PREDICTION OF NITROGEN NEEDS WITH NITROGEN-RICH STRIPS AND RAMPED NITROGEN STRIPS

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ABSTRACT

Both nitrogen rich strips and ramped nitrogen strips have been used to estimate topdress nitrogen needs for winter wheat based on in-season optical reflectance data. The ramped strip system places a series of small plots in each field with increasing levels of nitrogen to determine the application rate at which predicted yield response to nitrogen reaches a plateau. The nitrogen-rich strip system uses a nitrogen fertilizer optimization algorithm based on optical reflectance measures from the nitrogen-rich strip and an untreated strip in the same field. This paper uses Wilcoxon Signed-Rank Tests to determine which of these two systems is expected to be more profitable. Our results indicate that the ramped strip method produces significantly greater profits than the nitrogen-rich strip system. This result is robust to varying assumptions used by the nitrogen-rich strip method. On average, the ramped strip system is more profitable by \$55.69 ha^{-1}.

Keywords: Precision agriculture, nitrogen needs, yield potential

INTRODUCTION

Raun and Johnson (1999) estimate that 67% of applied N is lost through leaching, runoff, and volatilization because application does not correspond to plant needs either spatially or temporally. In effect, an average of 67% of N expenditures is wasted. Improved efficiency of agricultural N not only offers increased producer profits but also environmental benefits, such as reduction of eutrophication in the Gulf of Mexico (Scavia, Justić, and Bierman, 2004) and decreased emissions of nitrous oxide, a powerful greenhouse gas (Faeth and Greenhalgh, 2000).

Raun et al. (2002) have developed a nitrogen fertilizer optimization algorithm (NFOA) which can be used to predict the uniform N application rate that will maximize a field's average grain yield based on in-season optical reflectance imaging (ORI) measures from plants in an N-rich strip and an adjacent, untreated strip in the field. Such whole-field systems should be particularly useful in areas where within-field variability of N requirements is low, as they account only for between-field spatial variation and inter-annual variation, likely caused by spatial and intertemporal differences in climate.

This article compares the expected profitability of two such whole-field N needs prediction systems: 1) the N-rich strip system of Raun et al. (2002) described above and 2) a ramped strip system using small experimental plots arranged in a strip with increasing N application rates. We also compare the profitability of these with the profitability of following the current Extension Service recommendation of 90 kg N ha^{-1}. In both systems, the experimental strip is created prior to planting the crop. The systems mutually assume that grain yield is a function of the most limiting input, so that yield responds linearly to N application until the crop response ceases due to other constraining variables, such as rainfall and temperature. Based on in-season ORI measures from either the N-rich strip or the ramped strip, each system predicts the N application rate at which yield will cease to respond to additional N.

Why might these two systems make different predictions of the optimal N rate for any given field-year? The answer lies in the assumptions made by the different prediction systems. Both assume the yield intercept and the yield plateau vary between fields and across years. The ramped strip approach uses all observations and the parameters are estimated with least squares techniques. The nitrogen-rich strip (NRS) approach uses only the observation with no nitrogen applied and the largest level of nitrogen applied. With the NRS approach, the slope of the line is estimated based on agronomic factors and does not vary across fields. If the restriction imposed by the NRS approach is accurate the NRS approach could be superior to the ramped-strip approach. The ramped strip approach is estimating a nonlinear function with few observations and so its parameter estimates could have large standard errors. Also, Richter and Brorsen (2008) found little evidence that the slope of the line varied across time.

The purpose of this paper is to determine which of these prediction systems provides greater expected returns above N and application costs (hereafter called "expected returns"). The results will provide guidance for the research and development of a whole-field N needs prediction system that will assist producers in choosing an expected-profit maximizing N application rate annually.

THEORY

In maximizing expected profit, a producer must choose between at least three alternative criteria on which to base his in-season topdress N application decision: a) the current rate of 90 kg N ha^{-1} recommended by Oklahoma cooperative Extension (Zhang, Raun, and Hattey, 2008), b) the N-rich strip recommendation, and c) the ramped-strip recommendation. This problem can be expressed mathematically as follows:

$$(1) \qquad \max_{\lambda_{NRS},\lambda_{RS}\in\{0,1\}} E[\pi(\lambda_{NRS},\lambda_{RS})] = \lambda_{NRS}E[\pi_{NRS}] + \lambda_{RS}E[\pi_{RS}] + (1-\lambda_{NRS}-\lambda_{RS})E[\pi_{ER}]$$

$$s.t.$$

$$(1-\lambda_{NRS}-\lambda_{RS}) \in \{0,1\},$$

where π is profit, λ_{NRS} is a binary variable indicating that the N-rich strip recommendation is chosen, π_{NRS} is the profit from the N-rich strip method, λ_{RS} is a binary variable indicating the ramped strip prediction is used, π_{RS} is profit from the ramped strip method, π_{ER} is the profit from using the current Extension Service recommendation, and the constraint $(1-\lambda_{NRS}-\lambda_{RS}) \in \{0,1\}$ limits the producer to choosing only one of the three criteria as the basis for his N application decision. Thus, the profit maximizing producer will choose to employ the strategy with the highest expected profit. Here, the expected return for each of the three methods (k = *ER*, *NRS*, *RS*) is:

$$(2) \qquad E(\pi_k) = p_c E(y_k) - \mathbf{r}_k^{'}\mathbf{x}_k,$$

where π_k is the profit from using prediction method k, p_c is the price of the crop, $\mathbf{r}_k^{'}$ is a 1 x q vector of input prices for method k, $\mathbf{x}_k$ is a q x 1 vector of input requirements for method k, and q is the number of inputs in the input requirement set.

Crop yield (y_k above) depends upon a number of variables and their complex interactions, and any number of these variables may impose bounds on yield potential. Many of these factors are beyond producer influence, as are rainfall, temperature, soil type, and other environmental factors. Past literature supports the use of functional forms derived from the von Liebig hypothesis to model agricultural production (e.g., Paris and Knapp, 1989; Berck and Helfand, 1990; Paris, 1992; Chambers and Lichtenberg, 1996; Tembo, et al., 2008). These studies indicate that output is a function of the most limiting input, or that yield can be modeled as a linear response to applied N that reaches a plateau when other variables become limiting.

DATA

The data for this study come from experiments conducted at nine fields located throughout the state of Oklahoma between 1998 and 2006. The nine fields are located at the Perkins, Stillwater, Efaw, Hennessey, Haskell, Tipton, Lahoma, and Lake Carl Blackwell agricultural experiment stations.

Table 1. Lists location, experimental years, soil type, and nitrogen levels.

Experiment Station Location	Years	Soil Type	N Treatment Levels (kg ha^{-1})
Perkins 1	1998-2006	Teller sandy loam	0, 56, 112, 168
Perkins 2	1998	Teller sandy loam	0, 56, 112, 168
Tipton	1998	Tipton silt loam	0, 56, 112, 168
Stillwater	1999-2006	Norge silt loam	0, 45, 90, 134
Efaw	1999-2006	Easpur loam	0, 56, 90, 123
Hennessey	2000, 2002	Shellabarger sandy loam	0, 56, 90, 123
Haskell	1999-2002	Taloka silt loam	0, 112, 168
Lahoma	1999-2006	Grant silt loam	0, 22, 45, 67, 90, 112
Lake Carl Blackwell	2004, 2006	Port silt loam	0, 50, 100

Table 1 contains the specifics about N treatment levels, soil types, and dates for each experimental location. Each field received at least three different levels of N treatment. ORI measures for each observation were collected around Feekes growth stage 5, and yield was measured at harvest. These data can be used to approximate N-rich strips and ramped N strips. The N-rich strip is the area of each field on which the maximum N rate was applied. The ramped strips here are approximated by the different levels of N applied on plots throughout each field. These can be used to estimate the same regression that would be estimated with data from a ramped N strip, even though not as many different rates are included as would be in the strip. The NFOA and its parameters as used in this article may be found in Raun et al. (2005).

Based on local cooperative prices on April 26, 2008, this paper assumes an N price of \$1.28 kg^{-1} N from UAN 28-0-0. Custom application costs for UAN are assumed to be \$7.20 ha^{-1} (Kletke and Doye, 2001). We assume a wheat price of \$0.31 kg^{-1}. The cost of creating either a ramped or an N-rich strip measuring 19.8 m by 803 m is \$353.36, including N purchase and application costs at 168 kg N ha^{-1} (Biermacher et al., 2008). A representative field size is 64.7 hectares (Biermacher et al., 2008), so the cost of an experimental strip is \$5.46 ha^{-1}.

PROCEDURES

We begin by using our data to estimate a production function for each field in each year, where yield is a linear response-plateau function of applied N as follows:

(3) $$y_{it} = \min\{\beta_{0t} + \beta_{1t} N_{it}, P_t\} + \varepsilon_{it},$$

where y_{it} is the measured wheat yield on plot i of field-year t, β_{0t} is the yield intercept for field-year t, β_{1t} is the yield response for field-year t, N_{it} is the applied N on plot i in field-year t, P_t is the plateau yield for field-year t, and $\varepsilon_{ijt} \sim N(0,\sigma_t^2)$ is an error term specific to field-year t.

Next, we use each system to obtain a prediction of the optimal N application rate for each of the 42 field-years in our data set. We first complete this process using the N-rich strip system. The formula is as follows:

(4) $$N_{tNRS} = 0.0239\frac{YP_{tN} - YP_{t0}}{\eta},$$

where N_{jtNRS} is the N application rate in kg ha^{-1} recommended by the N-rich strip for field-year t, $YP_{t0} = 0.359e^{324.4R_{t0}}$ is the predicted yield intercept (in Mg ha^{-1}) based on the adjacent untreated strip in field j in year t, $YP_{tN} = \min(\max(YP_{t0},\ YP_{t0} \cdot R_{tN}/R_{t0}),\ 7)$ is the predicted plateau yield (in Mg ha^{-1}) based on the N-rich strip in field-year t, $0.5 < \eta < 0.7$ is N use efficiency, the coefficient 0.0239 is the decimal percentage of N in the grain by weight multiplied by a conversion constant, R_{t0} is the average ORI measure from the untreated strip in field-year t, and R_{tN} is the average ORI measure from the N-rich strip in field-year t (Raun et al., 2005). For this paper, we assume $\eta = 0.5$ as a conservative estimate of N use efficiency from in-season topdress N application.

The predicted optimal N application rate for each field-year is then predicted using the ramped strip system. To do so, we estimate a linear response-plateau function of ORI measures as a function of N application rate unique to each field-year as follows:

(5) $$M_{it} = \min\{\alpha_{0t} + \alpha_{1t}N_{it}, \phi_t\} + \upsilon_{it},$$

where M_{it} is the ORI measure on plot i in field-year t, α_{0t} is the ORI intercept for field-year t, α_{1t} is the ORI response for field-year t, N_{it} is the applied N on plot i in field-year t, ϕ_t is the plateau ORI measure for field-year t, and $\upsilon_{it} \sim N(0,\sigma_t^2)$ is an error term specific to field-year t. Thus, the predicted optimal rate for field-year t based on the ramped strip is:

(6) $$N_{tRS} = \begin{cases} \dfrac{\phi_t - \alpha_{0t}}{\alpha_{1t}}, & p_c\alpha_{1t} > p_n,\ p_c\phi_t - p_c\alpha_{1t} > p_a \\ 0, & \text{otherwise,} \end{cases}$$

where p_n is the price of one pound of N, p_a is the per hectare cost of N application, and all other parameters are as previously defined. The two conditions above ensure that N will not be applied if the value of the marginal product of N is less than the price of N or if the value gained from N application is less than the cost of N application. Note that the N-rich strip method and the Extension advice assume these two conditions are met.

Now we proceed to calculate expected returns for each field-year using each system by plugging the N recommendations and input requirement sets from each system into the expected returns function for each field-year so that:

(7) $$E(\pi_{jtk}) = p_cE(y_{tk}) - \mathbf{r}_k^{'}\mathbf{x}_{tk},$$

where π_{tk} is the return above N-related costs for field-year t using system k, y_{tk} is the yield for field-year t using system k, $\mathbf{x}_{tk} = [N_{tk} \quad A_{tk} \quad S_k]$ is the predicted optimal input requirement set for field-year t using system k, $\mathbf{r}_k = [p_n \quad p_a \quad p_s]$ is the vector of input prices, A_{tk} is a binary variable indicating whether method k predicts a non-zero N requirement for field-year t, S_k is a binary variable indicating whether an experimental strip is required by method k, p_s is the per hectare price of an N-rich or ramped strip, and all other symbols are as previously defined.

After calculating expected returns for each field in each year, we conduct three Wilcoxon Signed-Ranks Tests (Wilcoxon, 1945) of the paired differences to determine whether statistically significant profitability differences exist among the N-rich strip, ramped strip, and the Extension recommendation. This test is used in place of the Student's *t*-test due to nonnormality of the paired profit differences among the three systems.

We also conduct sensitivity analysis regarding the value of parameter η in the NFOA to determine its effect on the results of these paired differences tests. In addition to being tested assuming N-use efficiency of 0.5, we also test under the assumption of N-use efficiencies of 0.33 and 0.7 (see Raun et al., 2002). Paired differences tests are also conducted assuming N-use efficiency of 0.235, comparable to efficiencies found by López-Bellido, López-Bellido and López-Bellido (2006).

RESULTS

Table 2 displays estimates of production function parameters for each field-year. The mean slope of all production functions (excluding those for which the slope is zero) is 14.39, indicating that on average one can expect to increase yield by 14.39 kg ha^{-1} for each application rate increase of 1 kg N ha^{-1}. However, the slopes are widely dispersed around their mean, with a standard deviation of 10.64, meaning that the N-rich strip assumption of a constant marginal product of N is likely to be unrealistic. The constant slope assumed by the N-rich strip method is 20.92—i.e., $\eta/0.0239$ with $\eta = 0.5$—about 45% greater than the mean of the slopes of the estimated production functions. Tables 3 and 4 similarly display estimates of the predicted production functions from the ramped strip and N-rich strip methods, respectively.

Table 2. Displays Estimated Production Functions by Field-Year.

Year	Location	Intercept Yield	Slope	Plateau Yield	Optimal N Application
1998	Perkins 1	1145.50	8.17	2194.01	128
1998	Perkins 2	1312.89	1.38	1466.90	0
1998	Tipton	2937.18	12.39	5019.17	168
1999	Perkins 1	1076.38	12.71	2429.43	106
1999	Stillwater	855.47	10.90	1710.98	78
1999	Efaw	2167.43	19.27	3512.01	70
1999	Haskell	1911.43	1.49	2162.43	0
1999	Lahoma	1514.08	26.28	4439.73	111
2000	Perkins 1	2640.77	6.02	3315.26	112
2000	Stillwater	1135.55	16.60	3366.36	134
2000	Efaw	2132.44	4.16	2513.90	92
2000	Haskell	5343.46	0.00	5343.46	0
2000	Lahoma	1897.96	34.99	3378.44	42
2000	Hennessey	3841.64	0.00	3841.64	0
2001	Perkins 1	2489.29	0.00	2489.29	0
2001	Stillwater	1053.41	12.70	1678.93	49
2001	Efaw	2691.33	8.80	3299.47	69
2001	Haskell	4046.58	0.00	4046.58	0
2002	Perkins 1	2693.62	1.17	2889.68	0
2002	Stillwater	1034.41	15.04	2984.99	130
2002	Efaw	1559.92	24.41	3572.41	82
2002	Haskell	3498.32	0.00	3498.32	0
2002	Lahoma	2749.50	0.84	2843.09	0
2002	Hennessey	2870.67	1.15	2973.49	0
2003	Lahoma	2758.78	46.43	5655.49	62
2003	Stillwater	1357.32	13.25	2389.44	78
2003	Perkins 1	2794.58	12.81	3776.47	77
2003	Efaw	2790.00	20.31	4947.16	106
2004	Carl Blackwell	2224.42	18.28	4067.42	101
2004	Perkins 1	1934.85	19.77	3397.32	74
2004	Efaw	1952.48	20.58	4629.27	130
2004	Stillwater	1516.32	14.08	2117.18	43
2004	Lahoma	1403.31	20.32	3412.44	99
2005	Stillwater	1742.00	6.55	2329.06	90
2005	Lahoma	1687.54	20.24	2683.34	49
2005	Perkins 1	3354.42	13.13	4021.79	51
2005	Efaw	1132.06	5.15	2055.67	179
2006	Stillwater	1077.55	0.00	1077.55	0
2006	Efaw	1378.02	4.25	1821.44	104
2006	Lahoma	4475.87	0.00	4475.87	0
2006	Perkins 1	917.23	12.34	2053.63	92
2006	Carl Blackwell	1276.44	37.69	4374.10	82
Mean		2151.72	14.39	3196.54	66
(St. dev.)		(1047.48)	(10.64)	(1108.17)	(51)

Table 3. Displays Ramped Strip Predicted Yield Functions by Field-Year.

Year	Location	Intercept Yield	Slope	Plateau Yield	Optimal N Application
1998	Perkins 1	2347.77	6.45	3184.20	130
1998	Perkins 2	2173.68	3.30	2499.83	0
1998	Tipton	2787.83	3.02	3271.04	0
1999	Perkins 1	1873.84	7.67	2337.77	61
1999	Stillwater	2192.37	12.57	2717.78	42
1999	Efaw	2777.75	5.03	3099.83	64
1999	Haskell	2383.19	2.07	2736.91	0
1999	Lahoma	2492.09	6.86	3135.29	94
2000	Perkins 1	2591.77	6.29	2955.03	58
2000	Stillwater	1822.80	19.47	2845.39	53
2000	Efaw	2662.61	11.65	3304.00	55
2000	Haskell	2312.69	1.89	2630.26	0
2000	Lahoma	2135.53	27.07	2973.93	31
2000	Hennessey	2817.03	0.41	2901.04	0
2001	Perkins 1	2657.81	0.00	2678.84	0
2001	Stillwater	2255.35	9.16	2898.17	70
2001	Efaw	3120.86	1.89	3220.20	0
2001	Haskell	2475.55	1.75	2791.14	0
2002	Perkins 1	2795.23	1.40	3036.49	0
2002	Stillwater	1847.48	12.76	2715.11	68
2002	Efaw	2428.06	8.90	2937.24	57
2002	Haskell	2229.25	3.88	2900.72	0
2002	Lahoma	3198.80	0.00	3198.80	0
2002	Hennessey	2283.47	0.73	2399.36	0
2003	Lahoma	2218.63	36.41	3357.52	31
2003	Stillwater	1743.51	9.02	2541.59	88
2003	Perkins 1	1796.84	7.04	2473.26	96
2003	Efaw	2566.01	5.29	3200.02	120
2004	Carl Blackwell	1645.29	8.25	2476.89	101
2004	Perkins 1	1893.69	4.48	2424.51	118
2004	Efaw	2000.97	11.03	3127.34	102
2004	Stillwater	1992.23	18.50	2789.18	43
2004	Lahoma	1448.73	12.56	2687.86	99
2005	Stillwater	2059.15	6.32	2908.69	134
2005	Lahoma	1717.40	10.43	2550.39	80
2005	Perkins 1	2086.28	9.54	3066.10	103
2005	Efaw	1933.69	9.25	3003.68	116
2006	Stillwater	1349.35	15.98	2464.97	70
2006	Efaw	1127.75	4.74	1716.92	124
2006	Lahoma	1833.13	9.20	2624.72	86
2006	Perkins 1	1592.04	8.75	2421.29	95
2006	Carl Blackwell	1970.64	3.78	2352.03	0
Mean		2181.86	8.41	2798.94	57
(St. dev.)		(463.65)	(7.22)	(338.74)	(46)

Table 4. Displays Nitrogen-Rich Strip Predicted Yield Functions by Field-Year.

Year	Location	Intercept Yield	Slope	Plateau Yield	Optimal N Application
1998	Perkins 1	2511.26	20.92	3402.66	43
1998	Perkins 2	2170.19	20.92	2516.28	17
1998	Tipton	3549.42	20.92	4194.41	31
1999	Perkins 1	1693.20	20.92	2081.96	19
1999	Stillwater	2204.00	20.92	2413.06	10
1999	Efaw	3577.91	20.92	3941.66	17
1999	Haskell	2584.58	20.92	2967.13	18
1999	Lahoma	2628.98	20.92	3426.74	38
2000	Perkins 1	2619.05	20.92	3174.26	27
2000	Stillwater	1623.16	20.92	2611.02	47
2000	Efaw	3365.43	20.92	3585.76	11
2000	Haskell	2440.56	20.92	2789.36	17
2000	Lahoma	2102.72	20.92	3081.67	47
2000	Hennessey	3651.35	20.92	3735.31	4
2001	Perkins 1	3364.94	20.92	3373.27	0
2001	Stillwater	2321.97	20.92	2747.99	20
2001	Efaw	4753.23	20.92	4929.46	8
2001	Haskell	2833.38	20.92	3236.77	19
2002	Perkins 1	3863.53	20.92	4089.29	11
2002	Stillwater	1656.65	20.92	2434.33	37
2002	Efaw	2670.01	20.92	3237.54	27
2002	Haskell	2331.90	20.92	3100.84	37
2002	Lahoma	3705.81	20.92	3705.81	0
2002	Hennessey	2534.72	20.92	2598.23	3
2003	Lahoma	2252.45	20.92	3584.18	64
2003	Stillwater	1520.05	20.92	2211.94	33
2003	Perkins 1	1588.59	20.92	2329.05	35
2003	Efaw	2814.99	20.92	3620.64	39
2004	Carl Blackwell	1477.31	20.92	2227.43	36
2004	Perkins 1	1734.21	20.92	2209.76	23
2004	Efaw	1991.88	20.92	2913.25	44
2004	Stillwater	1867.53	20.92	1867.53	0
2004	Lahoma	1182.81	20.92	2207.09	49
2005	Stillwater	1960.08	20.92	2916.57	46
2005	Lahoma	1442.65	20.92	2266.46	39
2005	Perkins 1	2018.70	20.92	3067.46	50
2005	Efaw	1776.25	20.92	2750.00	47
2006	Stillwater	1096.87	20.92	1998.09	43
2006	Efaw	986.19	20.92	1521.87	26
2006	Lahoma	1596.79	20.92	2380.62	37
2006	Perkins 1	1340.93	20.92	2045.99	34
2006	Carl Blackwell	1901.23	20.92	2287.08	18
Mean		2316.84	20.92	2899.52	28
(St. dev.)		(861.35)	(0.00)	(729.18)	(16)

Assuming N-use efficiency of 0.5, the average application rates for the N-rich strip over all field-years was 28 kg ha^{-1}, while the ramped strip system suggested more nitrogen, averaging 57 kg ha^{-1}. Thus, both of these whole-field N requirement prediction systems lead to sizable average decreases in N acquisition costs as compared with the current Extension recommendation of 90 kg N ha^{-1}. Average yield using the Extension suggestion is about 3055 kg ha^{-1}, compared with 2857 and 2563 kg ha^{-1} for the ramped and N-rich strip systems, respectively. The average paired difference between profits based on the ramped strip and N-rich strip systems is \$55.69 ha^{-1} with a standard deviation of 139.85. The *t*-statistic for the signed-rank test is 3.23, while the *t*-critical value at the 0.01 level with 41 degrees of freedom is 2.701. Thus, we find strong evidence that expected profits are greater under use of the ramped strip system than the N-rich strip system. The average paired profit difference between the ramped strip system and the Extension advice is -\$22.81 ha^{-1}; however, the signed-rank test statistic of 0.19 (*t*-critical value is 2.701) indicates that the distribution of returns from the Extension recommendation is not significantly different from that of returns from using the ramped strip prediction method. Expected returns above N-related costs are \$746.70, \$802.40, and \$825.21 per hectare for the N-rich strip method, ramped strip method, and current Extension recommendation, respectively. The ramped strip system also performs better than the N-rich strip system by the mean-variance criterion, with mean and variance of ramped strip returns at 802.40 and 107,313.50, compared to \$746.70 and 114,993.70 for the N-rich strip returns. This result indicates that expected profits of the ramped strip system are higher on average, and involve less risk of losses.

For assumed N-use efficiency of 0.33 the mean paired difference in net returns between the ramped and N-rich strips is \$28.95 ha^{-1}. This difference is significant at the 0.05 level (p = 0.015). A profit difference of \$80.83 ha^{-1} is also significant at the 0.01 level when 0.7 N-use efficiency is assumed, while mean N application rate prescribed by the N-rich strip system decreases to 20 kg ha^{-1}. The Wilcoxon Signed-Rank Test shows that when N-use efficiency is assumed to be 0.235, the mean returns from the N-rich and ramped strip systems are indistinguishable—both equal to \$802.40 ha^{-1}. However, the median return for the ramped strip system is greater than that of the N-rich strip system by \$5.30 ha^{-1} (p = 0.066), meaning that half of producers make greater profits by using the ramped strip system.

The magnitude (but not the sign) of profitability differences between the two whole field systems are sensitive to assumptions made about N-use efficiency gained by applying mid-season topdress N instead of preplant N. Again, the results of Wilcoxon Signed-Rank Tests assuming $0.2 \le \eta \le 0.7$) show that the median paired difference is always statistically significant in favor of the ramped strip method. This means that at least half of the producers will always do better by applying the ramped strip prediction of N requirements.

As wheat price changes (assuming N-use efficiency of 0.5), the ramped strip system remains more profitable until the price drops to \$0.16 kg^{-1} or lower. Regardless of crop price, the N-rich system is never significantly more profitable than the ramped strip prediction system. Of course, very low wheat to N price ratios will inspire producers to apply less N to their crops automatically.

CONCLUSIONS

Our results strongly favor using the ramped strip method to predict mid-season topdress N requirements for winter wheat. Regardless of the assumption about N-use efficiency made in the NFOA, returns from the ramped strip system come from a distribution with a significantly higher median return per hectare. This may be due, in part, to the fact that the N-rich strip system uses only yield predictions from the N-rich strip and the untreated strip, while the ramped strip system also makes use of other location-specific ORI measures at multiple N treatment levels, which may allow more accurate estimation of the intercept, plateau, and slope of the true linear response-plateau function. The results favoring the ramped strip method are also robust with regard to fluctuations in the relative prices of wheat and N.

One important caveat is that available data are all from preplant applications. The research assumes that plant response to topdress applications are the same as from preplant applications. It is quite possible that the fixed nitrogen-use efficiency used in the NRS approach would do relatively better than the more noisy ramped strip approach in predicting plant response to topdress applications.

The ramped strip system is not significantly more profitable (nor significantly less profitable) than following the current Extension advice to apply 90 kg N ha^{-1}. Current incentives, specifically high and increasing crop prices and relatively low N prices, are such that producers are likely to continue to over apply N to avoid potential yield losses unless a system can be developed that shows significantly greater expected profitability than the current Extension advice. Future research should account for parameter uncertainty. Plateau models are nonlinear in the parameters and so the parameter uncertainty does not disappear when taking expectations as assumed with the plug-in method used here. Not accounting for parameter uncertainty may explain a portion of the yield losses experienced by the precision systems. Future research will also consider using Bayesian methods to incorporate additional information, such as average historical yields and historical application rates based on farmer practice.

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