropping Systems in Minnesota. Agronomy Journal, 103(5), 1372. doi:10.2134/agronj2011.0371

Delgado, J. A., Khosla, R., & Mueller, T. (2011). Recent advances in precision (target) conservation. *Journal of Soil and Water Conservation*, *66*(6), 167A–170A. doi:10.2489/jswc.66.6.167A

Ervin, D. E., & Washburn, R. A. (1981). Profitability of soil conservation practices - in Missouri. *Journal of Soil and Water Conservation*, 36(2), 107–111.

Griffin, T. W., & Lowenberg-DeBoer, J. (2005). Worldwide adoption and profitability of precision agriculture Implications for Brazil. Revista de Política Agrícola, 14(4), 20–37.

Kitchen, N. R., Sudduth, K. A., & Drummond, S. T. (1999). Soil electrical conductivity as a crop productivity measure for claypan soils. *Journal of Production Agriculture*, *12*(4), 607–617.

Kitchen, N. R., Sudduth, K. A., Myers, D. B., Massey, R. E., Sadler, E. J., Lerch, R. N., et al. (2005). Development of a conservation-oriented precision agriculture system: Crop production assessment and plan implementation. *Journal of Soil and Water Conservation*, *60*(6), 421–430.

Kitchen, N. R., Sudduth, K. A., Drummond, S. T., Scharf, P. C., Palm, H. L., Roberts, D. F., et al. (2010). Ground-based canopy reflectance sensing for variable-rate nitrogen corn fertilization. *Agronomy Journal*, *102*(1), 71–84. doi:10.2134/agronj2009.0114

Lambert, D. M., Lowenberg-DeBoer, J., & Malzer, G. L. (2006). Economic Analysis of Spatial-Temporal Patterns in Corn and Soybean Response to Nitrogen and Phosphorus. Agronomy Journal, 98(1), 43. doi:10.2134/agronj2005.0005

Liu, Y., Swinton, S. M., & Miller, N. R. (2006). Is Site-Specific Yield Response Consistent over Time? Does It Pay? American Journal of Agricultural Economics, 88(2), 471–483. doi:10.1111/j.1467-8276.2006.00872.x

Lerch, R. N., Kitchen, N. R., Kremer, R. J., Donald, W. W., Alberts, E. E., Sadler, E. J., et al. (2005). Development of a conservation-oriented precision agriculture system: Water and soil quality assessment. *Journal of Soil and Water Conservation*, *60*(6), 411–421.

Lowenberg-DeBoer, J., & Aghib, A. (1999). Average returns and risk characteristics of site specific P and K Management: Eastern corn belt on-farm trial results. *Journal of Production Agriculture*, *12*(2), 276–282. doi:10.2134/jpa1999.0276

Mallarino, A. P., Wittry, D. J., Dousa, D., & Hinz, P. N. (1999). Variable-rate phosphorus fertilization: On-farm research methods and evaluation for corn and soybean. In P. C. Robert, R. H. Rust, & W. E. Larson (Eds.), *Proceedings of the 4th International Conference on Precision Agriculture* (pp. 687–696). ASA-CSSA-SSSA, Madison, WI, USA.

Massey, R. E., Myers, D. B., Kitchen, N. R., & Sudduth, K. A. (2008). Profitability maps as an input for site-specific management decision making. *Agronomy Journal*, *100*(1), 52–59.

Edwards, W. & A. Johanns. (2007-2014). Iowa farm custom rate survey. Ag Decision Maker. Iowa State University Extension. FM1698b. Ames, IA.

Sadler, E. J., Sudduth, K. A., Drummond, S. T., Vories, E. D., & Guinan, P. E. (2015). Long-term agroecosystem research in the central Mississippi river basin: Goodwater creek experimental watershed weather data. *Journal of environmental quality*, *44*(1), 13–17. doi:10.2134/jeq2013.12.0515

SAS Institute Inc. (2011) Statistical Analysis System. Cary, NC, USA.

Sudduth, K. A., & Drummond, S. T. (2007). Yield Editor: Software for removing errors from crop yield maps. *Agronomy Journal*, *99*(6), 1471–1482. doi:10.2134/agronj2006.0326

Triplett, G. B., & Dick, W. A. (2008). No-tillage crop production: A revolution in agriculture! *Agronomy Journal*, 100(Supplement_3), S-153. doi:10.2134/agronj2007.0005c

USDA-Natural Resource Conservation Service. (2009). Variable-rate nitrogen fertilizer application in corn using in-field sensing of leaves or canopy. Missouri NRCS Agronomy Tech Note35. Available online at: http://extension.missouri.edu/sare/documents/AgronomyTechnicalNote2012.pdf. Last accessed [14 Sept 2016].

USDA-National Agricultural Statistics Service. (2017). Data and statistics-Quick Stats. *USDA-National Agricultural Statistic Service*, Washington, DC. www.nass.usda.gov/Quick_Stats/ (accessed 1 Jul. 2017).

Yost, M. A., Kitchen, N. R., Sudduth, K. A., Sadler, E. J., Baffaut, C., Volkmann, M. R., et al. (2016). Long-term impacts of cropping systems and landscape positions on claypan-soil grain crop production. *Agronomy Journal*, *108*(2), 713–726.

Yost, M. A., Kitchen, N. R., Sudduth, K. A., Sadler, E. J., Drummond, S. T., & Volkmann, M. R. (2017). Long-term impact of a precision agriculture system on grain crop production. *Precision Agriculture*, 18(5), 823–842. doi:10.1007/s11119-016-9490-5

Zollinger, R. K. (2007-2014). North Dakota Herbicide Compendium. North Dakota State University Extension. Available at https://www.ag.ndsu.edu/weeds/weed-control-guides/nd-weed-control-guide-1/wcg-files/18.1-Herb%20Comp.pdf. (accessed 1 Jul. 2017)