Can optimization associated with on-farm experimentation using site-specific technologies improve producer management decisions?

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Abstract. *Crop production input decisions have become increasingly difficult due to uncertainty in global markets, input costs, commodity prices, and price premiums. We hypothesize that if producers had better knowledge of market prices, spatial variability in crop response, and weather conditions that drive crop response to inputs, they could more cost-effectively make profit-maximizing input decisions. Understanding the drivers of variability in crop response and designing accompanying management strategies would hence allow increased resilience to economic or climatic perturbations or system stress. We have developed an on-farm precision experiment (OFPE) framework drawing on site-specific agriculture technologies to provide the best estimate of field-specific, site-specific profit-maximizing input application. Our test of the on-farm precision experiment framework was to site-specifically optimize nitrogen fertilizer application rates on 10 dryland winter wheat fields on wheat farms in Montana. After two years of implementing the on-farm precision experiment framework, we demonstrated that nitrogen rate experiments could be applied using a previous year's yield stratification with standard variable rate fertilizer applicators. In addition, using these empirical results we demonstrate that producers could increase net returns.*

Keywords. *Site-specific experimentation, Input optimization, Simulation experiment, Dryland agriculture.*

Introduction

Haber's 1918 discovery of anthropogenic nitrogen fixation catalyzed a century of booming agricultural production and development, swelling the world population and consumption of nitrogen fertilizer. The amount of nitrogen fertilizer applied in the United States reached 12 Tg N yr^{-1} in 2015 (Cao et al. 2017), furthering long held concerns about the ecological and environmental implications of intensive fertilizer use (Vitousek et al. 1997). Nitrogen fertilizers have been traditionally applied as a uniform rate across fields. The advent of precision agriculture spurred experimentation and development of site-specific nitrogen fertilizer applications with the expectation that nitrogen application would be reduced and crop productivity would be maximized (McBratney et al. 2005).

There are two major implications associated with site-specific nitrogen management. Divesting more resources from low profit potential areas than the investment of resources into high profit potential areas results in reduction of nitrogen applied over a field, and resulted in less expenditures by producers for fertilizer (Khosla et al. 2008; Koch et al. 2004). Across a range of simulation-based studies, site-specific nitrogen management increased net returns from as little as \$16 ha^{-1} for spring wheat grown in Oklahoma (Biermacher et al. 2009) to \$23-25 ha^{-1} for winter wheat in Montana (Lawrence et al. 2015). Site-specific management should be evaluated for efficacy on a field by field basis, as spatial variability results in fields where site-specific nitrogen management nets the greatest economic returns, and fields where other drivers besides nitrogen impact net returns (Koch et al. 2004; Link et al. 2008). The potential for site-specific nitrogen management to reduce the amount of nitrogen applied to agricultural fields not only decreases the amount spent by a grower on fertilizer, but addresses environmental concerns related to excess application of nitrogen (Auernhammer 2001). There is evidence that site-specific nitrogen management can potentially decreases application rates of nitrogen fertilizer across corn and wheat systems (Flowers et al. 2004; Khosla et al. 2002; Koch et al. 2004). Link et al. (2008) highlight that site-specific management is appropriate on a field-specific basis and that, even within similar cropping systems and geographies, responses often vary.

Our study tests the hypothesis that net return increases and total nitrogen applied decreases in fields under site-specific nitrogen fertilizer management compared to farmer selected uniformly applied rates and profit maximizing uniformly applied rates. We used a non-linear model empirically fit with on-farm data to simulate the net return and quantity of nitrogen applied under varying management scenarios in dryland winter wheat systems across Montana. Our specific objectives were:

1. To characterize the spatial and economic uncertainty in the relationship between nitrogen fertilizer rate, wheat grain yield and protein concentration.
2. To quantify the probability that site-specific nitrogen fertilizer application would increase field profits over uniform application of fertilizer.
3. To quantify the total amount of nitrogen fertilizer applied to fields using profit-maximizing site-specific management versus uniform fertilizer application.

Methods

Four winter wheat producing farms and at least two fields per farm in different climatic regions were selected for study in Montana. Producer collaborators were selected based on their willingness to participate in our study for up to 10 years, their experience with precision agriculture technologies (yield monitor, and protein monitoring data) and variable fertilizer rate application (VRA) in dryland winter wheat production (Figure 1 and Table 1).

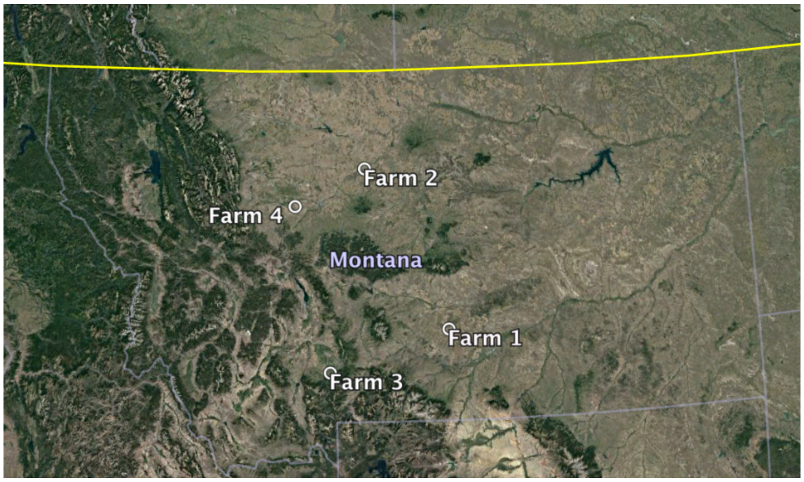

Fig. 1 Locations of farms in Montana

Table 1. Collaborator farms, fields, previous 3 years of crops plus 2017 crop, crop used for nitrogen treatment stratification for prescribed year

Farm	Field	Field size	Crops: 2014 / 2015 / 2016 / 2017[1]	Crop used for N rate treatment stratification
1	sec1east	158	WW / CF / WW / CF	2014 WW
	sec35west	233	WW / P / WW / CF	2014 WW
	sec1west	111	CF / WW / P / WW	2015 WW
	sec35middle	194	SF / WW / CF / WW	2015 WW
2	carlinwest	118	WW / SW / WW / CF	2015 SW
	minnies	49	SW / SW / WW / CF	2015 SW
	henrys	113	CF / WW / CF / WW	2013 WW
3	portnellsouth1	66	MB / WW / WW / MB	2016 WW
	davidsonmidwest2	59	MB / WW / WW / MB	2015 WW
4	sre1314	155	WW / CF / WW / CF	2015 WW

[1] WW = winter wheat, CF = chemical fallow, P = peas, MB = malt barley, SW = spring wheat, AL = alfalfa, WT = organic winter triticale wheat, SF = safflower

Field attributes are determined from GIS analysis of the digital elevation model (DEM) and prior crop year response is used to stratify input experimental rates of the input (Figure 2). In this case nitrogen fertilizer rates.

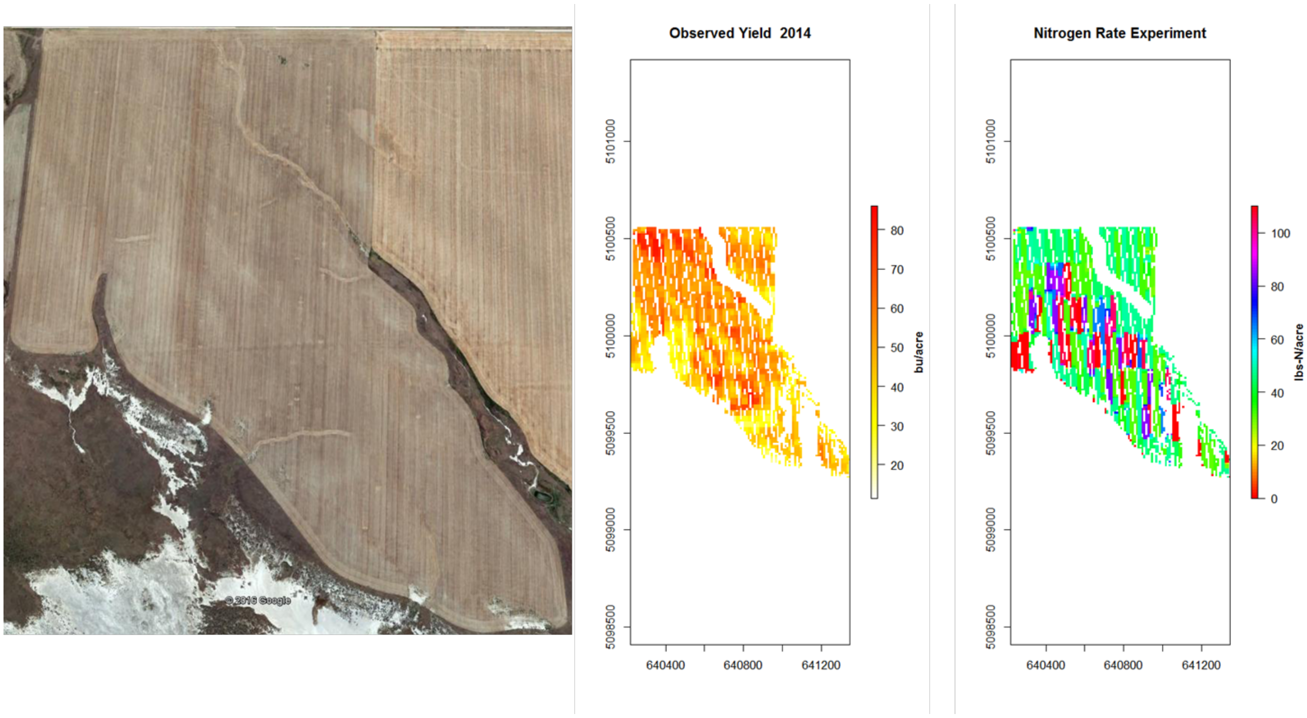

Fig. 2 Aerial imagery of sec1west field on Farm 1, yield map from previous winter wheat crop used to stratify experimental treatments and as-applied experimental nitrogen top dress rates on field

At harvest, georeferenced yield point data was obtained from each field that provided a measurement on average every 3 seconds, translating to 1-3 m distance along a combine harvester path. Grain protein concentration was measured with the CropScan 3000H analyzer[1] on average every 10 seconds (10-14 m between points). The monitoring data was cleaned using Yield Editor[2] the resulting cleaned data was then mapped (Figure 3).

[1] Crop Scan 3000H, Next Instruments, Australia (http://nextinstruments.net/index.php/products/cropscan/cropscan-3000h-on-header-analyser)

[2] Sudduth, K.A., Drummond, S.T., and D.B. Myers. (2012). Yield Editor 2.0: Software for Automated Removal of Yield Map Errors. ASABE Paper No. 121338243. St. Joseph, Mich.: ASABE.

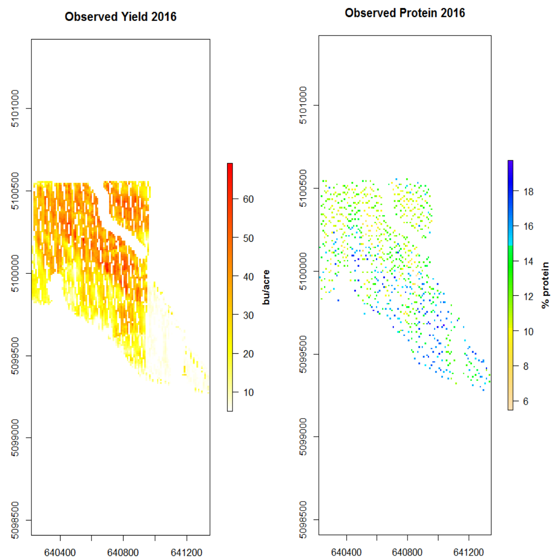

Fig. 3 Example of yield and protein monitor data from 2016 harvest of winter wheat in field sec1west on Farm 1

A universal non-linear hyperbolic regression function was fit to the grain yield and protein data from each field, and the significant parameters as well as their values were compared for spatial consistency. The non-linear equation (Equation 1) was selected because it was logical considering past research and experience with yield and protein response to nitrogen rates.

Equation 1. Universal equation fit to single year data from each field for comparison

$$Yield = \alpha + \frac{(\beta - \alpha)Nrate}{\frac{1}{\gamma} + Nrate}$$

Where β was assumed to be a linear function of a set of independent variables that included the previous crop year grain yield, current year NDVI (March) when a top-dress nitrogen fertilizer rate decision is typically made, and peak NDVI in the two years before the current year. α was assumed to be a linear function of the geographic variables that would be explanatory without addition of fertilizer and include the aspect of the point where the degree of north and south facing is the cosine of aspect and the degree that the point is facing east or west is the sin of aspect. In addition, the slope, elevation, topographic position index (TPI) and weed abundance at the monitor points were included as independent variables to predict α. All variables except weed abundance were estimated from the digital elevation model (DEM), a gridded map that is draped over the land surface and widely available for the whole state of Montana. TPI is a quantification of the terrain water capturing potential surrounding a point utilizing elevation measures within 10 m of each yield point. These independent variables are all associated with each crop grain yield and protein content monitor point in the field to help predict yield and protein.

The research question was examined by utilizing the best grain yield and protein response functions to compare current net returns for different top-dress nitrogen fertilizer application strategies (listed below).

1. Site-specific optimized (profit maximized) application rate at each yield monitor point in the field including a $4.00 per-acre discount for the technology required. (SS)
2. No nitrogen application anywhere in the field. (0 N)
3. The farmer selected uniform nitrogen application rate across the entire field. (FS)

4. The uniform nitrogen rate applied over the field that would maximize the full-field net return. (FF Opt.)
5. No nitrogen applied and a 10% reduction in yield, but with an organic price premium for the grain. (Org.)

By comparing the average net return per acre for each strategy under the historically observed variability in prices received for grain (USD/bu) and cost of nitrogen (USD/lbs) we determined the probability of each strategy outperforming the site-specific optimized strategy in each field. Multiple years of different climate scenarios are required for each field to make appropriate recommendations about the best nitrogen application strategy, but because we only are reporting on one year of data our uncertainty in outcomes was quantified using spatial variability in yield and protein as well as variability in prices received and costs of nitrogen fertilizers from the years 2000-2016. Once we have multiple years of data from a given field on the same crop we can incorporate the additional uncertainty caused by weather variation.

Results

The net returns of each strategy over 1000 simulations, where each simulation was run with a random selected year of price and cost information, were evaluated for each field to determine the probability that SS would yield higher net returns compared to the other strategies (Table 2). In all fields, the net return from SS was always higher than if no nitrogen was applied (0 N) and the farmer selected uniformly applied nitrogen rate (FS). The probability that SS would yield higher net returns compared to FF Opt. were 100% across all fields on Farm 2 and a single field on Farm 4. On Farm 3, SS never yielded a higher net return compared to the FF Opt. approach across both fields. Each field on Farm 1 showed different probabilities of SS outperforming the full field optimum rate; SS was never better than FF Opt. in sec35west and only generated higher net returns 5% of the time in sec1east. Results from sec1west showed SS netting higher returns 100% of the time while sec35middle saw the same result 92.1% of the time. In 7 out of the 10 fields SS never received higher net returns compared to organically grown and priced winter wheat. In sec35west, portnellsouth1, and davidsonmidwest2 SS produced higher net returns compared to organic production 99.4%, 66.9%, and 99.7% of the simulations respectively.

Table 2. Farm, field name, crop year, probability that site-specific management produced higher net returns in 1000 simulations

Farm	Field	Year	*SS ≥ 0 N*[1]	*SS ≥ FS*[1]	*SS ≥ FF Opt.*[1]	*SS ≥ Org.*[1]
1	sec1east	2017	1	1	0.05	0
	sec35west	2017	1	1	0	0.994
	sec1west	2016	1	1	1	0
	sec35middle	2016	1	1	0.921	0
2	carlinwest	2017	1	1	1	0
	minnies	2016	1	1	1	0
	henrys	2016	1	1	1	0
3	portnellsouth1	2016	1	1	0	0.669
	davidsonmidwest2	2016	1	1	0	0.997
4	sre1314	2016	1	1	1	0

[1] SS = site-specific nitrogen management, 0 N = no nitrogen added, FS = farmer selected nitrogen rate, FF Opt. = full field optimum uniform rate, Org. = organically produced and priced

The average net returns for each strategy were compared for each field. Organic production yielded the highest net returns on average while 0 N generated the lowest, and FF Opt. sometimes outperformed the SS. The FS uniform application nitrogen rate approach was always higher net return compared to 0 N but not as high as the uniform application FF Opt. approach.

The percent differences in the net returns of each strategy over the 1000 simulations for each field indicate that SS management was 42.45% higher net returns than 0 N and 18.14% more than the FS management scenarios (Table 3). However, SS net returns were on average only 1.94% higher than FF Opt. in 5 out of 10 fields. Organic production with no nitrogen fertilizer applied and no technology cost plus a 2-4 times higher price received for wheat was on average 102.86% higher net returns than SS.

Table 3. Farm, field name, crop year, mean percent difference in net return of each management strategy over 1000 simulations

Farm	Field	Year	Percent difference in Net Return (USD/ac)[1]			
			SS - 0 N	*SS - FS N*	*SS - FF Opt.*	*SS - Org.*
1	sec1east	2017	60.45	19.81	-0.6	-84.47
	sec35west	2017	83.42	40.67	-0.5	-16.29
	sec1west	2016	54.16	14.51	13.66	-149.84
	sec35middle	2016	57.79	6.75	2.43	-54.56
2	carlinwest	2017	2.66	11.89	2.55	-110.4
	minnies	2016	16.17	4.68	2.01	-300.85
	henrys	2016	12.63	3.46	2.23	-141.37
3	portnellsouth1	2016	74.89	30.12	-1.58	-40.02
	davidsonmidwest 2	2016	61.29	29.38	-0.91	-32.96
4	sre1314	2016	0.1	20.13	0.1	-97.93
	Mean		42.35	18.14	1.94	-102.86

[1] SS = site-specific nitrogen management, 0 N = no nitrogen added, FS = farmer selected nitrogen rate, FF Opt. = full field optimum uniform rate, Org. = organically produced and priced

Nitrogen applied was compared across all simulations, with average percent change reported in Table 4 for all fields. Because the 0 N approach adds no nitrogen to the field, the SS approach adds 100% more nitrogen. The SS approach resulted in more nitrogen applied compared to the results of the FS strategy in 7 out of 10 fields, however in fields where the SS approach suggested adding less nitrogen than the FS, there was a greater difference between the two approaches. This results in an average reduction in nitrogen applied of 441.33% across all fields. In only 2 out of 10 fields did SS add more nitrogen compared to a full field optimum rate, with an average increase in nitrogen applied across all fields of 15.18% using the SS strategy compared to the FF Opt. N.

Table 4. Farm, field name, crop year, percent difference in total nitrogen applied by each management strategy over 1000 simulations.

			Percent difference in Total N Applied (lbs)		
Farm	Field	Year	*SS - 0 N*	*SS - FS N*	*SS - FF Opt. N*
1	sec1east	2017	100	65.72	-2.16
	sec35west	2017	100	71.21	-1.88
	sec1west	2016	100	15.12	4.72
	sec35middle	2016	100	36.77	-9.13
2	carlinwest	2017	100	-412.09	76.64
	minnies	2016	100	-20.27	-5.76
	henrys	2016	100	21.13	-7.67
3	portnellsouth1	2016	100	56.87	-1.76
	davidsonmidwest2	2016	100	57.28	-1.65
4	sre1314	2016	100	-4305.07	100
	Mean		100	-441.33	15.14

[1] SS = site-specific nitrogen management, 0 N = no nitrogen added, FS = farmer selected nitrogen rate, FF Opt. = full field optimum uniform rate, Org. = organically produced and priced

Discussion

The results of this study support that site-specific nitrogen management shows potential to increase the net returns of winter wheat producers in Montana compared to current nitrogen fertilizer application practices. The net return from SS was consistently higher in every field than the net returns received from management utilizing the farmer selected nitrogen rate or no nitrogen application even when a technology cost was imposed. The application of nitrogen in a variable manner boosted protein and yield in specific areas of the field that counteracted the cost from having to buy and apply more nitrogen.

The performance of a site- specific management approach compared to applying an optimum rate across the full field insinuate that the difference between these approaches is largely field specific. Two farms (2,4) showed that SS generated higher net returns than FF Opt. every time, whereas Farm 3 showed that FF Opt. outperformed the SS approach consistently, perhaps insinuating that there is a geographic driver in strategy performance. It is at Farm 1 where two fields benefitted more from a full field rate and two fields benefitted more from a site- specific approach, representing a finer spatial factor than farm to farm in the performance of site-specific nitrogen management and indicating that an appropriate management strategy will vary from field to field. However, when averaged across all farms, there is marginal difference between the two approaches and a consensus that either approach will be financially beneficial compared to a farmer selected nitrogen rate. When comparing the performance of SS and FF Opt. strategies, the strategy producing the most income for a grower is not always linked to the difference in nitrogen applied. As mentioned before, only in two fields was more nitrogen applied during a site-specific approach while in five fields the full-field rate produced higher net returns. The average increase of nitrogen applied during site specific management compared to the farmer selected strategy can be attributed to the subjectivity of the rate chosen. The rate was established simply by asking the farmer how much nitrogen they would uniformly apply to the field, a number which potentially changes annually or not indicative of reality since the poll occurred months in advance of the decision-making point in March.

Although a specific nitrogen management strategy was not determined to be consistently more economically productive than another method across farms, applying nitrogen on a site-specific basis always yielded higher net returns than the rate that a farmer would have uniformly applied in that year. Thus, there would be a financial benefit to producer adoption of site-specific nitrogen management. Despite being a no nitrogen added strategy, organic production will net more economic return for a grower than any other conventional strategy because of the higher prices received for organic winter wheat, the lack of technology cost and under the assumption of only a 10% yield reduction due to lack of weed control. At least one farmer cooperator felt that the yield reduction could be more realistically set at 40% under organic management. The economics of organic production also did not include the three-year conversion to organic when inputs could not be used and the premium would not be received. Regardless, if reduction in total nitrogen fertilizer for the wheat growing region of Montana was the objective, incentives for converting to organic production may be an appropriate policy.

The apparent advantage that the profit maximizing uniform application FF Opt. approach over the SS approach to nitrogen fertilizer management on certain farms may be due to historic management of nitrogen fertilizer on some farms. When the grain yield and protein response in the data is relatively flat the uniform rate can outperform the SS. The flatness of the rate response curve is likely due to a surplus of nitrogen in the soil from a history of over application. This fits the pattern that we see in the data based on our casual conversations with the farmers. In addition, the economics of the FF Opt. approach do not include a technology cost but perhaps it should because there is no way to know the optimum without the response function which requires the experiment, which in turn, requires the technology to apply the experiment. A site-specific approach to nitrogen fertilizer was shown to have more consistent potential to decrease the amount of nitrogen applied compared to a full field optimum application and thus we can safely conclude that adoption of the site-specific technology allowing variable rate application of nitrogen fertilizer will reduce nitrogen use in the wheat growing region of Montana. However, key to this conclusion is the ability to parameterize the grain yield and protein content response to nitrogen fertilizer rate function, which requires the on-farm experiment.

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