The Profitability of Variable Rate Lime in Wheat

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Abstract. *Grid sampling allows a variable rate of lime to be applied and has been marketed as a cost saver to producers. However, there is little research that shows if this precision application is profitable or not. Previous research on variable-rate lime has considered only a small number of fields. This paper uses soil sampling data from 170 fields provided by producers in Oklahoma and Kansas. We compare net returns of variable rate to uniform rate lime for grain only wheat production, dual-purpose wheat grain and forage production, and a wheat-soybean rotation. Using university lime rate recommendation tables, we calculated the lime rate for variable rate using grid sampling and uniform rate using an estimated composite sample. We then calculated expected yield over a five year period to estimate the difference in net returns from variable rate lime for the three production systems. We evaluated a range of target pHs from 6.0 to 6.9. On average, net revenues were maximized at a target pH of 6.5 for variable and uniform rates. At this level, variable rate averaged $3.42/acre less net returns for grain only and $8.56/acre less with dual-purpose. For grain only, 66 of the 170 fields had higher net returns for variable rate at the optimal target pH. In a dual-purpose system only 32 of the 170 fields had higher net returns with a variable rate. For a wheat-soybean rotation at the optimal target pH of 6.5, variable rate had $6.02/acre higher average net returns than a uniform rate. Thus, variable rate liming is a marginal investment, but there are times when it can pay.*

Keywords. *Wheat, Lime, Precision Agriculture, Variable Rate, Profitability*

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Introduction

Precision farming techniques are widely available to help manage soil pH. The pH of the soil impacts the availability of nutrients for crops and can cause conditions, such as aluminum toxicity, that result in reduced yields. The pH of the soil is impacted by many different factors and some soils are even naturally acidic. Application of nitrogen fertilizer decreases soil pH (Zhang et al. 2017a). Even the harvesting of crops itself can increase acidity due to crops absorbing lime-like elements, such as cations. These cations offset acidity caused from other processes. So when these are removed, the soil does not offset these acidity causing processes as well and the soil becomes more acidic (Johnson and Zhang 2017).

To remediate an acidic soil, producers can apply agricultural limestone (aglime). The most common way this has been done historically is by taking a composite soil sample of the field, where samples are taken from a few locations across the field and mixed together. However, pH can have a high spatial variability (Cline 1944). Using a composite sample assumes the field is uniform and does not take this variability into account. This can lead to over/under application of lime and thus decreased expected yields as pH levels become too high/low. Over application of lime can become especially problematic as there is no economically efficient way to reduce pH.

Grid sampling is a strategy that many have promoted to reduce misapplication. In grid sampling, samples are obtained from different locations across the field and each sample is analyzed for buffer pH and soil nutrients. Instead of using one sample as an average of the whole field each sample represents a grid cell within the field. These grid cells can range in size from 1 acre, 2.5 acre, or 5 acres. This helps capture the variability within the field by allowing fertilizer or lime to be applied at a variable rate. However, grid sampling is significantly more expensive than a composite sample and companies typically charge more for applying a variable rate. So while many are promoting this precision technology, the research is more divided on its profitability.

The common structure of a variable rate study is to use a randomized complete block design within a single field and conduct an experiment over a relatively short time period of a few years. In the case of lime, Bongiovanni and Lowenberg-DeBoer (2000) found site-specific lime application was profitable in the fields they studied that had a corn-soybean rotation. However, Weisz et al. (2003) found that for wheat, 3 years of grid sampling and variable rate lime application were not profitable compared to a uniform application. The difference in the conclusions of these two studies could be that for lower valued commodities, such as wheat, the benefits from variable rate fertilizer are less than for those of higher valued commodities, such as corn or soybeans. None of these studies have compared variable rate and uniform rate at the field level as well as across a large number of fields as this study has done. This allows us to determine how results change depending on how much pH varies across a field. By using a large number of fields we are able to further determine if certain field conditions allow for variable rate to become profitable even in lower valued commodities.

The objective of this paper is to determine whether variable rate lime application is profitable in continuous wheat, dual purpose wheat and forage, and a soybean-wheat rotation. The objective of this paper is accomplished using soil sample data sent to us by producers. In total 170 fields were used from producers in Oklahoma and Kansas. Each field was grid sampled and included both pH and Buffer pH. The Buffer pH values were found by taking a soil sample and mixing them in a buffer solution. In the Midwest the common buffer test used is the SMP buffer, which is set to an initial pH of 7.5. When an acidic soil is mixed with the buffer solution, the pH of the solution drops. This new pH is known as the soil buffer index or buffer pH (Mengel 2016b). The lower the Buffer pH, the more lime that is needed to raise the pH of the soil to a desired level. The Buffer pH is used by universities to find recommended lime application rates, such as those in Table 1. In grid sampling this process is done for each grid cell across the field. Whereas in a composite sample, samples are taken from across the field, mixed together, and then submitted to the test. Since the data used in this study was grid sampled a composite sample was not available. Therefore, a composite sample was estimated from the available grid samples for each field. Using this grid sampled data, the optimal application strategy is found by simulating five years of yield data under a uniform and variable rate lime application to determine which application maximizes net present value. We also do this over a range of target pHs in order to determine the optimal pH that maximizes net revenue over this five year period. Wheat grain and forage yield was estimated by using response curves from a multi-field study by Oklahoma State soil scientists (Lollato 2012).

Soybean yield was estimated from yield response curves from Peters et al. (2006). Recommended lime application rates were found from using lime recommendation tables from Iowa State University, which can be seen in Table 1 (Mallarino et al. 2013).

Theory

This paper uses the following objective function to determine the lime application rate, variable or uniform, that maximizes net present value for wheat grain only production:

$$\max_{\theta} \ \text{NPV} = \sum_{t=0}^{T} \sum_{n=1}^{N} \left(\frac{P_G * G(pH_{tn})}{(1+i)^t} - \theta(r_L LR(tpH, BpH_n) + r_{AVR} LR(tpH, BpH_n) + r_{s1}) - (1-\theta)(r_L LR(\overline{BpH_n}) + r_{AUR} LR(\overline{BpH_n}) + r_{s2}) \right) \quad (1)$$

$$\theta \in \{0,1\}$$

where NPV is the present value of returns net of the cost of lime application and soil sampling, P_G is the price of wheat, $G(pH_{tn})$ is the expected yield of wheat which is a function of the pH at location *n* and year *t*, *i* is the discount rate, r_L is the cost of lime, $LR(tpH, BpH_n)$ is the lime application rate for variable rate lime which is a function of the target pH and the buffer pH at location *n*, r_{AVR} is the lime application cost per ton for variable rate lime, r_{S1} is the cost of grid sampling the field, $LR(\overline{BpH_n})$ is the lime rate when using a composite buffer index of the field, r_{AUR} is the lime application cost per ton for uniform rate lime, and r_{s2} is the cost of a composite soil sample. The choice variable is θ where θ equal to one is variable rate lime application and θ equal to zero is uniform rate lime application. This model assumes that the producer only chooses between variable and uniform application with all other production decisions being the same.

Data and Methods

Producers were asked to send us their grid sampled data from their available fields. In total, producers sent us 278 grid sampled fields from Oklahoma, Kansas, Missouri, and Texas. Due to missing or incomplete data 170 fields were used for this study. For each field, soil samples were taken which provide initial pH and buffer pH for various points within a field. The number of samples per field varies since the fields are from a large amount of producers and grid size varied from 1 to 5 acre grids. For this study the price of grid sampling was fixed at $10 per acre, which is the price charged by a local firm for 2.5 acre grids.

The impact of pH on wheat grain yield and wheat forage yield was determined from multi-field studies by Oklahoma State soil scientists. Data on yield response at a pH greater than 7 was not available. But wheat yields are known to decrease at a high pH so we assumed a decrease in wheat grain at these levels of pH. According to the same study wheat forage does not have this same decrease at a high pH. When pH is below 5 and above 7 there is a significant reduction in wheat yields. A pH range of 4 to 8.2 was used as soil pH is typically between this range. The following equation was determined as wheat grain's yield response to pH:

$$G_{tn} = -2.88 + .917pH_{tn} + .1717pH_{tn}^2 - .0796pH_{tn}^3 + .00992pH_{tn}^4 - .000445pH_{tn}^5 \quad (2)$$

where G_{tn} is the wheat yield in year *t* and point *n*, and pH_{tn} is the pH in year *t*. Figure 1 is a graphical representation of this equation. Wheat forage yield was estimated by the following equation:

$$F_{tn} = -2.88 + .917pH_{tn} + .1717pH_{tn}^2 - .0796pH_{tn}^3 + .00992pH_{tn}^4 - .000445pH_{tn}^5 \quad (3)$$

where F_{tn} is the forage yield in year *t* and within field location *n*, and pH_{tn} is the pH in year *t* and point *n*. A graphical representation of this equation can be seen in Figure 2. Soybean yield was estimated using the following deterministic plateau function:

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$$\mathrm{pH} \leq 7.5 \qquad S_{tn} = \min(-0.2474 + 0.202pH_{tn}, P) \qquad (4)$$
$$\mathrm{pH} > 7.5 \qquad S_{tn} = 1.0252 - 0.202 * (pH_{tn} - 7.5)$$

where S_{tn} is the soybean yield in year *t* and field point *n,* and *P* is the plateau where an increase in pH will not have an effect on yield. This plateau was set a pH of 6.3. A high pH is known to have adverse effects on yields, so soybean yields were decreased at a pH greater than 7.5. Lime recommendation data were from tables provided by Iowa State University (Mallarino et al. 2013). Table 1 includes the lime recommendations that were used in this study. While the recommendations are for Iowa the numbers are similar to the recommended rates in Oklahoma and Kansas. Other lime recommendation tables either rounded their numbers or did not provide sufficient target pH recommendations. For this study we used a range of target pHs from 6.0 to 6.9 in order to determine which target pH is optimal.

In order to determine the lime recommendations for target pH values not in Table 1 we regressed buffer pH and target pH (tpH) on lime rate. This coincides with the variable $LR(tpH, BpH_n)$ from Eq(1) and gives us the equation:

$$LR_n = 3.00049 * tpH - 2.74074 * BpH_n \qquad (5)$$

where LR_n is the lime rate at point *n* in the field, *tpH* is the target pH and BpH_n is the buffer pH at point *n* in the field. But, as Eq (2) showed, yield is a function of pH not buffer pH. This issue is further compounded by the relationship between BpH and pH not being constant across soil types. In other words, for every BpH there is a range of pH values due to different soil characteristics. For example, a sample can have a buffer pH of 6.7 and an initial pH of 5.3. Another sample can have the same buffer pH of 6.7 and an initial pH of 6.3. Given the same lime application these two soils will have different changes in pH. However, data showing the relationship between BpH and pH for all soil types is not available. Therefore, we estimated this relationship using the lime recommendation data in Table 1. To do this we first assumed the Table makes an assumption about the relationship between pH and BpH. In other words, at a BpH of 6.6 and a target pH (tph) of 6.0 no lime applied. Thus, the pH is assumed to be 6.0. Similarly, at a BpH of 6.9 and tpH of 6.5 there is no lime applied so pH is assumed to be 6.5. Using these assumptions, the following equation was used to estimate the relationship between BpH and pH:

$$BpH = \frac{(7.5 + ipH - 0.2*(|7.5 - \mathrm{ipH}|)}{2} \qquad (6)$$

which can be rewritten as:

$$ipH = \frac{2BpH - 7.5}{1.2} + 1.25 \qquad (7)$$

where ipH is the initial pH before lime is applied. Assuming the relationship between BpH and pH is constant, then the change in pH (*cpH*) is equal to the difference between the target pH and the initial pH:

$$cpH = tpH - ipH \qquad (8)$$

The results can be seen in Table 2. In order to estimate how lime rates impact the change in pH, we regress the lime rates from Table 1 on the change in pH from Eq(8) to get the equation:

$$cpH = (0.567 * LR - 0.021 * (LR * BpH)) \qquad (9)$$

where cpH is the change in pH, and LR is the lime rate, and $LR * BpH$ is an interaction term where a given lime rate will have a smaller impact on pH as pH increases. However, as has been discussed, the relationship between initial pH and buffer pH is not constant. In order to account for this we multiply Eq. (9) by the following:

$$\frac{BpH - pH_{\text{actual}}}{BpH - ipH} \quad (10)$$

where pH_{actual} is the pH from the 170 fields and ipH is the pH predicted from Eq. (7) and can be seen in Table 2. This ratio allows for different changes in pH depending on soil type. A sandy soil will have a larger difference between BpH and pH than a clay soil. Thus, a sandy soil will have a larger change in pH than a clay soil when the same amount of lime is applied. Since crop production and applying nitrogen leads to a decrease in pH we had to assume a decrease in pH over the five year time period. It takes 3.6 pounds of lime to offset every pound of nitrogen applied as ammonium nitrate (Mengel 2016a). For example, a 40 bushel wheat crop would require 80 pounds of nitrogen (Zhang et al. 2017b). If these 80 pounds of nitrogen are applied as ammonium nitrate it would take 0.144 tons of lime per year to offset the decrease in pH. Using Eq (9), the lime needed to offset the nitrogen application can be substituted for LR to determine the yearly decrease in pH.

Since the grid sampled data used does not give a composite sample we estimated this composite sample given the buffer pH of the samples for each field. The composite for each field is estimated with the formula:

$$\overline{\mathrm{BpH}}_j = -\log 10 \left(\frac{\sum_{n=1}^{N} 10^{-\mathrm{Bph}_n}}{N}\right) \quad (10)$$

where $\overline{\mathrm{BpH}}_j$ is the composite Buffer pH for field *j*, and Bph_n is the Buffer pH at field point *n*. Due to the logarithmic property of pH, this should give a more accurate estimate compared to a mean. The lime rate needed for a given field was then estimated by substituting this composite Buffer pH into Eq. (4).

The price of lime and the cost of application for both variable and uniform rate were obtained from Farmers Grain Company, located in Pond Creek, Oklahoma. Lime, at 55 percent ECCE (effective calcium carbonate equivalent), was priced at $9/ton with an application cost of $10/ton for variable rate and $7/ton for uniform rate. A transportation cost of $5/ton was used for both the uniform and variable rate lime. Since the per acre cost of composite sampling is quite small it was set to zero. The wheat price used was $3.00/bushel. Sensitivity analysis was done using wheat prices of $4.00 and $5.00 per bushel. A price of $0.096/kg was used for forage, which is based on the beef gain from forage consumption (Tumusiime et al. 2011). The discount rate used was 0.05.

Results

Lime application

In lower target pHs, variable rate applies a higher total amount of lime across all fields than a uniform rate. However, this is mostly due to variable rate applying lime when uniform does not. At a target pH of 6.0, there are 89 fields where variable rate is applied and only 37 fields where both variable and uniform rate are applied. Of these 37 fields where both variable and uniform rate are applied, 20 fields apply more lime with a variable rate. However, at a target pH of 6.9 only 2 fields out of 170 had higher amounts of lime applied for variable rate. The total amount across all the fields was also significantly less for variable rate than a uniform rate at this target pH. The full results are available in Table 3. So, while variable rate is marketed as a cost saver this is not always the case. Cost savings are dependent on the variability of pH within a field and the amount of lime needed to get to the intended pH.

Wheat only production

For wheat grain only production, variable rate had on average a lower net return than a uniform rate for all target pH values. Net revenue was maximized at a target pH of 6.5, which is significantly higher than the university recommendations for wheat. A comparison of net revenues between the two liming rates can be seen in Figure 4. However, while on average variable rate is not profitable, a few fields did have higher net returns. At a target pH of 6.5, 63 fields had higher net returns for variable rate compared to a uniform rate. This is out of 168 fields where a variable rate applied lime. These results can be found in Table 4. A sensitivity analysis using wheat grain prices of $4 and $5 per bushel was also conducted. For $4 wheat grain, variable rate had lower average net returns than a uniform rate from a target pH of 6.0 to 6.4. However, at the optimal target pH of 6.5, variable rate had slightly higher average net returns (Fig. 5). At a wheat grain price of $5, variable rate had slightly higher average net returns for target pHs, except for at 6.9 (Fig. 6). This sensitivity analysis shows that the value of the crop is important to the profitability of grid sampling. The fields where variable rate was profitable had both a low mean pH and a high variability of pH.

Dual-purpose wheat

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In a wheat and forage, or dual-purpose, production system the average net returns for variable rate were lower than a uniform rate across all target pH values. Optimal target pH was again found to be 6.5 (Fig. 7). At the optimal target pH, 37 of the 168 fields that applied variable rate lime had higher average net revenues for variable rate. This was significantly less than in grain only production. This can be attributed to the forage yield function that was used. In the function used, forage yield is not negatively impacted by high pH and overapplication is less of an issue. So, although the value of production is higher in a dual-purpose system than a grain only, the yield function used has a significant impact on the results. Determining the true yield functions is important in evaluating the profitability of variable rate. A sensitivity analysis using wheat grain prices of $4 and $5 per bushel had similar results. However, at these prices the optimal target pH increased to 6.6 for variable rate. But net revenues were still less than a uniform rate. Overall the difference in average net revenue was less than $10 per acre between the two application rates. So, while variable rate increases revenue it is not enough to offset the cost of grid sampling and added application cost for variable rate.

Wheat-Soybean Rotation

Lastly, a wheat-soybean rotation was examined. Variable rate had lower net returns from a target pH of 6.0 to 6.3. At all other target pH values it had a higher average net return (Fig. 8). At the optimal target pH of 6.5, 89 of the 168 fields that applied variable rate lime had higher net revenues. As with the dual-purpose system, the yield function has a large impact on the results. The soybean yield function plateaus at 6.3, so below this pH there are yield losses. While a variable rate applies more lime at these low target pHs the yield gains are not enough to offset the costs. In other words if a field has only a few points in the field that need lime and the amount of lime needed is small, than a variable rate would have less net returns. A different yield function may have an impact on the results.

Conclusion

The objective of this paper was to determine whether variable rate lime is profitable for wheat production. Using grid sampled data from 170 fields sent to us from producers, we compared net revenues of applying a variable rate to a uniform rate over a five-year period and across a range of target pH values. This was done for a wheat grain only system, a dual-purpose system, and a wheat-soybean rotation.

For a wheat grain-only system average net revenues were lower for variable rate application compared to a uniform rate. The difference between the two applications was less than $10/acre. Therefore, while variable rate increased revenue it was not enough to offset the costs of grid sampling and variable rate application. There were still fields where variable rate had higher net revenues. These fields had both a low mean pH as well as a high variability of pH within the field. The optimal target pH was 6.5, which is considerably higher than university recommendations. Increasing wheat price increased the viability of variable rate.

In a dual-purpose system variable rate lime also had lower average net revenues. The difference was again less than $10/acre. While there were some fields where variable rate had higher net revenue it was significantly less than in a grain only system. This is due in part to the yield function of forage. Further research in to the true yield response functions will allow for a more accurate comparison between variable and uniform rate.

The wheat-soybean rotation had lower average net revenues for variable rate at target pHs of 6.3 and below. But had higher average net revenues at all other target pHs. This follows the shape of the soybean yield function as pHs below 6.3 result in large decreases in revenue due to revenue losses. Again, the yield functions have a large effect on the results of the study so further research is needed.

In all three systems the difference between variable and uniform rates was relatively small over a 5-year period. A reduction in the costs associated with grid sampling could increase the profitability of variable rate. There could be also be gains with modifying the way in which lime recommendations are determined. The current method of using BpH and a target pH does not account for differing changes in pH from lime. Since lime is not applied annually it is important to know these changes in order to give a more accurate target pH to producers to maximize revenue between liming applications. Grid sampling could allow for different optimal target pHs within a field given the different changes in pH. As this study has shown, liming in general has a large impact on revenue. So applying the correct amount of lime can have a large effect on producer revenue.

The yield function has a large impact on the results. Further research using a variety of different yield functions may provide a more accurate comparison of variable to uniform rate. Lastly, having a true composite sample for each field instead of estimating it may result in a different lime rate for uniform rate. Since we construct a composite using the buffer pHs found from grid sampling it may differ from a true composite sample. A true composite sample would most likely not contain as many samples within a field and would thus be less likely to be closer to the true mean.

Precision agriculture has become increasingly popular and is often marketed as a cost saver for producers. This is especially true in years of low commodity prices where producers try to cut costs. However, while a variable rate can decrease lime application it does not always apply a lower amount. It has been shown to increase revenue but this does not offset the high cost of grid sampling. This is even more prevalent when the crop price is low. This study did not account for changes in costs from different grid sizes. Depending on the variability within a field, accounting for differences in grid sizes could have different results. Further research to determine optimal grid size is needed to determine the profitability of these precision ag technologies.

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Table 1. Lime Recommendations Based on SMP Buffer Method to Increase pH to a Desired Target pH

Buffer pH	tpH 6.0	tpH 6.5	tpH 6.9
	Amount of Lime to Apply (tons/acre) to reach target pH		
5.7	2.45	4.30	5.90
5.8	2.16	3.94	5.49
5.9	1.86	3.58	5.08
6	1.56	3.21	4.67
6.1	1.27	2.85	4.25
6.2	0.97	2.49	3.84
6.3	0.68	2.13	3.43
6.4	0.38	1.76	3.01
6.5	0.08	1.40	2.60
6.6	0.00	1.04	2.19
6.7	0.00	0.67	1.77
6.8	0.00	0.31	1.36
6.9	0.00	0.00	0.95
7	0.00	0.00	0.54
7.1	0.00	0.00	0.12
7.2	0.00	0.00	0.00

Source: Mallarino (2013)

Table 2. Change in pH Across Buffer pHs and Target pHs

		tpH 6.0	tpH 6.5	tpH 6.9
BpH	ipH	cpH	cph	cph
5.7	4.50	1.50	2.00	2.40
5.8	4.67	1.33	1.83	2.23
5.9	4.83	1.17	1.67	2.07
6	5.00	1.00	1.50	1.90
6.1	5.17	0.83	1.33	1.73
6.2	5.33	0.67	1.17	1.57
6.3	5.50	0.50	1.00	1.40
6.4	5.67	0.33	0.83	1.23
6.5	5.83	0.17	0.67	1.07
6.6	6.00	0.00	0.50	0.90
6.7	6.17	0.00	0.33	0.73
6.8	6.33	0.00	0.17	0.57
6.9	6.50	0.00	0.00	0.40
7	6.67	0.00	0.00	0.23
7.1	6.83	0.00	0.00	0.07
7.2	7.00	0.00	0.00	0.00

Table 3. Comparison of amounts of lime applied by variable and uniform application

			Number of Fields		
tpH	VR[a]	UR*	VR applies lime	Both VR and UR apply lime	VR applies more lime than UR
6.0	1813.56	1567.61	89	37	20
6.1	3199.74	2962.94	122	62	27
6.2	5534.77	5286.00	148	100	39
6.3	8850.63	8592.85	162	130	44
6.4	12664.89	12557.28	164	147	45
6.5	16586.65	17130.23	168	156	21
6.6	20805.04	21957.08	169	163	10
6.7	25207.63	26980.29	169	166	5
6.8	29740.75	32075.96	170	168	3
6.9	34444.18	37275.86	170	170	2

[a] Values in tons applied for all fields

Table 4. Comparison of Variable Rate and Uniform Rate Lime Application for a Grain Only Production

	Number of fields			
		VR has higher net revenue than UR		
tpH	VR applies lime	Wheat price $3/bu	Wheat price $4/bu	Wheat price $5/bu
6.0	89	51	64	75
6.1	122	58	69	78
6.2	148	54	68	77
6.3	162	56	72	80
6.4	164	56	69	81
6.5	168	63	78	87
6.6	169	72	82	93
6.7	169	70	89	97
6.8	170	62	77	88
6.9	170	44	52	60

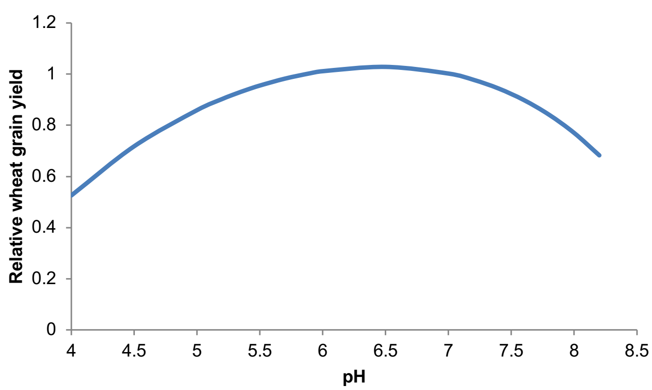

Fig. 1 Relative wheat yield response to pH level

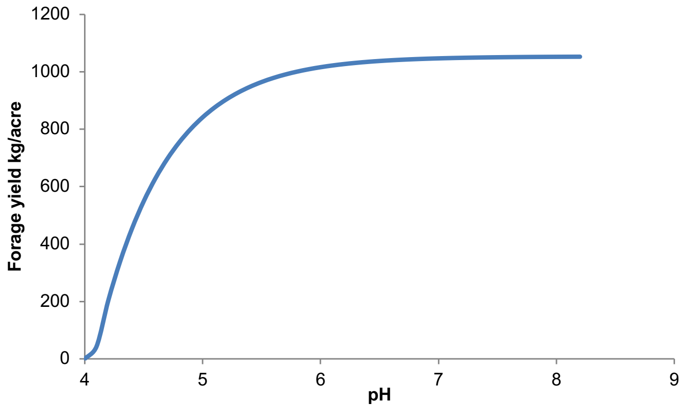

Fig. 2 Forage yield response to pH

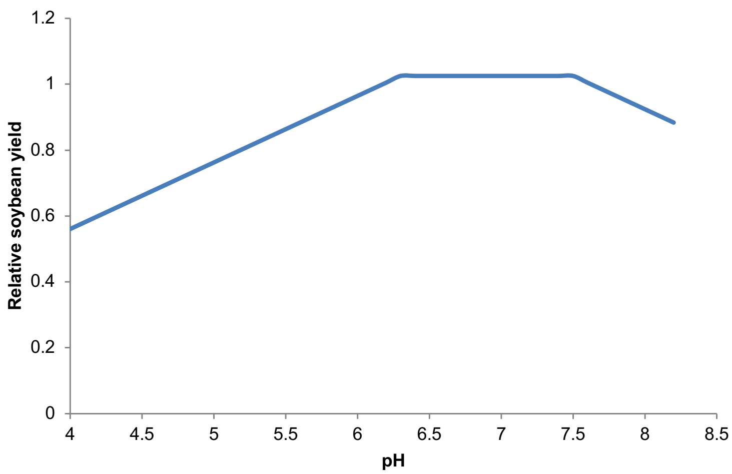

Fig. 3 Relative soybean yield response to pH

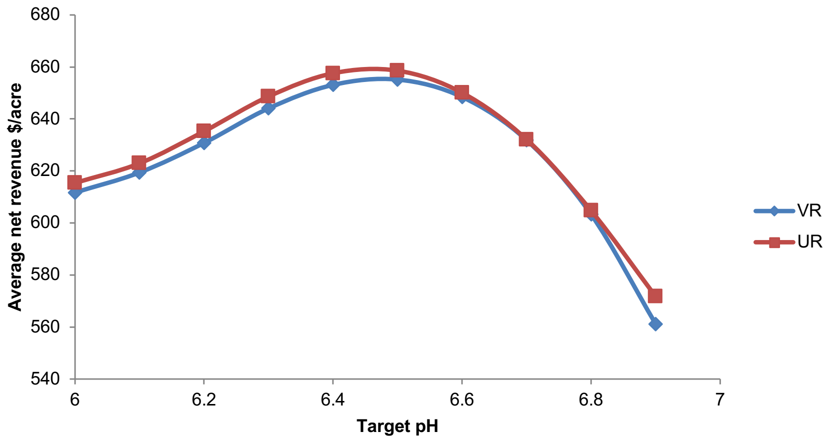

Fig. 4 Average net returns for grain only production for variable and uniform lime rate at grain price $3/bu

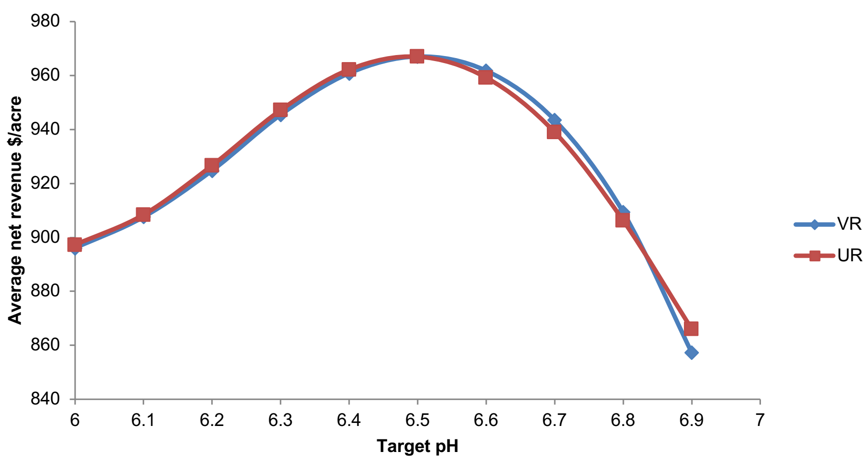

Fig. 5 Average net returns for grain only production for variable and uniform lime rate at grain price $4/bu

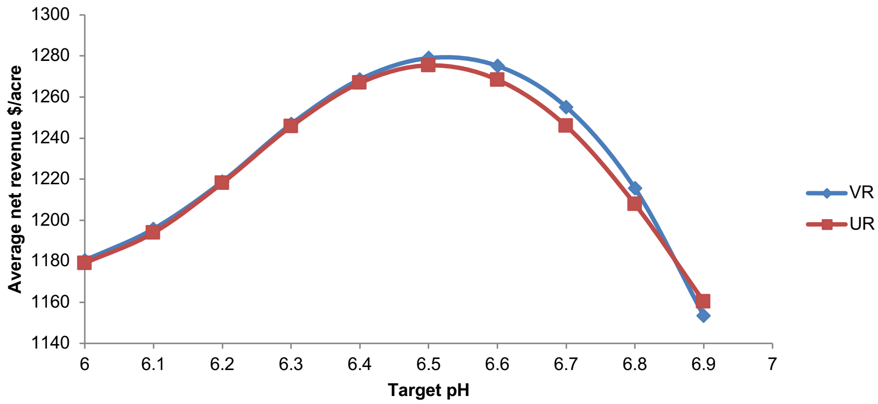

Fig. 6 Average net returns for grain only production for variable and uniform lime rate at grain price $5/bu

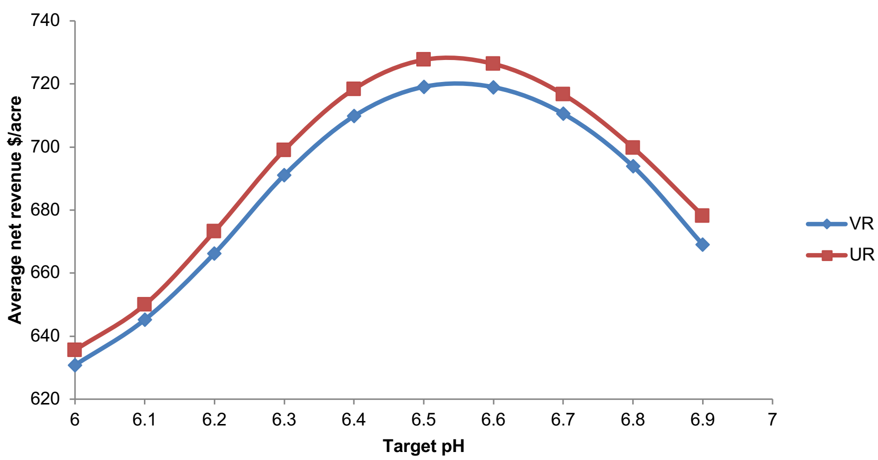

Fig. 7 Average net returns for grain and forage production for variable and uniform rate lime at grain price of $3/bu

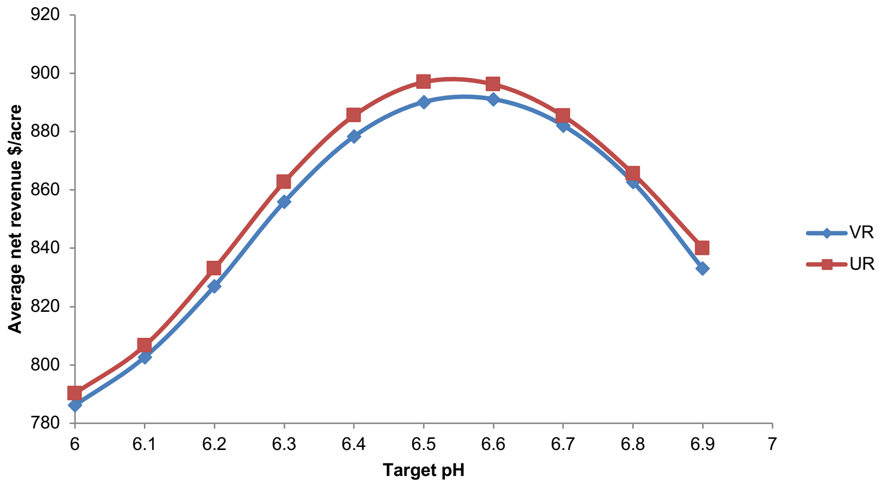

Fig. 8 Average net returns for grain and forage production for variable and uniform rate lime at grain price $4/bu

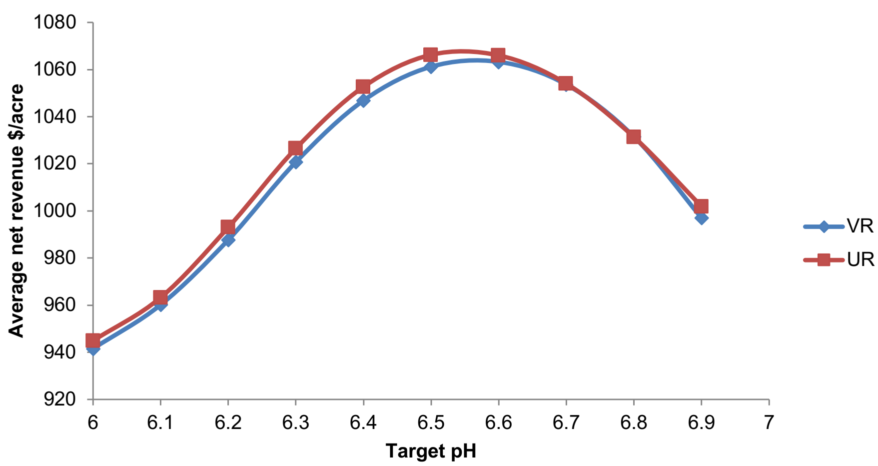

Fig. 9 Average net returns for grain and forage production for variable and uniform rate lime at grain price $5/bu

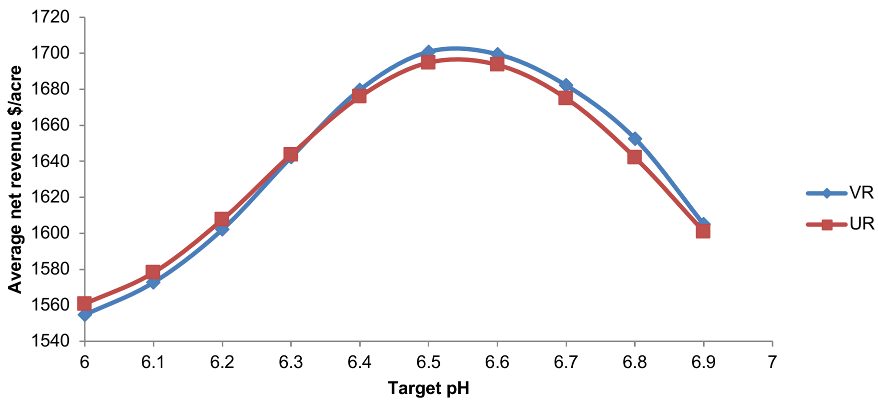

Fig. 10 Average net returns for a wheat-soybean rotation for variable and uniform rate lime