

# FERTILIZER MANAGEMENT

## Economics of Lime and Phosphorus Application for Dual-Purpose Winter Wheat Production in Low-pH Soils

Simeon Kaitibie, Francis M. Epplin,\* Eugene G. Krenzer, Jr., and Hailin Zhang

### ABSTRACT

After decades of continuous cropping, the pH of many soils used to produce continuous winter wheat (*Triticum aestivum* L.) in the southern plains of Oklahoma has declined to levels that limit wheat grain and forage yield. Data from a 3-yr study were used to determine the effect of lime and diammonium phosphate (DAP) application on fall-winter forage yield and grain yield of winter wheat grown in extremely acid soil and to determine the economically optimal strategy for dual-purpose (forage plus grain) wheat production. A split-split plot with sub-subplot treatments arranged in a randomized complete block design was used, with lime in the main plots, variety in the subplots, and DAP in the sub-subplots. Grain yield significantly increased ( $\alpha = 0.05$ ) with lime at 2800 kg ha<sup>-1</sup> effective calcium carbonate equivalent (ECCE), DAP at 73 kg ha<sup>-1</sup> applied in seed furrows, or DAP at 146 kg ha<sup>-1</sup> broadcast. Forage yields were greatest when DAP was applied at 146 kg ha<sup>-1</sup> in seed furrows ( $\alpha = 0.05$ ). When lime costs were fully assessed in the year of application, the strategy of applying 73 kg ha<sup>-1</sup> DAP in seed furrows and zero lime generated the greatest expected returns across all forage value estimates and grain prices. With lime costs amortized over a 5-yr period, the optimal strategy included both the application of lime before the initial season and 73 kg ha<sup>-1</sup> DAP in seed furrows in each season.

HISTORICALLY, acidity was not a problem for soils of the Southern Great Plains of Oklahoma used to produce continuous monoculture winter wheat. However, a 1985 survey of Oklahoma fields cropped continuously to winter wheat found that more than 30% of 17 000 samples had a pH level of less than 5.5 (Johnson et al., 1991). A similar survey in 1996 found that 39% of samples had a pH less than 5.5 (Zhang et al., 1998a). These soil-testing programs were not conducted for the purpose of drawing statistical inferences regarding changes in pH over time or proportion of the state's cropland with various pH levels. However, these data suggest that acidity levels in many wheat fields in the region may be sufficiently high to limit yields and that the number of fields for which acidity is a problem has increased over time.

Grazing winter wheat during its vegetative stage is a common practice in the U.S. Southern Plains. Pinchak et al. (1996) estimate that 30 to 80% of the 8 million ha seeded annually to wheat in the region are grazed. Epplin et al. (1998) reported that in some growing sea-

sons, up to two-thirds of the winter wheat seeded in Oklahoma is intended for dual-purpose (fall-winter forage and grain) production. Wheat may be seeded in the late summer and grazed throughout the fall and winter. If livestock are removed in late winter, before the development of the first hollow stem (Redmon et al., 1996), the wheat will mature and produce a grain crop.

Mahler and McDole (1987) evaluated wheat grain yield response to pH in artificially acidified soil in northern Idaho. They determined that pH levels below 5.19 to 5.37 restricted grain yield. Westerman (1987) came to similar conclusions from work conducted in Oklahoma. Both used agricultural limestone to treat acid soils.

In extremely acid soils, metals including Al and Mn are relatively more available. The major cause of crop failure in extremely acid Oklahoma soils is Al toxicity (Boman et al., 1992). Under these conditions, P reacts with the Al, and both become insoluble. One recommended strategy for managing low-pH soils for continuous wheat production is to band a P fertilizer with the seed. Metal toxicity in the vicinity of the plant roots is reduced, and P applied in the band is more readily available to the crop (Johnson et al., 1991).

No prior research has simultaneously evaluated the alternative management strategies of lime application and P banding for dual-purpose wheat production on extremely acid soils. This research is unique in combining lime and P treatments in a coordinated design for dual-purpose winter wheat production. The objective of this research was to determine the effect of lime and diammonium phosphate (DAP) application on both fall-winter forage yield and grain yield of winter wheat grown in extremely acid soil and to determine the economically optimum strategy for dual-purpose (forage plus grain) wheat production. Economic analysis is conducted to determine the best strategy for producers who must recover the cost of lime in the year of application as well as for those who have the advantage of amortizing the cost of lime over a period of 5 yr.

### MATERIALS AND METHODS

This study was conducted over a 3-yr period, from the 1997-1998 winter wheat production season to the 1999-2000 season, on a site near Eakly, OK, on a Carey silt loam soil (fine-silty, mixed, superactive, thermic Typic Agriustolls). The initial soil pH level was 4.6. For soils used to produce continuous winter wheat with a pH level of 4.6, the Oklahoma State

S. Kaitibie and F.M. Epplin, Dep. of Agric. Econ., and E.G. Krenzer, Jr., and H. Zhang, Dep. of Plant and Soil Sci., Oklahoma State Univ., Stillwater, OK 74078. Received 28 June 2001. \*Corresponding author (epplin@okstate.edu).

**Abbreviations:** DAP, diammonium phosphate (18-46-0); ECCE, effective calcium carbonate equivalent.

University Soil, Water, and Forage Analytical Laboratory would recommend a lime application of 2800 kg ha<sup>-1</sup> for the purpose of raising the pH to 5.5 (Zhang et al., 1998b). Based on the results of prior research, a pH of 5.5 is considered to be sufficient for continuous wheat (Mahler and McDole, 1987; Westerman, 1987). The initial soil test P index on the study site was measured at 96 (Mehlich 3 extraction method). This initial level of P was relatively high, such that the Oklahoma State University Soil, Water, and Forage Analytical Laboratory would report a 100% sufficiency level for small-grains production (Zhang et al., 1998b).

The trials were conducted in a split-split plot with sub-subplot treatments arranged in a randomized complete block design with three replications. Lime was applied in the main plots at 0 and 2800 kg ha<sup>-1</sup> [effective calcium carbonate equivalent (ECCE)] in July of 1997. Lime was broadcast and immediately incorporated with a rototiller. Both limed and unlimed plots were tilled. Limed blocks were 13 by 21 m with a 6-m buffer between limed and unlimed blocks. Winter wheat varieties, 'Tonkawa' and '2137', constituted the subplot factors. Diammonium phosphate (18-46-0) was applied in the sub-subplots. There were four DAP treatments: zero, 73 kg ha<sup>-1</sup> applied in seed furrows, 146 applied in seed furrows, and 146 broadcast. Diammonium phosphate is the most common and least expensive source of P available for use by farmers in the region. Each sub-subplot contained six 15-cm rows by 6.4 m. The two levels of lime and four levels of DAP resulted in eight different combinations of soil management strategies for each of two varieties. Additional N was applied annually preplant at a rate of 134 kg ha<sup>-1</sup> across all experimental units.

Measurements of fall–winter forage yields were obtained by two hand clippings removing all aboveground dry matter. Two 1-m row areas were clipped from each plot, samples dried, and forage yield computed and reported as kilograms per hectare oven-dry forage. The first clipping was conducted in the late fall. The second clipping was conducted on the same 1-m row segments of the plot prior to first hollow stem in late winter after emergence from dormancy. Hence, the estimate of dry matter forage yield was based on the sum of the two clippings. Cattle removed forage from the unharvested portion of the plot within 3 d after hand clipping. The plants were permitted to mature and produce grain. Grain yield was obtained with a small-plot combine harvesting the center 5.3 m of all six rows.

Aluminum toxicity generally affects root development. One method of assessing wheat tolerance to low-pH soils is to measure root development of plants grown in different concentrations of Al (Bolt, 1996). By this measure, the two varieties used in the experiment showed different degrees of tolerance to low soil pH. On a scale of 1 to 4, variety 2137 was classified as 1 (highly tolerant) while Tonkawa was classified as 4 (highly susceptible).

### Statistical Analysis

The SAS MIXED procedure was used to estimate a linear mixed model by the method of maximum likelihood. The method is appropriate because cross-sectional time series data are prone to the twin problems of autocorrelation and unequal variance across seasons. The estimator is asymptotically efficient, consistent, and asymptotically normal under assumptions of normality. Littell et al. (1996) presented a basic linear mixed model that is based on a split-plot experimental design. The split-split plot is a special case of the split plot in which the subplots are further divided into sub-subplots.

The factors lime, DAP, and variety were classified as fixed effects, together with all possible combinations of the three.

The replication × year interaction was characterized as a random effect. Additional analyses were performed to compare the responses of the two wheat varieties to lime and DAP. Means of significant treatment factors were separated using Tukey's test at  $\alpha = 0.05$ .

### Economic Analysis

Expected returns above variable costs were determined for each of the eight strategies for both varieties. Based on the economic assumption that the farmer maximizes expected returns above variable costs, optimal input levels that maximize these returns are calculated. The economic problem can be described as a multiproduct nonallocable factor production process. The multiple products are wheat grain and wheat forage. The factors, lime and DAP, are said to be nonallocable because for the study, the quantity of a factor used to produce grain cannot be distinguished from the quantity used to produce forage. Beattie and Taylor (1985) discuss the economic theory of a multiproduct nonallocable factor production process. The returns above variable costs for each strategy were determined according to the following equation:

$$\pi(l,d,v) = p_g Y_g(l,d,v) + p_f Y_f(l,d,v) - c_l l - c_d d - c_a A(l,d) - c_h h(Y_g) \quad [1]$$

where

$\pi$  = the farmer's net returns per hectare, as determined by the variable factors of production—lime ( $l$ ), DAP ( $d$ ), and variety ( $v$ )

$p_g$  = price of grain

$Y_g$  = wheat grain yield

$p_f$  = price of forage

$Y_f$  = wheat forage yield

$c_l$  = the per-unit price of lime

$c_d$  = the per-unit price of DAP

$c_a$  = the per-unit cost of application for both lime and DAP

$A$  = total amount of input applied

$c_h$  = the per-unit cost of harvest

$h$  = quantity of grain harvested

No differences in input costs or output prices were assumed across the two varieties. The total cost function may be separated into fixed and variable costs. If the fixed costs are assumed to be constant, the variable costs can be incorporated into the profit function, to give a net returns function, with robust outcomes. These conditional variable costs allow for the accounting of harvest costs and input application costs that are discontinuous.

Oklahoma City market June wheat prices for the years 1998, 1999, and 2000 were \$0.10, \$0.08, and \$0.09 kg<sup>-1</sup>, respectively (Oklahoma Agric. Stat. Serv., 2000). In the later two seasons, Oklahoma producers were eligible to receive a loan deficiency payment such that the net prices (market plus government subsidy) for the years 1998, 1999, and 2000 were \$0.10, \$0.095, and \$0.095 kg<sup>-1</sup>, respectively. These prices were used in the analyses.

Prices for standing fall–winter wheat forage are not routinely reported. However, some wheat producers lease their pasture to livestock owners, and in informal surveys over the time period of the field trials, farmers reported a range on lease rates of \$0.55 to \$0.88 kg<sup>-1</sup> beef gain for winter wheat pasture (Doye et al., 2001). In these lease arrangements, payments from livestock owners to wheat producers are based on net live weight gain attributable to the wheat pasture. These lease arrangements are made based on price expectations and

are typically not changed if the price of cattle increases or decreases beyond the expected levels.

The quantity of winter wheat forage required per kilogram of beef gain has not been precisely determined. Based on the National Research Council net energy equations used to estimate livestock requirements and based on nutrient analysis of wheat forage, an average of 7 kg of forage would be required per kilogram of gain for a 200-kg steer gaining 0.9 kg d<sup>-1</sup> for 115 d. Seven kilograms would be the minimum possible allowance, assuming 100% harvest efficiency and no allowance for nonconsumptive loss (Krenzer et al., 1996). Allowing for nonconsumptive loss, it is assumed that 1 kg of beef gain is expected to require 10 kg (dry matter) of standing wheat forage. By this measure, over the time period of the study, the value of standing fall-winter forage was approximately \$0.055 (\$0.55/10) to \$0.088 (\$0.88/10) kg<sup>-1</sup> dry matter. Additional field research would be required to refine the estimate. For the present study, given the lack of precision relative to forage prices, the economic analysis was conducted for three sets of forage prices—\$0.035, \$0.07, and \$0.105 kg<sup>-1</sup> dry matter.

Lime costs, including delivery and application, were estimated at \$0.02 kg<sup>-1</sup> ECCE. The cost of DAP was determined to be \$0.29 kg<sup>-1</sup>. It was assumed that there were no differences in application costs between applying 73 and 146 kg ha<sup>-1</sup> in bands because the drill with its fertilizer attachment would cover the same time and distance per unit area. However, seed furrow application at \$9.88 ha<sup>-1</sup> is more costly than broadcasting at \$6.18 ha<sup>-1</sup> (Hobbs, personal communication, 2001). The seed furrow application costs include the variable and fixed costs of the fertilizer attachment on a grain drill and the additional cost of handling the fertilizer in the field. Custom grain harvest values were based on \$32.00 ha<sup>-1</sup> and \$0.01 kg<sup>-1</sup> for each additional kilogram above 1344 kg ha<sup>-1</sup>.

Expected utility maximization was used to select a complete and unique strategy among all optimal strategies. There are methodological and practical difficulties inherent in directly deriving a decision-maker's utility function, hence the need to assume one. The negative exponential utility function allows us to model both the risk-neutral decision-maker and the risk-averse decision-maker.

The negative exponential utility function indicates a conservative entrepreneur (Freund, 1956) and exhibits constant absolute risk aversion. Following Freund, if net revenue is assumed to be normally distributed, the decision-maker maximizes expected utility [E(u)]

$$\text{Max } E(u) = \int_{-\infty}^{\infty} (1 - e^{-\gamma r}) e^{-(r - \mu)^2/2\sigma^2} dr \quad [2]$$

where  $\gamma$  is the Arrow-Pratt coefficient of absolute risk aversion,  $r$  is the net revenue,  $\mu$  is expected income, and  $\sigma^2$  is the variance of income. This can be achieved in a programming model by

$$\text{Max } Z = \mu - \frac{\gamma}{2} \sigma^2 \quad [3]$$

where  $Z$  represents the utility, or the value to maximize, at a given level of risk aversion  $\gamma$ . If  $\gamma$  is equal to zero, the risk-neutral decision-maker maximizes the net revenue. A decision-maker whose utility is best described by a negative exponential utility function would

$$\text{Max } Z = \sum_j c_j X_j - \frac{\gamma}{2} \sum_k X_k \sum_j X_j \sigma_{jk}^2 \quad [4]$$

subject to the following restrictions:

$$\sum_j a_{ij} X_j \leq b_i \quad [5]$$

$$X_j = X_k \geq 0 \quad [6]$$

$c_j$  represents the expected (or mean annual) returns to activity  $j$ , which would be the strategies;  $X$  is a choice variable such as units or acres allocated to strategy  $j$ ;  $a$  represents the input-output coefficients; and  $b$  is the quantity of the resource. King and Oamek (1983) defined a risk-averse dryland wheat farmer based on whole-farm data as one with an Arrow-Pratt absolute risk aversion coefficient that ranges from 0.00005 to 0.0001. This analysis was carried out for a risk-neutral farmer ( $\gamma = 0$ ) and a risk-averse farmer ( $\gamma = 0.00005$ ).

With land being the only limiting resource,  $a_{ij} = 1$  for each strategy to reflect the fact that all returns were estimated on a 1-ha basis. The average wheat farm size for Oklahoma was estimated at 181 ha (USDA, 1997).

For simplicity, it is assumed that a farmer would use a single strategy. Hence, the objective is to identify the single strategy (combination of variety, DAP quantity and application method, and lime quantity) from among the 16 discrete possibilities evaluated that maximizes the decision-maker's utility, rather than a combination of strategies. Wheat grain prices, grain yields, and forage yields across the three seasons were used to compute the variance-covariance matrix of returns ( $\sigma_{jk}^2$ ) estimate necessary for Eq. [4].

## RESULTS AND DISCUSSION

### Agronomic

Table 1 shows that lime and two of the three DAP treatments significantly increased grain yields and that grain yield was significantly greater for variety 2137 than for Tonkawa. The application and incorporation of lime at 2800 kg ha<sup>-1</sup> ECCE before the initial season increased average grain yield over the three seasons by approximately 10% greater than the no-lime case. It also shows that DAP at 73 kg ha<sup>-1</sup> applied in seed furrows gave highest grain yield even though this was not significantly different from 146 kg ha<sup>-1</sup> broadcast. Average grain yield was significantly greater with the 73 kg ha<sup>-1</sup> DAP seed furrow treatment relative to the 146 kg ha<sup>-1</sup> seed furrow treatment. The reason for the decline in grain yield with the doubling of seed furrow DAP is not known. The yield increase over the control is approximately 16 to 20%. Variety 2137 had a 22% greater yield than Tonkawa.

**Table 1. The effect of lime and diammonium phosphate (DAP) on wheat grain yields for two varieties in western Oklahoma.**

| Treatments          |         |         | Grain yield†        |                   |                   |
|---------------------|---------|---------|---------------------|-------------------|-------------------|
| Lime                | DAP     | Variety | Lime                | DAP               | Variety           |
| kg ha <sup>-1</sup> |         |         | kg ha <sup>-1</sup> |                   |                   |
| 0                   |         |         | 2964 <sup>b‡</sup>  |                   |                   |
| 2800                |         |         | 3249 <sup>a</sup>   |                   |                   |
|                     | 0       |         |                     | 2825 <sup>b</sup> |                   |
|                     | 146 SF§ |         |                     | 2958 <sup>b</sup> |                   |
|                     | 146 B   |         |                     | 3264 <sup>a</sup> |                   |
|                     | 73 SF   |         |                     | 3377 <sup>a</sup> |                   |
|                     |         | Tonkawa |                     |                   | 2796 <sup>b</sup> |
|                     |         | 2137    |                     |                   | 3416 <sup>a</sup> |

† The significant factors are lime, DAP, and variety.

‡ Identical letters in the same column indicate no significant difference at  $p = 0.05$ .

§ SF, applied in seed furrows.

|| B, broadcast applied.

**Table 2. The effect of lime and diammonium phosphate (DAP) on wheat fall–winter forage yields for two varieties in western Oklahoma.**

| Treatments          |        |                    |
|---------------------|--------|--------------------|
| Lime                | DAP†   | Forage yield       |
| kg ha <sup>-1</sup> |        |                    |
| 0                   | 0      | 1234 <sup>d‡</sup> |
| 0                   | 146 SF | 2506 <sup>a</sup>  |
| 0                   | 146 B  | 1761 <sup>c</sup>  |
| 0                   | 73 SF  | 1804 <sup>c</sup>  |
| 2800                | 0      | 1864 <sup>c</sup>  |
| 2800                | 146 SF | 2453 <sup>a</sup>  |
| 2800                | 146 B  | 2166 <sup>b</sup>  |
| 2800                | 73 SF  | 2155 <sup>b</sup>  |

† SF, applied in seed furrows; B, broadcast applied.  
 ‡ Identical letters in the same column indicate no significant difference at  $p = 0.05$ . Forage yields are reported on a dry matter basis.

Average forage yields more than doubled in the unlimed plots when DAP was applied at 146 kg ha<sup>-1</sup> in seed furrows (Table 2). The application of lime generally increased forage yields in the presence of DAP but not when DAP was applied at 146 kg ha<sup>-1</sup> in seed furrows, the level at which average forage yields were highest. The effects of lime and DAP on the two varieties were further investigated. As illustrated in Table 3, the susceptible Tonkawa wheat variety showed a marked increase in forage yield with the application of 2800 kg ha<sup>-1</sup> lime. This did not happen in the case of the tolerant variety, 2137.

Further analyses were performed to determine the effects of lime and DAP on yield of each variety. The results are reported in Tables 4 and 5. Grain yields for both varieties increased when 73 kg ha<sup>-1</sup> DAP was applied in seed furrows when lime had been applied (Table 4). The increase was significant on the limed plots. For Tonkawa, this was not significantly different from the yield obtained from broadcasting 146 kg ha<sup>-1</sup> DAP in the presence of 2800 kg ha<sup>-1</sup> lime. The results for variety 2137 show that the yields obtained from applying 73 kg ha<sup>-1</sup> DAP in seed furrows are statistically indistinguishable from those obtained from broadcast application of 146 kg ha<sup>-1</sup>.

Table 4 shows that both varieties have similar relative responses to lime and DAP. Average forage yields were greatest when DAP was applied at 146 kg ha<sup>-1</sup> in seed furrows. This yield, in the case of Tonkawa, was not significantly different from yields obtained by applying 73 kg ha<sup>-1</sup> DAP in seed furrows, or broadcast-applying 146 kg ha<sup>-1</sup>, in the presence of lime. On the other hand, 2137 obtained greatest average forage yields when DAP was applied at 146 kg ha<sup>-1</sup>. The grain yield for both

**Table 3. Treatment means for wheat fall–winter forage yields for each lime–variety combination.**

| Treatments          |         |                    |
|---------------------|---------|--------------------|
| Lime                | Variety | Forage yield       |
| kg ha <sup>-1</sup> |         |                    |
| 0                   | Tonkawa | 1730 <sup>†</sup>  |
| 0                   | 2137    | 1922 <sup>bc</sup> |
| 2800                | Tonkawa | 2343 <sup>a</sup>  |
| 2800                | 2137    | 1976 <sup>b</sup>  |

† Identical letters in the same column indicate no significant difference at  $p = 0.05$ . Forage yields are reported on a dry matter basis.

**Table 4. Treatment means for fall–winter forage and grain yields by variety.**

| Lime                | DAP†   | Tonkawa‡           |                     | 2137§              |                     |
|---------------------|--------|--------------------|---------------------|--------------------|---------------------|
|                     |        | Forage             | Grain               | Forage             | Grain               |
| kg ha <sup>-1</sup> |        |                    |                     |                    |                     |
| 0                   | 0      | 1091 <sup>d¶</sup> | 2416 <sup>c</sup>   | 1455 <sup>d</sup>  | 3052 <sup>c</sup>   |
| 0                   | 146 SF | 2634 <sup>a</sup>  | 2583 <sup>c</sup>   | 2409 <sup>a</sup>  | 3132 <sup>c</sup>   |
| 0                   | 146 B  | 1642 <sup>c</sup>  | 2687 <sup>bc</sup>  | 1882 <sup>c</sup>  | 3431 <sup>abc</sup> |
| 0                   | 73 SF  | 1602 <sup>c</sup>  | 2750 <sup>abc</sup> | 2008 <sup>bc</sup> | 3604 <sup>abc</sup> |
| 2800                | 0      | 1957 <sup>bc</sup> | 2635 <sup>c</sup>   | 1778 <sup>c</sup>  | 3174 <sup>c</sup>   |
| 2800                | 146 SF | 2725 <sup>a</sup>  | 2746 <sup>bc</sup>  | 2188 <sup>ab</sup> | 3320 <sup>bc</sup>  |
| 2800                | 146 B  | 2337 <sup>ab</sup> | 3149 <sup>ab</sup>  | 1995 <sup>bc</sup> | 3780 <sup>ab</sup>  |
| 2800                | 73 SF  | 2370 <sup>ab</sup> | 3256 <sup>a</sup>   | 1941 <sup>bc</sup> | 3885 <sup>a</sup>   |

† SF, applied in seed furrows; B, broadcast applied.  
 ‡ Tonkawa is classified as being susceptible to low-pH soils.  
 § 2137 is classified as a variety that is tolerant of low-pH soils.  
 ¶ Identical letters in the same column indicate no significant difference at  $p = 0.05$ . Forage yields are reported on a dry matter basis.

varieties was significantly greater on limed plots with the 73 kg ha<sup>-1</sup> DAP seed furrow treatment relative to the 146 kg ha<sup>-1</sup> seed furrow treatment. As noted, the reason for the decline in grain yield with the 146 kg ha<sup>-1</sup> seed furrow DAP treatment is not known. Additional research will be required to more precisely determine grain yield response to seed furrow applications of DAP in a dual-purpose environment. Table 5 confirms that DAP increased the forage yield for both Tonkawa and 2137 in both limed and unlimed plots.

**Economic**

Total revenue for the dual-purpose wheat enterprise is obtained from both grain yield and forage yield. The variable factors that account for cost differences are lime and DAP and their application costs. The standard combine harvest costs that are a function of grain yield are also included.

The net returns above variable costs were calculated by subtracting the costs (and application costs) of lime and DAP and the harvest costs from the total revenue. Table 6 shows a base budget for estimating returns above variable costs in a dual-purpose wheat production enterprise. The mean net returns, averaged over 3 yr, were then separated using Tukey’s test at  $\alpha = 0.10$ . This procedure was repeated under conditions where lime costs are amortized over a 5-yr period. The results are

**Table 5. Simple effects of lime and diammonium phosphate (DAP) on lime × DAP interactions for fall–winter forage and grain yields.**

| Factor†             | Lime   | DAP | Tonkawa |       | 2137   |       |
|---------------------|--------|-----|---------|-------|--------|-------|
|                     |        |     | Forage  | Grain | Forage | Grain |
| kg ha <sup>-1</sup> |        |     |         |       |        |       |
| DAP                 | 0      |     | *       | NS    | *      | NS    |
| DAP                 | 2800   |     | *       | *     | *      | *     |
| Lime                | 0      |     | *       | NS    | *      | NS    |
| Lime                | 146 SF |     | NS      | NS    | NS     | NS    |
| Lime                | 146 B  |     | *       | NS    | NS     | NS    |
| Lime                | 73 SF  |     | *       | NS    | NS     | NS    |

\* Significant at  $p = 0.05$ .  
 † Simple effects analyzed using SAS MIXED procedure with SLICE option of the LSMEANS statement. For example, Lime 0 shows the effect of DAP when no lime was applied. Lime 2800 shows the effect of DAP when 2800 kg ha<sup>-1</sup> [effective calcium carbonate equivalent (ECCE)] lime was applied.

**Table 6. Base budget for dual-purpose wheat production.**

| Item                              | Unit                | Price | Quantity | Value |
|-----------------------------------|---------------------|-------|----------|-------|
| <b>Gross receipts</b>             |                     |       |          |       |
| Grain                             | kg                  | -†    | -        | -     |
| Forage                            | kg                  | -     | -        | -     |
| Total revenue                     | \$ ha <sup>-1</sup> |       |          | -     |
| <b>Variable costs‡</b>            |                     |       |          |       |
| DAP (18-46-0)                     | kg                  | 0.29  | -        | -     |
| DAP broadcast cost                | ha                  | 6.18  | 1        | 6.18  |
| DAP seed furrow applic. cost      | ha                  | 9.88  | 1        | 9.88  |
| Lime + application cost           | kg                  | 0.02  | 2800     | 56.00 |
| Custom harvest                    | ha                  | 32.00 | 1        | 32.00 |
| Custom harvest                    | kg                  | 0.01  | -        | -     |
| Total variable cost (broadcast)   | \$ ha <sup>-1</sup> |       |          | -     |
| Total variable cost (seed furrow) | \$ ha <sup>-1</sup> |       |          | -     |
| Returns above variable costs      | \$ ha <sup>-1</sup> |       |          | -\$   |

† Grain prices of \$0.10, \$0.095, and \$0.095 kg<sup>-1</sup> were used for 1998, 1999 and 2000, respectively. Forage prices of \$0.035, \$0.07, and \$0.105 kg<sup>-1</sup> dry matter were used.

‡ Costs for inputs that did not change across treatments, such as cost of seed and tillage operations, are not included.

§ Returns above variable costs were averaged over 3 yr.

shown in Tables 7 and 8 for each of the three forage price estimates.

If the entire cost of lime application had to be recovered in the year of application, no lime would be applied. In this case, highest net returns per hectare are obtained by applying 73 kg ha<sup>-1</sup> DAP to variety 2137 and no lime for each of the three alternative forage price estimates. The returns are not statistically different from four other strategies when forage price is \$0.035 kg<sup>-1</sup>, from three other strategies when forage price is \$0.07 kg<sup>-1</sup>, and from six other strategies when the forage price is \$0.105 kg<sup>-1</sup>, as shown in Table 7. Amongst those strategies is the case where 2800 kg ha<sup>-1</sup> lime is applied in the first season followed by annual applications of 73 kg ha<sup>-1</sup> DAP in the seed furrow with variety 2137. The latter strategy generates the greatest net returns when lime costs are amortized over a 5-yr period (Table 8). Again, there are multiple strategies that are not statistically different. The finding of the lack of a uniquely preferred strategy is consistent with the observation that farmers in the region do not use a consistent strategy.

Because multiple strategies were statistically indistin-

guishable, the expected utility maximization procedure was used to select a unique strategy, the one that maximized the decision-maker's expected utility, under assumptions of risk aversion and risk neutrality. The results are displayed in Tables 9 and 10.

Table 9 shows that when lime costs are fully assessed in the year of application, the risk-neutral farmer maximizes expected returns by applying no lime, applying 73 kg ha<sup>-1</sup> DAP in the seed furrow each season, and planting 2137 rather than Tonkawa. When lime costs are amortized over a 5-yr period (Table 10), the same individual applies 2800 kg ha<sup>-1</sup> lime before planting in the initial season. In addition, 73 kg ha<sup>-1</sup> DAP should be applied in each year in the seed furrows. The variety 2137 clearly dominates the variety Tonkawa. For forage prices of \$0.035 and \$0.07 kg<sup>-1</sup>, the strategies are the same for the risk-averse farmer. For the high forage price (\$0.105 kg<sup>-1</sup>), the optimal strategy when lime costs are amortized over 5 yr is to apply no lime but apply 73 kg ha<sup>-1</sup> DAP each year in the seed furrows and plant variety 2137. As shown in Table 3, application of lime did not significantly increase forage yield for variety 2137.

### CONCLUSIONS

Grain yield significantly increased ( $\alpha = 0.05$ ) with lime at 2800 kg ha<sup>-1</sup> ECCE, DAP at 73 kg ha<sup>-1</sup> applied in seed furrows, or DAP at 146 kg ha<sup>-1</sup> broadcast. Forage yields were greatest when DAP was applied at 146 kg ha<sup>-1</sup> in seed furrows ( $\alpha = 0.05$ ). There exists a trade-off between grain yield and forage yield when DAP is increased from 73 to 146 kg ha<sup>-1</sup> applied in seed furrows. Forage yield is significantly increased while grain yield is significantly decreased.

The 2137 variety produced significantly greater wheat grain yield than the Tonkawa variety. Lime application significantly increased forage yield for Tonkawa but not for 2137. In the limed plots, Tonkawa forage yields were significantly greater in treatments that received 73 kg ha<sup>-1</sup> DAP in seed furrows or 146 kg ha<sup>-1</sup> broadcast

**Table 7. Expected average returns to management strategies when lime costs are fully assessed in the year of application.**

| Factor levels       |         |                     | Expected returns‡                       |   |   |
|---------------------|---------|---------------------|---|---|---|
| Lime                | DAP†    | Wheat variety       | Forage price = \$0.035 kg <sup>-1</sup> | Forage price = \$0.070 kg <sup>-1</sup> | Forage price = \$0.105 kg <sup>-1</sup> |
| kg ha <sup>-1</sup> |         |                     | \$ ha <sup>-1</sup> yr <sup>-1</sup>    |   |   |
| 0                   | 0       | Tonkawa             | 238 <sup>efg</sup>                      | 285 <sup>e</sup>                        | 330 <sup>e</sup>                        |
|                     |         | 2137                | 295 <sup>abc</sup>                      | 345 <sup>bcd</sup>                      | 395 <sup>bcd</sup>                      |
|                     | 146 SF  | Tonkawa             | 252 <sup>cdef</sup>                     | 343 <sup>bcd</sup>                      | 434 <sup>ab</sup>                       |
|                     |         | 2137                | 287 <sup>abcd</sup>                     | 370 <sup>ab</sup>                       | 453 <sup>a</sup>                        |
|                     | 146 B   | Tonkawa             | 224 <sup>fg</sup>                       | 285 <sup>e</sup>                        | 346 <sup>de</sup>                       |
|                     |         | 2137                | 292 <sup>abc</sup>                      | 359 <sup>abc</sup>                      | 426 <sup>ab</sup>                       |
| 73 SF               | Tonkawa | 246 <sup>defg</sup> | 304 <sup>de</sup>                       | 363 <sup>de</sup>                       |   |
|                     | 2137    | 328 <sup>a</sup>    | 398 <sup>a</sup>                        | 468 <sup>a</sup>                        |   |
| 2800                | 0       | Tonkawa             | 228 <sup>fg</sup>                       | 296 <sup>e</sup>                        | 365 <sup>cde</sup>                      |
|                     |         | 2137                | 261 <sup>bcddef</sup>                   | 324 <sup>cde</sup>                      | 387 <sup>bcd</sup>                      |
|                     | 146 SF  | Tonkawa             | 207 <sup>g</sup>                        | 298 <sup>de</sup>                       | 389 <sup>bcd</sup>                      |
|                     |         | 2137                | 241 <sup>efg</sup>                      | 314 <sup>de</sup>                       | 387 <sup>bcd</sup>                      |
|                     | 147 B   | Tonkawa             | 231 <sup>fg</sup>                       | 313 <sup>de</sup>                       | 395 <sup>bcd</sup>                      |
|                     |         | 2137                | 274 <sup>bcdde</sup>                    | 343 <sup>bcd</sup>                      | 413 <sup>abc</sup>                      |
|                     | 73 SF   | Tonkawa             | 259 <sup>bcddef</sup>                   | 342 <sup>bcd</sup>                      | 425 <sup>ab</sup>                       |
|                     |         | 2137                | 299 <sup>ab</sup>                       | 367 <sup>abc</sup>                      | 435 <sup>ab</sup>                       |

† SF, applied in seed furrows; B, broadcast applied.

‡ Means separated using SAS least squares means; means with the same letter are not significantly different at  $\alpha = 0.10$ .

**Table 8. Expected average returns to management strategies when lime costs are amortized over a 5-yr period.**

| Lime                | Factor levels |                    | Expected returns‡                       |   |   |
|---------------------|---------------|--------------------|---|---|---|
|                     | DAP†          | Wheat variety      | Forage price = \$0.035 kg <sup>-1</sup> | Forage price = \$0.070 kg <sup>-1</sup> | Forage price = \$0.105 kg <sup>-1</sup> |
| kg ha <sup>-1</sup> |               |                    | \$ ha <sup>-1</sup> yr <sup>-1</sup>    |   |   |
| 0                   | 0             | Tonkawa            | 238 <sup>gh</sup>                       | 285 <sup>g</sup>                        | 330 <sup>f</sup>                        |
|                     |               | 2137               | 295 <sup>bcd</sup>                      | 345 <sup>cdef</sup>                     | 395 <sup>cde</sup>                      |
|                     | 146 SF        | Tonkawa            | 252 <sup>efgh</sup>                     | 343 <sup>cdef</sup>                     | 434 <sup>abc</sup>                      |
|                     |               | 2137               | 287 <sup>bcd</sup>                      | 370 <sup>abcde</sup>                    | 453 <sup>ab</sup>                       |
|                     | 146 B         | Tonkawa            | 224 <sup>h</sup>                        | 285 <sup>g</sup>                        | 346 <sup>ef</sup>                       |
|                     |               | 2137               | 292 <sup>bcd</sup>                      | 359 <sup>bcd</sup>                      | 426 <sup>abc</sup>                      |
| 73 SF               | Tonkawa       | 246 <sup>fgh</sup> | 304 <sup>fg</sup>                       | 363 <sup>def</sup>                      |   |
|                     | 2137          | 328 <sup>ab</sup>  | 398 <sup>ab</sup>                       | 468 <sup>a</sup>                        |   |
| 2800                | 0             | Tonkawa            | 270 <sup>defg</sup>                     | 339 <sup>ef</sup>                       | 407 <sup>bcd</sup>                      |
|                     |               | 2137               | 303 <sup>abcd</sup>                     | 366 <sup>abcde</sup>                    | 429 <sup>abc</sup>                      |
|                     | 146 SF        | Tonkawa            | 249 <sup>fgh</sup>                      | 340 <sup>def</sup>                      | 432 <sup>abc</sup>                      |
|                     |               | 2137               | 283 <sup>cdef</sup>                     | 356 <sup>bcd</sup>                      | 429 <sup>abc</sup>                      |
|                     | 146 B         | Tonkawa            | 274 <sup>defg</sup>                     | 355 <sup>bcd</sup>                      | 437 <sup>abc</sup>                      |
|                     |               | 2137               | 316 <sup>abc</sup>                      | 386 <sup>abc</sup>                      | 456 <sup>ab</sup>                       |
|                     | 73 SF         | Tonkawa            | 301 <sup>abcd</sup>                     | 384 <sup>abcd</sup>                     | 467 <sup>a</sup>                        |
|                     |               | 2137               | 341 <sup>a</sup>                        | 409 <sup>a</sup>                        | 477 <sup>a</sup>                        |

† SF, seed furrow applied; B, broadcast applied.

‡ Means separated using SAS least squares means; means with the same letter are not significantly different at  $\alpha = 0.10$ .**Table 9. Optimal management strategies for a risk-neutral farmer.**

| Years of amortization | Optimal strategy†  | Expected net returns                 |                        |                        |
|-----------------------|--|--------------------------------------|------------------------|------------------------|
|                       |  | Forage price = \$0.035               | Forage price = \$0.070 | Forage price = \$0.105 |
|                       |  | \$ ha <sup>-1</sup> yr <sup>-1</sup> |                        |                        |
| 0                     | 0 lime;<br>73 kg ha <sup>-1</sup> DAP (18-46-0)<br>in seed furrow;<br>Variety 2137                             | 328                                  | 398                    | 468                    |
| 5                     | 2800 kg ha <sup>-1</sup> ECCE lime;<br>73 kg ha <sup>-1</sup> DAP (18-46-0)<br>in seed furrow;<br>Variety 2137 | 341                                  | 409                    | 477                    |

† DAP, diammonium phosphate; ECCE, effective calcium carbonate equivalent.

**Table 10. Optimal management strategies for a risk-averse farmer.**

| Years of amortization | Optimal strategy†  | Expected net returns                 |                        |                        |
|-----------------------|--|--------------------------------------|------------------------|------------------------|
|                       |  | Forage price = \$0.035               | Forage price = \$0.070 | Forage price = \$0.105 |
|                       |  | \$ ha <sup>-1</sup> yr <sup>-1</sup> |                        |                        |
| 0                     | 0 lime;<br>73 kg ha <sup>-1</sup> DAP (18-46-0)<br>in seed furrow;<br>Variety 2137                             | 328                                  | 398                    | 468                    |
| 5                     | 0 lime;<br>73 kg ha <sup>-1</sup> DAP (18-46-0)<br>in seed furrow;<br>Variety 2137                             |                                      |                        | 468                    |
|                       | 2800 kg ha <sup>-1</sup> ECCE lime;<br>73 kg ha <sup>-1</sup> DAP (18-46-0)<br>in seed furrow;<br>Variety 2137 | 341                                  | 409                    |                        |

† DAP, diammonium phosphate; ECCE, effective calcium carbonate equivalent.

DAP than in plots that did not receive lime. Limed plots that received 73 kg ha<sup>-1</sup> DAP in seed furrows generated greater yields than plots that received no lime and no P. In general, economic returns were greater for the 2137 variety.

Economic analysis was conducted to determine the economically optimal strategy for dual-purpose wheat production. Average returns above variable costs were calculated for all strategies. When lime costs were fully assessed in the year of application, the economically optimal strategy was to apply 73 kg ha<sup>-1</sup> DAP in seed furrows and to not apply lime. With lime costs amortized

over a 5-yr period, the optimal strategy includes both the application of lime and DAP in seed furrows. With the expected value of forage (\$0.07 kg<sup>-1</sup>), the optimal strategies are the same for both risk-neutral and risk-averse farmers.

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