SELECTING AMONG ALTERNATIVE PRODUCTION FUNCTIONS, EFFECT OF LIME COST ON OPTIMAL NITROGEN LEVELS AND VERTICAL INTEGRATION IN THE WEST AFRICAN COTTON SECTOR

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ESSAY I

DETERMINING THE OPTIMAL LEVEL OF NITROGEN FERTILIZER USING RANDOM PARAMETER MODELS[1]

Abstract

The parameters of yield response functions can vary by year. Past studies usually assume yield functions are nonstochastic or ‘limited’ stochastic. In this study, we estimate rye-ryegrass yield functions where all parameters are random. Optimal nitrogen recommendations are calculated for two yield response functions: linear response plateau and Spillman-Mitscherlich. Nonstochastic models are rejected in favor of stochastic parameter models. The stochastic models lead to smaller recommended levels of nitrogen, but the economic benefits of using fully stochastic models are small since expected profit functions are relatively flat for the stochastic models.

[1] This paper has been accepted for publication in the Journal of Agricultural and Applied Economics. It is included in this dissertation in the format requirement of JAAE.

Introduction

Optimal nitrogen (N) fertilizer recommendations are often obtained by fitting yield response models to yield data (Lanzer and Paris 1981; Cerrato and Blackmer 1990; Babcock 1992; Makowski and Wallach 2002; Mooney et al. 2008). Unfortunately, model based nitrogen rate recommendations are vulnerable to misspecification of the yield response functions. This misspecification can affect the accuracy of optimal N recommendations, and any errors can reduce the profit of producers who follow the recommendations and potentially have negative environmental effects if excess N is applied. Of particular interest here is the possible misspecification of assuming parameters are constant when they are stochastic. The objective of this study is to determine expected net return maximizing nitrogen rate recommendations for a winter cereal rye (*S.cereale*)/ryegrass (*Lolium multiflorum Lam*) forage crop based on models that differ in functional form and whether or not model parameters are assumed stochastic.

Previous work on crop response to nitrogen fertilizer has usually used either limiting nutrient response functions or polynomial models. Plateau functional forms tend to best fit data from field studies (Heady and Pesek 1954, Lanzer and Paris 1981, Grimm, Paris, and Williams 1987). Past studies have often assumed that the parameters of the yield function are nonstochastic or 'limited' stochastic (some parameters are considered stochastic and others are not), and that all model errors are independent. This often leads to the estimation of the mean yield function as conditional on fertilizers, but neglects the possible interaction between weather events in a given year with the associated fertilizer response. Research suggests, however, that parameters of yield response functions can vary by year (Cerrato and Blackmer 1990, Makowski and Wallach 2002, and Tembo et al 2008). Given that the parameters of the yield response function can vary by year, estimating a random parameter model could give a more realistic model of producers' profit expectations.

Random parameter models have been suggested by Berck and Helfand (1990), Paris (1992), Makowski and Wallach (2002), and Tembo et al (2008). Berck and Helfand (1990), and Paris (1992) consider linear response plateau models where the intercept and plateau parameters are random, but without random effects. Tembo et al adds uncorrelated random effects to the intercept and plateau, but not to the slope. The Tembo et al. approach was successfully used to model wheat forage data (Kaitibie et al. 2003; Taylor et al. 2010) as well as wheat yield data (Biermacher et al. 2009). Only Makowski and Wallach (2002) treat all of the model parameters as random. Makowski and Wallach (2002) consider a linear-plus-plateau function in which wheat yield response is related to N uptake, and nitrogen uptake is related to applied nitrogen.

We consider three crop response functions: the simple linear response plateau (LRP), the Spillman-Mitscherlich, and the quadratic; and we make all model parameters random. Our random parameter model lets parameters vary stochastically by year. The data used are annual rye-ryegrass forage data collected from a long-term nitrogen fertilization experiment in south-central Oklahoma. We conduct nested likelihood ratio tests to choose between nonstochastic and stochastic models (Greene, 2008), and evaluate the economic value of using the alternative models by comparing expected profit. The ultimate goal of this study is to evaluate the economic importance of using a random parameter model to make optimal nitrogen rate recommendations for cool season cereal rye (*S.cereale*)-ryegrass (*Lolium multiflorum Lam*) forage producers in southern Oklahoma.

Determining the Profit Maximizing Level of Nitrogen Fertilizer

Consider a risk-neutral forage producer whose objective is to maximize expected net returns from winter cereal rye-ryegrass forage. The producer seeks to maximize expected net return above nitrogen cost:

$$(1) \qquad \max_N E(R_t|N) = pE[y_t] - rN$$
$$\text{s.t.} \quad y_t = F(N), N \geq 0,$$

where R_t is the producer's net return at time *t*, y_t is the forage yield, *N* is the level of applied nitrogen, *r* is the price of applied nitrogen fertilizer, and *p* is the price of forage. Yield expectations are obtained through the production function *F*(*N*). We consider the three production functional forms in turn.

Linear Response Plateau

A stochastic linear response plateau function is specified as

$$(2) \qquad y_{it} = \min(\beta_0 + (s_t + \beta_1)N_{it},\ \mu_p + v_t) + u_t + \varepsilon_{it},$$

where y_{it} is the forage yield of cereal rye-ryegrass from the i^{th} plot in year t, N_{it} is the level of nitrogen fertilizer, μ_p is mean plateau yield, s_t is the slope random effect, v_t is the plateau year random effect, u_t is the (intercept) year random effect, and ε_{it} is a random error term that is normally distributed and independent of the three random effects. The intercept random effect is added to the whole equation rather than just to β_0 so that the model of Tembo et al. (2008) is a special case**.** The variance parameters u_t, s_t, and v_t are correlated and normally distributed. Makowski and Wallach (2002) use a model where $(\beta_0, \beta_1, \mu_p) \sim N(\boldsymbol{\beta}, \boldsymbol{\Omega})$. Our model is parameterized differently, but is equivalent to Makowski and Wallach (2002).

The random effect u_t shifts the whole function up or down, which could be due to a variety of weather factors, insects or disease. The slope random effect s_t may be due to nitrogen losses from leaching, soil or weather characteristics, or weed pressure during critical growth periods. The plateau year random effect v_t shifts the yield potential from applying more nitrogen, which mostly varies due to rainfall in a given year. For example, when growing conditions are favorable in a given year, the plateau yield increases as does the amount of nitrogen that the plants can use. When the model is nonstochastic, the random variables v_t and s_t will be zero, but u_t may still be included.

The function is continuous, but its derivatives do not exist with respect to either its parameters or *N* at the knot point where the response and the plateau are joined, but the derivatives of expected yield do exist for the stochastic model. Choosing the level of nitrogen (*N**) that maximizes equation (1) follows the rule from economic theory that marginal factor/input cost (MFC) should equal marginal expected product value (MVP).With a nonstochastic linear response plateau function, equation (2) will exhibit constant positive marginal product when $\mu_p > \beta_0 + \beta_1 N$. If MVP > MFC, then nitrogen should be applied until MVP=MFC. Increasing *N* beyond the level required to reach μ_p will generate negative marginal returns. Therefore, with the nonstochastic LRP, *N** would either be the level required to reach the plateau (N_p) or zero:

$$(3) \qquad N^* = \begin{cases} N_p, & \text{if VMP} > MFC \\ 0\,, & \text{otherwise.} \end{cases}$$

For the stochastic LRP, the random variable u_t in equation (2) enters linearly, and therefore it drops out after taking expectations. Therefore, the expectation of y becomes

$$(4) \qquad E(y_t) = E\left[\min\left(\beta_0 + (\beta_1 + s_t)N, \mu_p + v_t\right)\right].$$

Since s_t and v_t are random and correlated, the expectation in (4) requires integrating with respect to s_t and v_t, which defines a double integral that must be solved numerically:

$$(5) \qquad E(y_t) = \iint\left[\min\left(\beta_0 + (\beta_1 + s_t)N, \mu_p + v_t\right)\right]\varphi(s_t, v_t)\partial s_t \partial v_t ,$$

where $\varphi(s_t, v_t)$ is the multivariate normal probability density function. Tembo et al. (2008) use the approach developed for Tobit models and obtain N^* by evaluating a univariate normal probability density function since they do not allow the slope to be random. Makowski and Wallach (2002) solve the integral using Monte Carlo integration. The integration in (5) can also be solved using other numerical approximation methods such as Gaussian cubature (DeVuyst and Preckel 2007). We use Monte Carlo integration to solve the double integral. The optimal level of N is obtained by direct non-linear optimization (grid search would also work since there is only one choice variable).

Spillman-Mitscherlich

The Spillman-Mitscherlich yield response function is an exponential function (Spillman 1923). A univariate stochastic form of this function is

$$(6) \qquad y_{it} = a - (b + s_t)\exp\left((-c + v_t)N_{it}\right) + u_t + \varepsilon_{it},$$

where a is the maximum or potential yield obtainable by applying nitrogen under the conditions of the experiment; b is the increase in yield due to applied nitrogen; c is the ratio of successive increments in output a to total output y; u_t, s_t, and v_t are correlated random effects; and ε_{it} is the independent error term. When the model is nonstochastic, the random variables s_t and v_t are zero, but u_t is still included.

Equation (6) shows that as the application rate of nitrogen increases, the yield increases at a decreasing rate and asymptotically approaches a maximum as the application rate (theoretically) approaches infinity. The function does not strictly adhere to the law of the minimum like in the case of the linear response plateau (allows for convex rather than right-angled isoquants), but unlike the polynomial functions, it exhibits a plateau. The function exhibits sufficient flexibility to accommodate from near perfect substitution to near zero factor substitution if the data and production process so suggest (Frank, Beattie, and Embleton1990).

The optimal level of nitrogen is obtained by substituting (6) into (1) and then solving the optimization problem. For the nonstochastic Mitscherlich yield function, the optimal level of nitrogen (N*) is obtained by solving the first order condition for N, which gives

$$(7) \qquad N^* = \frac{1}{-c}\left[\ln\left(\frac{(r/p)}{cb}\right)\right].$$

For the stochastic Mitscherlich, since the random variables s_t and v_t do not enter linearly in (6), the expectation of y is obtained by numerically solving the integral:

$$(8) \qquad E(y_t) = \iint [a + (b + s_t)\exp(-c + v_t)\,N]\varphi(s_t, v_t)\partial s_t \partial v_t.$$

The double integral is solved using Monte Carlo integration. Monte Carlo approximates (8) with a summation, which is then substituted into (1) and the optimal level of nitrogen is then obtained by nonlinear optimization.

Quadratic Response

A random parameter quadratic response model is specified as

$$(9) \qquad y_{it} = \beta_0 + (\beta_1 + v_t)N_{it} + (\beta_2 + s_t)N_{it}^2 + u_t + \varepsilon_{it},$$

where β_0 is the intercept parameter whose position (value) can be shifted up or down from year to year by the year random effect u_t, β_1 is the linear response coefficient with random effect parameter v_t, β_2 is the quadratic parameter whose value can be shifted up or down by the random effect s_t, and ε_{it} is the independent error term assumed to be normally distributed. The random effects v_t, s_t and u_t are correlated and normally distributed. When the model is nonstochastic, the random effects v_t and s_t would be zero, but u_t is still included.

Since (9) is continuously twice differentiable and all the random parameters enter in (9) linearly, (1) gives the same analytical solution for both stochastic and nonstochastic models. Note that for the nonstochastic model, the values of v_t, s_t and u_t are all zero. Hence the problem of calculating N* simplifies to:

$$(10) \qquad N^* = (\beta_1 - r/p)/2\beta_2.$$

Model Fit and Selection Criteria

Likelihood ratio tests are used to choose between stochastic and nonstochastic models (Greene 2008). The calculated likelihood ratio statistics have a chi-square distribution under the null hypothesis. To choose between competing model functional forms, Davidson and Mackinnon (1981) suggest using formal non-nested tests such as the J-test and P-test. These tests, however, cannot be used here since they can only be used when the nonoverlapping parameters are associated with fixed effects.

The literature on non-nested hypothesis tests provides a variety of criteria to select the model that best fits the data. When competing non-nested models are fully parameterized and estimated by maximum likelihood, a popular criterion is the adjusted model log-likelihood such as AIC (Akaike, 1974) and BIC (Schwarz 1978). However, these criteria do not take into account whether the differences in the penalized log-likelihoods are statistically significant or not. When observations are independent and identically distributed, a test can be done following Vuong (1989). Pollak and Wales (1991) introduced the Likelihood Dominance Criterion (LDC). The LDC provides rationale to compare two models based on the difference in estimated likelihoods, with adjustments for differences in the number of parameters, and for a given significance level (Pollak and Wales 1991; Grewal, Lilien, and Mallapragada 2006). The criterion involves a fictitious experiment where two competing hypothesis are nested in a composite and the concept of dominance ordering is used to choose among the two. This criterion is the one we use for testing hypothesis to choose between our non-nested models.

Let H_1 and H_2 be two models (hypotheses) with n_1 and n_2 parameters, respectively, and let L_1 and L_2 be the log likelihoods. Let $C(v)$ denote a critical value of the chi-square distribution with v degrees of freedom at significance level α. According to the LDC:

1. Select H_1 if $L_2 - L_1 < [C(n_2 + 1) - C(n_1 + 1)]/2$.

2. Select H_2 if $L_2 - L_1 > [C(n_2 - n_1 + 1) - C(1)]/2$.

3. Otherwise, model selection is indeterminate.

When $n_1 = n_2$ (our case), the indeterminate region reduces to zero and the criterion reduces to a simple comparison of estimated maximum likelihood values (Pollak and Wales 1991).

Data

Forage yield data are cross-sectional times-series from a long-term experiment conducted by the Agricultural Division of The Samuel Roberts Noble Foundation (1997-2008) at Red River demonstration and research station near Burneyville, in south-central Oklahoma. The experiment began in 1979 and was aimed at evaluating the effect of nitrogen fertilization rate and harvest timing on the annual rye-ryegrass forage production system, using a randomized complete block design. Details of the experimental set up are described in Altom et al. (1996) who analyzed the data from 1979 to 1992.

Our dataset covers 14 years from fall 1993 to spring 2007. Six treatment levels of nitrogen (34-0-0) were administered: 0, 100, 150, 200, 300, and 400 pounds per acre per year. Treatments were replicated three times for each level of nitrogen. Split applications were used. Ammonium nitrate was broadcast and incorporated prior to planting in the fall. Spring applications were not incorporated. Fall fertilization was done between September 24 and October 25. Spring fertilization was between February 20 and March 17. Phosphorous was banded with the seed at a rate of 50lbs P_2O_5/acre every year, Potassium was broadcast and incorporated prior to planting at an average rate of 100 lbs K_2O/acre. Lime was applied to the plots used in the study.

Forage yields were determined by clipping individual plots that were 12 by 13 ft. Plots were clipped multiple times to simulate grazing. Yearly dry matter forage yields were the sum of all clippings for that year. Average annual rye-ryegrass yield response to nitrogen fertilization is shown in figure 1.

Estimation

The models are estimated using NLMIXED procedure in SAS (SAS Institute Inc. 2003). The dependent variable is yield, and the independent variable is nitrogen. For the quadratic, nonstochastic LRP and nonstochastic Mitscherlich models, the error term and random effects enter the equation linearly. In the stochastic LRP and the stochastic Mitscherlich models, the two non-intercept random effects enter the equations nonlinearly. The random effects are estimated as free correlated parameters, but the error term is independent.

The NLMIXED procedure fits nonlinear mixed models by maximizing the likelihood integrated over the random effects (SAS Institute Inc. 2003). As is common in nonlinear optimization, convergence can be difficult and computing the objective function and its derivatives can lead to arithmetic overflows (SAS Institute Inc. 2003). The models have no closed form and can only be approximated numerically. To achieve convergence, three efforts are employed: scaling, varying starting points, and using different optimization techniques.

Pinheiro and Bates (1995) provide evidence that of the several different integrated likelihood approximations methods, adaptive Gaussian quadrature is one of the best. We use adaptive Gaussian quadrature to approximate the likelihood function integrals and maximize the function by the dual quasi-Newton optimization algorithm. Other optimization techniques that enabled convergence are the Newton-Raphson method with ridging and the Trust-

Region Method (SAS Institute Inc. 2003). The quadratic and nonstochastic Mitscherlich models converge with less need of scaling and changing starting point values. Estimates obtained are then used to determine the optimal level of nitrogen.

For the stochastic LRP and stochastic Mitscherlich, the estimated parameters are used in Monte Carlo integration. The random vector $[s_t, v_t] \sim N(\mathbf{0}, \mathbf{\Omega})$. We use the Cholesky decomposition, $\mathbf{\Omega} = \mathbf{PP}$, where $\mathbf{P}$ is a lower triangular matrix. Let $\mathbf{Z}$ be a 2x1 vector of independent draws, then $\mathbf{PZ} \sim N(\mathbf{0}, \mathbf{\Omega})$. With sufficient draws, the sample average of the function being integrated provides an approximation to the integral (Greene 2008, pp. 576-583). We use 10,000 draws for our approximation. To obtain the optimal level of N, we use the SAS PROC NLP procedure and maximize our objective function (1) using Newton-Raphson with ridging.

Results and Discussion

Estimated parameters are reported for the quadratic model in table 1, linear response plateau in table 2, and Mitscherlich in table 3. For all models, the mean parameters and variance estimates are statistically significant at the 5% level based on Wald t-tests. Covariance parameters of the stochastic quadratic model are not statistically significant at the 5% level. Covariance parameters of the stochastic Mitscherlich and the covariance between the plateau and the slope in the stochastic LRP are statistically significant. The likelihood ratio (LR) statistic for the stochastic quadratic versus the nonstochastic quadratic model is 170; the LR for the stochastic linear response plateau versus the nonstochastic linear response plateau is 269.4; and the LR for the stochastic Mitscherlich versus the nonstochastic Mitscherlich is

262.8. All the LR statistics are greater than the critical chi-square (X_5^2) value[2] at any conventional significance level. Stochastic models fit our data better than the alternative non-stochastic models.

Based on the LDC (Pollak and Wales, 1991), we choose the functional form that fits our data best. The estimated maximum likelihood value for the stochastic LRP is 2295.1. The likelihood value for the stochastic quadratic is 2348.6, and for the stochastic Mitscherlich it is 2300.0. Both models have the same number of parameters (*n*=9). Hypothesis testing on model functional form according to the LDC ranking favors the stochastic LRP over the stochastic Mitscherlich and the stochastic Mitscherlich over the stochastic quadratic model. From the illustration in figure 1, a quadratic model may be considered a poor choice for this dataset on the basis that it assumes symmetry. It indicates that yield decreases past the peak at the same rate it increases before the peak. We base our optimal N rate recommendations on the stochastic LRP, the best fitting model.

Profit maximizing level of nitrogen is evaluated at 2009 input and output prices. Although nitrogen 34-0-0 ammonium nitrate was used in the experiment, The Samuel Roberts Noble Foundation Agricultural Division currently recommends using 46-0-0 urea. The prices of nitrogen 34-0-0 and 46-0-0 as reported by input suppliers in south-central Oklahoma are \$.51/lb of N and \$.41/lb of N, respectively. We do a sensitivity analysis by determining nitrogen rate recommendations as nitrogen prices vary. The per pound price of forage is determined as the cost of beef gain per pound divided by the pounds of forage

[2] Note that there is a potential nuisance parameter problem with this hypothesis test since imposing that the two variances are zero also imposes that the three covariances are zero. We do not explore this issue since all null hypotheses are rejected even using the more conservative critical value.

required by a stocker animal to produce a one-pound gain (Coulibaly et al., 1996; Kaitibie et al., 2003; Belasco et al., 2009). Based on the National Research Council (1984) net energy equations used to estimate livestock requirements, Ishrat , Epplin, and Krenzer (2003) and Krenzer et al (1996), show that one pound of beef gain requires 10 lbs (dry matter) of standing forage. Within the south-central Great Plains, the cost per pound of gain has ranged from $0.32/lb since 2005 to $0.55/lb in 2009 (The Samuel Roberts Noble Foundation, Inc. 2009). Kaitibie et al. (2003) used an average daily weight gain equation and determined the cost of beef gain at $0.54/lb. Due to decreased prices of corn and fertilizer, this cost declined to $.45/lb, (which is approximately the mean across the period). Therefore, at the cost of beef gain per pound of $0.45, the price per pound of forage is $0.45/10=$0.045. Our optimal nitrogen rate recommendations are based on nitrogen prices of $0.41/lb and forage sale prices of $0.045/lb.

The estimated optimal nitrogen rates and their standard errors for the models are included in the respective tables of results. At the assumed prices, the profit maximizing level of nitrogen obtained with the nonstochastic linear response plateau model is 182.3 lbs/acre, the level of nitrogen required to reach the plateau. Applied nitrogen increases yield at a rate of 13.8 lbs/acre until the plateau yield level of 8235.7 lbs/acre. At $0.045 sale price of forage, the marginal value product of nitrogen is $ 0.62 per pound, which is greater than the $ 0.41/lb price of nitrogen. The 95% confidence interval of the optimal level of nitrogen obtained with the nonstochastic LRP is 209.4 lbs/acre to 154.6 lbs/acre.

Maximum profits for the stochastic linear response plateau are achieved with nitrogen fertilization rate of 143.6 lbs/acre. The 95% confidence interval for this estimate is to apply 115.5 lbs/acre to 171.8lbs/acre of nitrogen. The nonstochastic LRP gives an optimal level of nitrogen that is 38.7 lbs/acre higher than the stochastic LRP. Based on the average expected plateau yield and optimal N obtained with the stochastic LRP, the marginal productivity of nitrogen is higher with the stochastic model. On average, nitrogen increases forage yield at a rate of 16.3 lbs/acre compared to 13.8 lbs/acre for the nonstochastic model. The stochastic LRP function leads to diminishing marginal productivity of nitrogen that is supported by data from agronomic experiments (Paris, 1992). The expected profit function of the nonstochastic LRP is higher than that of the stochastic LRP (Figure 2a). Figure 2a shows that the expected profit curve predicted by the nonstochastic LRP increases linearly as a function of N, and decreases sharply when N exceeds the optimal N level. Because of the initial linear section, the profit maximizing N rate is insensitive to N prices. The deterministic LRP function overestimates yield potential in years when growing conditions are not good. This explains the large difference between N recommendations calculated using the stochastic model and nonstochastic LRP. The loss (to the producer) from using the nonstochastic LRP to predict optimal nitrogen levels when the stochastic LRP is the true model is approximately $9.0 per acre. This loss is small because the expected profit function of the stochastic LRP is relatively flat. If the prices of N increase relative to the price of forage, the cost of using a nonstochastic model to determine N recommendations increases.

Profit maximizing level of nitrogen obtained with a non-stochastic Mitscherlich is 113.5 lbs/acre. The 95% confidence interval for this estimate is 95.4 lbs/acre to 130.4 lbs/acre of nitrogen. The optimal level of nitrogen obtained with a stochastic Mitscherlich model is 107.4 lbs/acre. The 95% confidence interval for the optimal level of nitrogen obtained with the stochastic Mitscherliuch is 103 lbs/acre to 110.6 lbs/acre. The expected profit function of the non-stochastic Mitscherlich model is higher than that of the stochastic

Mitscherlich (Figure 2b). The loss from using the nonstochastic Mitscherlich model to predict the optimal level of nitrogen when the stochastic Mitscherlich is the true model is approximately $1.0 per acre. The economic benefits of using fully stochastic models are small since optimal nitrogen rates do not differ greatly between stochastic and nonstochastic models and the expected profit functions are relatively flat.

The analysis presented above does not account for the environmental/social costs of over fertilization due to using a nonstochastic model to determine N rates. While not quantified, there are additional costs to over estimating crop nitrogen needs. For instance, Tumusiime et al. (2011) has shown that applying N above the consumptive potential of the growing plant can increase lime costs. There is a potential social cost due to potential groundwater contamination from nitrogen fertilizer over application. Since the stochastic models recommend lower nitrogen levels; accounting for these additional costs would increase the advantage of the stochastic models.

Profit maximizing level of nitrogen obtained with a nonstochastic quadratic model is 144.3 lbs/acre, and the optimal level of nitrogen obtained with a stochastic quadratic model is 171.4 lbs/acre. We notice from figure 3 that fertilizer recommendations for the stochastic linear response plateau and the stochastic Mitscherlich can be less or more than fertilization rates recommended with the alternative nonstochastic model, depending on price ratios of the input and the output. The use of the stochastic LRP or Mitscherlich function to determine N recommendations provides insight as to why some farmers may apply more or less nitrogen than would appear optimal. Also, the expected profit function is relatively flat so the optimal level is likely difficult for farmers to determine. The stochastic quadratic model consistently estimates higher optimal levels of nitrogen than the alternative nonstochastic model.

Summary and Conclusions

Models predicting crop yield response to nitrogen fertilizer are often used to recommend optimal fertilizer rates. Past studies usually assume the parameters of the yield function are nonstochastic or ‘limited’ stochastic, and that all model errors are independent. Given that research suggests that the parameters of the yield functions vary by year, estimating a random parameter model could give a more realistic model of producers’ profit expectations. In this study, we consider yield functions where all parameters are random. The approach was applied to cereal rye/ryegrass forage data collected from a long-term nitrogen fertilization experiment in south-central Oklahoma to determine and compare the profitability of nitrogen estimated from stochastic models and the alternative nonstochastic models. The model functional forms considered are the linear response plateau, the quadratic, and the Spillman-Mitscherlich.

Constant parameter models are rejected in favor of random parameter models. Quadratic models fit the data poorly. The stochastic LRP provided the best fit to the data among the yield functions studied. Our results support the findings of Tembo et al. (2008), and Kaitibie et al. (2003) that LRP with stochastic plateau provide a better fit than a deterministic plateau function. The value of using a stochastic LRP instead of a deterministic model was estimated to be $9/acre so the economic benefit is not huge. The finding by Makowski and Wallach (2002) that it pays to use a random parameter model to calculate nitrogen rates is supported but the loss from not using random parameter models to determine the optimal level of nitrogen is small since optimal nitrogen rates do not differ greatly between stochastic and nonstochastic models and the expected profit function is relatively flat. Another implication of this study regarding the flatness of the profit function is that it brings into question the economic feasibility of variable rate application technologies that are being developed to improve nitrogen use efficiency. If forage producers have a wide margin of error when deciding how much nitrogen to apply, the cost of obtaining a more accurate estimate of N may not exceed the benefit since the cost of ‘being roughly right’ in N rate is not large.

The observation by Cerrato and Blackmer (1990) and other researchers that the quadratic model estimates a higher optimal nitrogen rate than a linear response plateau is supported for stochastic models but not for nonstochastic models. The quadratic model implies a yield decline beyond the maximum yield due to excess nitrogen fertilization, which is rarely observed in field studies. Nevertheless, our data do show an unsustained yield decline at a high nitrogen rate. Other studies do find a quadratic model providing a better statistical fit (Belanger et al. 2000) which means yield functions with plateau may not dominate in every situation. In a practical farm extension context, stochastic production functions provide a way of incorporating production uncertainty into input decisions. The methodology developed to determine N recommendations is applicable to other crops as well as other areas. The methodology is of benefit to producers as it improves the precision of optimal N recommendations under production uncertainty as well as improving nitrogen use efficiency, and farm profitability.

Current recommendations of fertilizing annual cool season cereal rye-ryegrass pastures from the Noble Foundation are to apply 100 to 200 lbs/acre. Our estimated optimal rates are within this range. Based on the estimates from the stochastic LRP, the 95% confidence interval level is to apply between 115.5 lbs/acre to 171.8lbs/acre annually.

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Tables

Table 1. Rye-Ryegrass Yield (1000lbs/acre) Response to Nitrogen (100lbs/acre) Using the Nonstochastic and Stochastic Quadratic Models

Parameter	Stochastic Quadratic		Nonstochastic Quadratic	
	Estimate	SE	Estimate	SE
Intercept (β_0)	5.74	0.54	5.77	1.15
Slope (β_1)	1.74	0.44	1.64	0.18
Quadratic term (β_2)	-0.24	0.10	-0.25	0.04
Variance of intercept random effect (σ_u^2)	13.46	3.29	19.32	7.08
Variance of error term (σ_ε^2)	1.89	0.11	2.43	0.14
Variance of slope random effect (σ_v^2)	1.93	0.35		
Variance of quadratic term random effect (σ_s^2)	0.47	0.20		
Covariance (σ_u^2, σ_s^2)	1.62	1.51		
Covariance (σ_s^2, σ_v^2)	-0.004	0.38		
Covariance (σ_u^2, σ_v^2)	-0.03	0.06		
Optimal level of N (100lbs/acre)	1.71	0.12	1.44	0.15
-2 Log Likelihood	2348.6		2433.6	

Table 2. Rye-Ryegrass Yield (1000lbs/acre) Response to Nitrogen Using the Nonstochastic and Stochastic Linear Response Plateau Models

Parameter	Stochastic Linear Plateau		Nonstochastic Linear Plateau	
	Estimate	SE	Estimate	SE
Intercept (β_0)	5.67	0.29	5.72	1.15
Slope (β_1)	1.62	0.31	1.38	0.17
Yield plateau (μ_p)	8.01	0.12	8.23	1.14
Intercept random effect (σ_u^2)	13.96	1.53	19.32	7.08
Variance of error term (σ_ε^2)	1.85	0.11	2.42	0.14
Plateau random effect (σ_v^2)	3.65	0.33		
Variance of slope random effect (σ_s^2)	0.89	0.16		
Covariance (σ_u^2, σ_s^2)	-1.41	0.74		
Covariance (σ_u^2, σ_v^2)	0.89	0.82		
Covariance (σ_s^2, σ_v^2)	1.54	0.18		
Optimal level of N (100lbs/acre)	1.44	0.14[a]	1.82	0.14[a]
-2 Log Likelihood	2295.10		2429.80	

[a] The standard error of N* for the stochastic LRP is obtained by Monte Carlo methods, while the standard error of N* for the nonstochastic LRP is obtained using the delta rule.

Table 3. Rye-Ryegrass Yield (1000lbs/acre) Response to Nitrogen Using the Nonstochastic and Stochastic Spillman-Mitscherlich Models

Parameter	Stochastic Mitscherlich		Nonstochastic Mitscherlich	
	Estimate	SE	Estimate	SE
Maximum (potential) yield (a)	7.91	0.12	8.47	1.15
Response due to nitrogen (b)	3.28	0.38	2.81	0.23
Ratio of successive increments (c)	1.31	0.26	0.89	0.16
Variance of error term (ε_t)	1.85	0.11	2.42	0.14
Intercept random effect (σ_u^2)	19.44	1.10	19.35	7.09
Variance of slope random effect (σ_s^2)	5.89	1.45		
Plateau random effect (σ_v^2)	0.37	0.15		
Covariance (σ_u^2, σ_s^2)	8.36	1.16		
Covariance (σ_s^2, σ_v^2)	1.67	0.36		
Covariance (σ_u^2, σ_v^2)	0.80	0.19		
Optimal level of N (100lbs/acre)	1.07	0.02[b]	1.13	0.09[b]
-2 Log Likelihood	2300.0		2431.4	

[b]The standard error of N* for the stochastic Mitscherlich is obtained by Monte Carlo methods, while the standard error of N* for the nonstochastic Mitscherlich is obtained using the delta rule

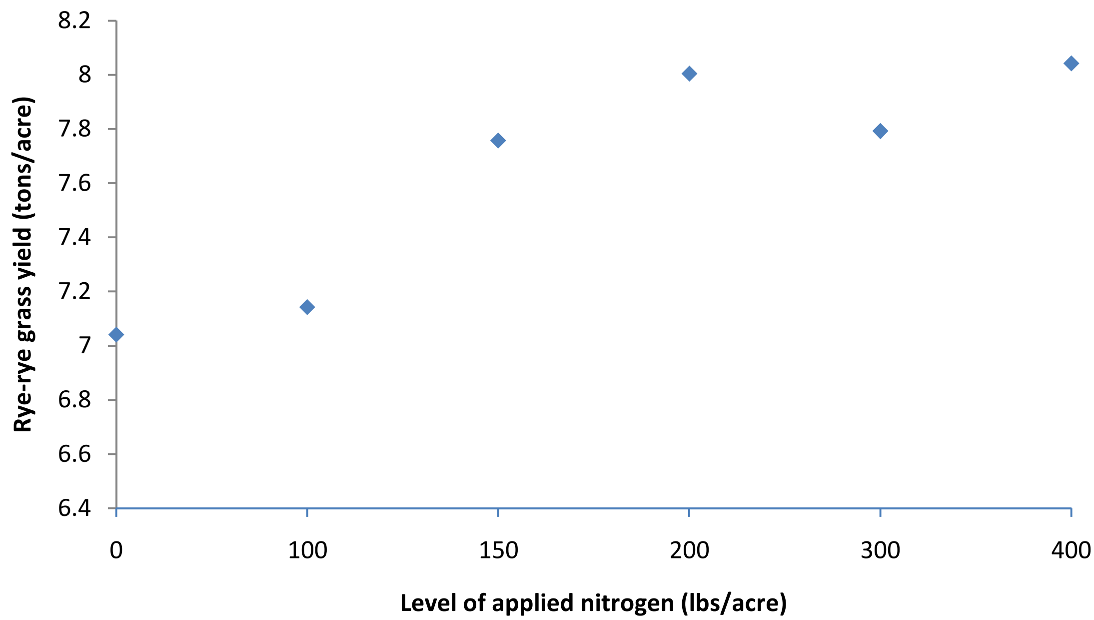
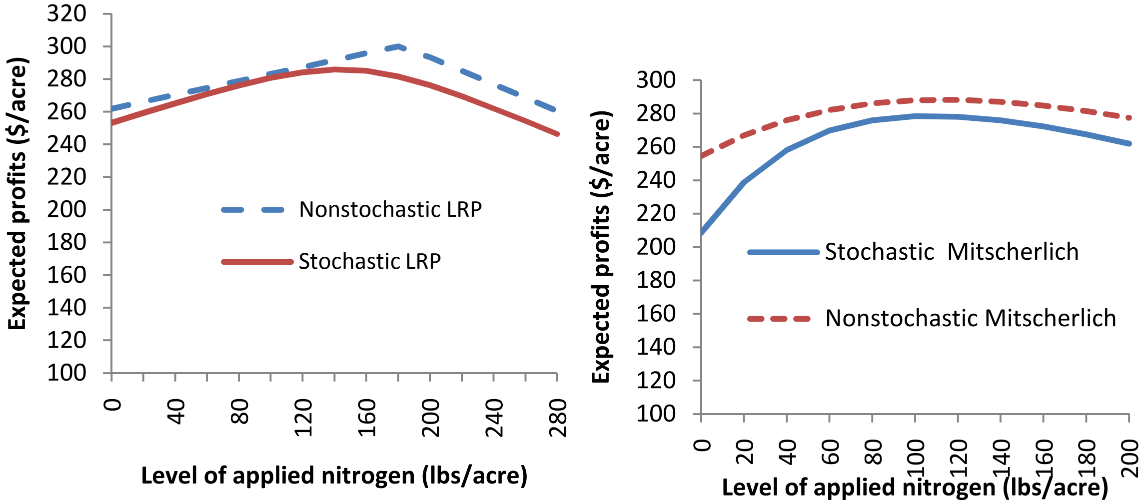


Figure 1. Ryegrass yield response to applied nitrogen



(a) **(b)**

Figure 2. Expected profit functions (Price of ryegrass =$.0450/lb, price of nitrogen=$.41/lb)

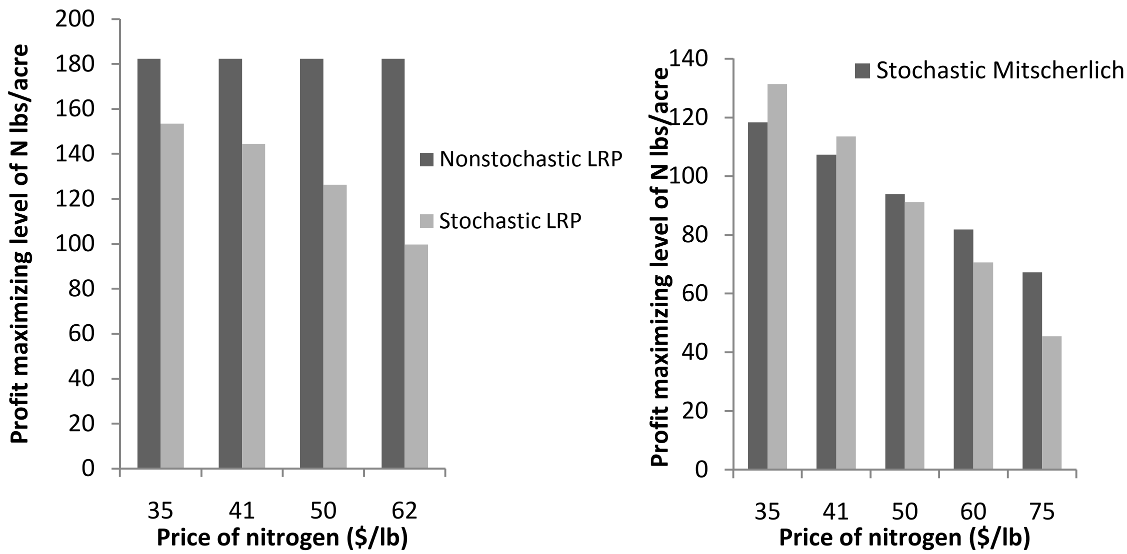


Figure 3. Optimal level of N at varying prices for the LRP models and Mitscherlich models (price of ryegrass is constant at $ 0.045)

ESSAY II

HOW MUCH DOES CONSIDERING THE COST OF LIME AFFECT THE RECOMMENDED LEVEL OF NITROGEN[3]

Abstract

Ammonium based nitrogen fertilizers acidify soils. Lime used to correct soil pH is a substantial cost to producers. Recommendations about the optimal levels of nitrogen to apply typically ignore the cost of lime needed due to nitrogen fertilization acidification. This study aimed to determine the effect of considering the cost of lime on recommendations about the optimal level of nitrogen. Yield response and soil pH change functions were estimated and used to determine the optimal levels of nitrogen and lime. The study also developed a new version of a linear response plateau function that allows the yield plateau to vary by year with respect to nitrogen but not soil pH. The stochastic linear response plateau fit the data best. At current input and output prices, considering the cost of lime reduced the optimal level of nitrogen by as much as 11.3% from 168 to 149 kg ha^{-1} yr^{-1}. Acidification potential due to N fertilizer increased nonlinearly as N rate increased. Nitrogen acidification appears to be more severe with N application rates above consumptive potential of the crop than with N that is used by the plant. Timing of N application had no significant effect on forage yield, but splitting N into fall and spring applications significantly reduced acidification due to excess N fertilization. Recommendations of how much N to apply were 149 kg ha^{-1} yr^{-1} with pH at least 5.88.

[3] This paper was published in the Agronomy journal. It is included in this dissertation as it appears in *Agronomy Journal* 103:404-412.

Introduction

Using ammonium based nitrogen (N) fertilizers in crop production has been shown to acidify soils (Mahler and Harder, 1984; Pierre et al., 1971). Acidification due to N fertilization results from three major factors. One is the removal of base cations such as calcium and magnesium through crop harvest. Nitrogen fertilizers increase yields and thus increase the removal of bases in the harvested crop. The second effect comes from nitrates that are not taken up by the growing crop. Nitrates are very soluble and, if not taken up by plants, leach to deeper soil layers taking with them base elements like calcium and magnesium (Mahler and Harder, 1984). The other is microbial oxidation of ammoniacal fertilizers (nitrification), a process that releases hydrogen ions (H^+) into the soil (Adams 1984). Acidity from nitrification is, however, partly or wholly countered by the alkalinity produced during the uptake and assimilation of nitrate N to its organic form (Bolan et al., 1991; Bouman et al., 1995).

Historically, soil acidity has not been a problem for most croplands in the southern Great Plains of the USA (Shorey, 1940). However, in the past decades, soil pH values have declined due to continuous cropping and long-term use of large amounts of ammonium-based N fertilizers (Zhang and Raun, 2006). A survey in 1985 supported by the Oklahoma Cooperative Extension Service of wheat fields cropped continuously showed more than 30% of 17,000 soil samples analyzed had pH levels less than 5.5. In 1995, a similar survey of 3,709 samples showed that 39% of the samples had pH levels less than 5.5 (Zhang et al., 1998). These surveys suggest that soil pH levels in fields under continuous cultivation in the region have declined to levels that Zhang and Raun, (2006) argue to be yield limiting, and that the problem has increased over time.

Associated with very acidic soils are problems that limit crop and pasture growth and yield. Plant utilization of many nutrients becomes less efficient as soil acidity increases (Haynes and Ludecke, 1981; Black, 1993). Detrimental effects from soil acidity vary with crop, rooting depth, and crop tolerance (Black, 1993). The most serious problems are due to aluminum and manganese toxicities that increase as soil pH drops below 5.0. Aluminum toxicity restricts the development of crop root systems, which in turn reduces nutrient uptake. Manganese toxicity results in deficiencies of the essential mineral nutrients calcium, phosphorous, and molybdenum (Black, 1993).

Acidic soils can be amended by liming. Benefits of liming include improved N fixation and availability of the essential nutrients calcium, phosphorous, and molybdenum and decreased solubility of toxic elements aluminum and manganese (Haynes and Ludecke, 1981). The per unit cost of lime is low relative to other fertilizers, but lime application rates are significantly higher than rates for fertilizers such as N and phosphorous. Because large amounts of neutralizing material are often needed, liming can be expensive. Recommendations about how much N to apply typically ignore the cost of lime due to N fertilization. Ignoring the cost of lime may lead to higher than optimal N recommendations.

Past literature on crop yield response to N fertilizer has often favored a linear response and plateau model (Paris, 1992; Ackello-Ogutu et al., 1985). With this response function, the optimal level of the input does not matter over a wide range of input prices because it ignores production uncertainty. Recent empirical research however, has shown that the plateau yield varies across years (Tembo et al., 2008; Makowski and Wallach, 2002). Tembo et al. (2008) and Tumusiime et al. (2010) showed that with a variable plateau model, the producer's expected profit function is relatively flat near the optimum N level. The relative flatness of the profit function near the optimum input level means that considering the cost of liming could change recommended N levels. Further, precision sensing systems to improve N use efficiency have been shown to be marginal in terms of economics (Lambert et al., 2006; Biermacher et al., 2009). A large enough cost of liming could make precision sensing systems more competitive economically.

Forage rye-ryegrass responds well to high N fertilizer levels and performs well in soils with pH values ranging from 5.5 (Zhang and Raun, 2006) to 8 (Barnes et al., 2003). The problem of soil acidity is likely greater on croplands under forage production than on those under grain production since grains contain less basic materials than stems or leaves. Moreover, forage harvested by grazing or by baling is removed from the place of production, meaning base elements are not released back to the soil. Considering the cost of lime is expected to lower recommended levels of N.

Of interest is whether or not excess N that is not used by the plant leads to a greater reduction in soil pH than does N that is used by the plant to produce forage. If this effect turns out to be large, then the study would have favorable implications on the economic competitiveness of precision sensing systems. This research will also benefit producers by giving much more precise estimates of optimal soil pH and N fertilization strategies that may be useful in improving fertilizer use efficiency and increasing farm net returns.

The objective of this study is to determine the effect of considering the cost of lime on recommendations about the optimal level of N to apply. To achieve this objective, the study determines the effect of N fertilization rate, N fertilization timing and lime application on soil pH change; and the effect of soil pH, and N fertilization rate and timing on forage yield. Data are from a long-term N fertilization and liming experiment in south-central Oklahoma, USA that provides annual rye-ryegrass (*Lolium multiflorum*) forage yields and soil pH levels.

Materials and Methods

a) Data

A long-term experiment was conducted at the Red River Research and Demonstration Farm near Burneyville, Oklahoma by The Samuel Roberts Noble Foundation's Agricultural Division. The experiment started in 1979 and its aim was to establish the effect of liming, N fertilization rate and timing on forage yields of a mixture of rye (*Secale cereal*) and ryegrass (*Lolium multiflorum*) as well as soil pH dynamics. The effect of N fertilization rates on forage yield and quality was analyzed by Altom et al. (1996) using data from 1979 to 1992. The data set for this project is for rye-ryegrass pasture for the period from fall 1993 to spring 2007.

The soil at the site is Minco fine sandy loam (coarse-silty, mixed, superactive, thermic Udic Haplustolls). Since 1993, rye-ryegrass has been planted in early fall at a seeding rate of 22 kg ha^{-1}. A split-plot randomized complete block design with three replications was used. Six treatment levels of N were administered: 0, 112, 168, 224, 336 and 448 kg N ha^{-1} yr^{-1}. Nitrogen fertilizer applied as ammonium nitrate (34-0-0) was applied in a single application (all applied pre planting in fall, or all applied in spring) and in two split applications: fall and spring. Nitrogen fertilizer was broadcast and incorporated prior to planting in the fall. Ammonium nitrate applied in the spring was broadcast. Phosphorous applied as diammonium phosphate (18-46-0) was banded with the seed at a rate of 24 kg P ha^{-1}. Potassium as potassium chloride KCl, (0-0-60) was broadcast and incorporated prior to planting at an average rate of 93 kg K ha^{-1}.

Lime (dolomitic) was applied in 1979, 1996, 1998, and 2004. In 1979, lime was applied at a rate of 4483 kg ha^{-1}. Over time, the soil acidified**.** Experimental plots were limed to raise the soil pH to 6.0-6.5. In 1996, 5604 kg ha^{-1} of effective calcium carbonate equivalent (ECCE) was added to all plots on the east half (split plot). In 1998, lime was applied again to the east half of the split plots, but was varied with N rates as follows: to plots that had not been fertilized with N, no extra lime was added; to plots that had received 112 kg and 168 kg of N, 2242 kg ha^{-1} of ECCE was added; while plots that had been fertilized at a rate of 224 kg, 336 kg, and 448 kg ha^{-1} of N, 3362 kg, 4483 kg, and 5604 kg ha^{-1} respectively of ECCE was added. In 2004, lime was applied at a rate of 2242 kg ha^{-1} to all of the east side plots.

Top soil pH was measured twice every season: at the start and at the end of the season. The pH value used is the average of the two measurements. Soil pH was determined in a 1:2 soil/water suspension. The pH reading was then taken using a glass electrode on a pH meter. Observations of soil pH in 1994 and 2003 were missing from the dataset. They were estimated as an average of the previous and subsequent year observations measured on the same plot. Forage yields were determined by clipping from individual plots that were 3.6 by 4 meters. Plots were clipped multiple times to simulate grazing. Yearly dry matter forage yields were the sum of all clippings for that year. Additional information regarding the experiment can be found in Altom et al. (1996). A total of 1261 observations were collected from the experiment; 270 of which were observations for fall N application, 449 for spring N application and 542 for split N application.

b). Theoretical Models

(I) Rye-ryegrass response to lime and nitrogen

Crop response to lime is principally a response to pH and the related secondary benefits (Haynes and Ludecke, 1981). In this study, rye-ryegrass yield response is represented as a function of soil pH and applied N. Agronomic studies suggest that crop response to a factor is observed when the input is limiting. That is, crops will respond to lime applications only if pH levels are limiting crop performance. This physiological concept is described by the limiting linear response plateau (LRP) model (Ackello-Ogutu et al., 1985; Paris, 1992). For yield response to soil pH, Adams (1984) observed that the function should exhibit decreasing marginal return to lime and/or that the plateau yield should begin somewhere below pH 7. These characteristics are exhibited by the quadratic and linear response plateau functions.

Mahler and McDole (1987) addressed a similar issue. They used 5 years of data and fit quadratic and linear plateau models consisting of intersecting straight lines for wheat, barley, pea, and lentil yield response to artificially acidified soils in northern Idaho. They described the knot point of the linear response and plateau model as the minimum soil pH required to reach the plateau yield. Their findings showed that the LRP model provided a better representation of data than the quadratic model. Lukin and Epplin (2003) used 4 years of wheat yield data obtained from a lime rate experiment in Oklahoma. They fit linear response plateau, quadratic and quadratic plateau models and found that plateau functions produced soil pH estimates that were more rational from the agronomic point of view.

A linear response plateau (LRP) function and a quadratic function are considered in this study. Following Tembo et al., (2008), the hypotheses on whether the plateau yield of the LRP is stochastic or deterministic was tested. A non-stochastic linear response plateau model involving N and pH with N timing variables is specified as

$$(1) \qquad y_{it} = \min(\beta_0 + (\beta_1 + \beta_2 Split_i + \beta_3 Spring_i) N_{it}, \gamma_0 + \gamma_1 pH, P_{it}) + u_t + \varepsilon_{it},$$

where y_{it} is the forage yield from the i^{th} plot in year t, N_{it} is the level of N fertilizer, pH_{it} is the pH level, $Split_i$ is a split N application dummy variable ($Split_i = 1$ if N was applied in two splits: fall and spring, zero otherwise), $Spring_i$ is a spring application dummy variable ($Spring_i = 1$ if all N was applied in spring, zero otherwise), P_{it} is expected plateau yield, u_t is the (intercept) year random effect, and ε_{it} is a random error term. The parameters β_0 and γ_0, are responses at the origin, β_1 is a linear slope parameter of N application, and γ_1 is a linear slope parameter of soil pH. The random parameters u_t and ε_{it} are normally distributed and uncorrelated. Equation (1) suggests that at the plateau yield P_{it}, the factors N and pH are no longer limiting and do not affect crop yield (Paris, 1992).

The assumption behind the non-stochastic LRP is that all factors that define plateau yield are fixed and completely controllable. With the stochastic linear response plateau model of Tembo et al. (2008), the plateau itself becomes a random variable that varies by year depending on growing conditions. The effect of soil pH is not expected to be affected by growing conditions in a given year. That is, the plateau yield is stochastic with respect to N but not with respect to soil pH. When growing conditions are favorable in a given year, the plateau yield increases as does the amount of N that the plant can use. Under this consideration, we specify a new version of a stochastic LRP model as

$$y_{it} = \min(\gamma_0 + \gamma_1 pH_{it}, 1)\min(\beta_0 + (\beta_1 + \beta_2 Split_i + \beta_3 Spring_i)N_{it}, P_{it} + v_t) + u_t + \varepsilon_{it} \tag{2}$$

where the first bracket parameters define a deterministic plateau for soil *pH*, and the second bracket defines forage yield response to N with a stochastic plateau. The parameter v_t is the plateau year random effect. The random parameters v_t, u_t and ε_{it} are normally distributed and uncorrelated. Unlike the model by Tembo et al. (2008), equation (1) is not nested in (2).

A quadratic response model is also estimated[4]:

$$y_{it} = \alpha_0 + \alpha_1 pH_{it} + \alpha_2 pH_{it}^2 + \alpha_3 N_{it} + \alpha_4 N_{it}^2 + \alpha_5 Split_i * N_{it} + \alpha_6 Spring_i * N_{it} + u_t + \varepsilon_{it} \tag{3}$$

where α_0 is the response parameter at the origin, α_1 and α_3 are slope parameters, α_2 and α_4 are quadratic parameters, α_5 and α_6 are N timing slope dummy variables, u_t is year random effect, and ε_{it} the random error term.

[4] An interaction term between nitrogen and soil pH was not included (even though it was statistically significant) because doing so yielded an estimated model that was not concave with the second order derivative conditions for net return maximization not holding so that the optimal solution would be infinite N and infinite pH.

(II) Soil pH change model

Soil pH change is a complex phenomenon dependent on both site and management factors. According to Black (1993) and Mahler and Harder (1984), change in soil pH over time is a function of crop uptake, N acidification, leaching, and the soil's buffering capacity. Gasser (1973) showed that the rate of pH change varies with initial soil pH. Empirical models estimated by Goulding et al. (1989) also showed that the magnitude and duration of the effect of lime varies by initial soil pH, fertilizer additions, and crop grown.

Soil pH change was modeled as a function of N fertilizer inputs, lime, initial soil pH, and a time trend[5]. For a multiple application model, the total effect of lime and N applications accumulates the effects of all previous applications. The cumulative effect of lime and N applications on soil pH change over *T* years is represented as:

(4)

$$\Delta pH_{it} = \eta_0 + \eta_1 \sum_{k=0}^{t} LR_{it-k} + \eta_2 \sum_{k=0}^{t} N_{it-k} + (\eta_3 + \eta_4 Split_i + \eta_5 Spring_i) \sum_{k=0}^{t} N_{it-k}^2 + \eta_6 T_t + S_i + u_t + \varepsilon_{it}$$

where ΔpH_{it} is the difference between pH at time t (pH_t) in the i^{th} plot and pH_0 at the start of the experiment in 1993, LR_t is the lime rate in year t, T is the time trend variable (T=1,…,14), u_t is year random effect, S_i is plot random effect included to account for potential measurement errors in initial pH (pH_0), and ε_{it} is the random error term. Equation (4) is dynamic, with initial soil pH included. The sum of the square of N is

[5] Forage yield was not included in the estimated model as an independent variable because it proved to be highly collinear with N and insignificant.

included as an independent variable to capture the possible effect of excess N fertilization on soil pH. The interaction between N squared term and seasonal N application dummy variables are included to account for the effect of N timing on soil acidification due to excess N (slope dummies for the linear term were not statistically significant).

(III) Quantity of lime required to neutralize the acidifying effect of nitrogen

The acidifying effect of N fertilizer is estimated in equation (4). The quantities of lime required to neutralize this acidity can be calculated. Most soil testing laboratories use a special buffered solution to measure exchangeable acidity. By calibrating pH changes in the buffered solution with known amounts of acid, the amount of lime required to bring the soil to a particular pH can be determined.

Pierre et al. (1971) and Gasser (1973) showed that the theoretical requirement of lime required to neutralize the acidity produced from fertilizer N inputs is 3.6 kg calcium carbonate for 1 kg N applied as ammonium nitrate, and 7. 2 kg calcium carbonate for 1 kg N applied as ammonium sulphate. Archer's (1985) study of forage grasses, found that 200-300 kg of calcium carbonate are required to neutralize the acidifying effect of 100 kg N applied as ammonium nitrate or urea, and 500- 700 kg of calcium carbonate if N fertilizer is applied as ammonium sulphate.

The actual lime needed to neutralize acidity from N fertilizer inputs is likely less than the theoretical requirement because some ammonium and nitrate are lost by other processes such as volatilization, denitrification, and microbial fixation (Chambers and Garwood, 1998). In this study, the acidity from N fertilizer is measured by determining the quantity of lime required to neutralize this acidity. To simplify the derivation, we assume all N was applied in the fall, but the same approach can be extended to the case where all N was applied in the spring and split (spring and fall) applications. Abstracting from (4), at constant soil pH:

$$(5) \qquad \eta_1 L + \eta_2 N + \eta_3 N^2 = 0.$$

The quantity of lime (L) required to neutralize acidity from a given amount of N fertilizer is then calculated as:

$$(6) \qquad L = [\eta_2 N + \eta_3 N^2] / \eta_1.$$

This quantity of agricultural lime is the amount required to offset acidity produced by application of N fertilizer. When (6) is evaluated at the optimum N level, the quantity of lime required to keep soil pH constant is obtained[6].

From (6), the marginal effect of N on the amount of lime required is:

$$(7) \qquad \partial L / \partial N = [(\eta_2 + 2\eta_3 N) / \eta_1].$$

The cost of liming due to N fertilization is obtained by multiplying (7) by the unit cost of liming. This economic consideration suggests that for every kg of N fertilizer applied, a cost is incurred by the producer in liming to offset the acidity created.

(c) Economic evaluation

The producer's expected net return (NR) maximization is defined as

$$(8) \qquad \max_N E[NR] = p_y E[y(N, pH)] - w(N)N$$

$$\text{s.t. } pH = pH^*, \text{ and } w(N) = r_n + [(\eta_2 + 2\eta_3 N) / \eta_1] p_l,$$

---

[6] Lukin and Epplin (2002) determined the optimal level of lime and liming frequency using dynamic programming (DP). A DP model was estimated, but application timing varies considerably depending on initial pH, and such results would be more difficult to communicate. The long run effect from DP, however, is not substantially different from the results reported in this study.

where p_y is the price of forage, p_l is the unit cost of lime, pH^* is the optimal pH level, and $w(N)$ is the cost of N which is split into the unit buy price of N (r_n) and the cost of liming due to N acidification defined from (7) as $[(\eta_2 + 2\eta_3 N)/\eta_1]p_l$. To determine the effect of considering the cost of lime on recommendations about the optimal level of N, (8) is evaluated when $w(N) = r_n$ (ignoring the cost of liming) and when $w(N) = r_n + [(\eta_2 + 2\eta_3 N)/\eta_1]p_l$.

Yield expectation in (8) is obtained by taking the expectation of the production function $y(N, pH)$. For the quadratic yield function, a solution to (8) is obtained by marginal analysis since (3) is continuously differentiable. With the non-stochastic LRP, the function is continuous, but its derivatives do not exist with respect to either its parameters or the inputs (*N* and *pH*) at the knot point where the response and the plateau are joined. Optimal level of N (N^*) will be at the knot point or at zero. Thus, yield maximizing and net revenue maximizing level of N are the same except in the case where the value marginal product of N is less than the marginal factor cost of N. Considering the case where all N was applied in fall and assuming zero is not optimal, the optimal level of N with a non-stochastic LRP is $N^* = (P - \beta_0)/\beta_1$, and enough lime needs to be applied to reach the optimal pH of $pH^* = (P - \gamma_0)/\gamma_1$.

For the stochastic LRP, the random variable v_t is nonlinear in the yield function (2), and therefore does not drop out after taking expectation as does the variable u_t. The expectation of $y(N, pH)$ in (8) becomes

(9) $$E[y] = E[\min(\gamma_0 + \gamma_1 pH, 1)\min(\beta_0 + \beta_1 N, P + v)].$$

Optimal soil pH is $pH^* = (1-\gamma_0)/\gamma_1$. Note that at pH^*, the term $\min(\gamma_0 + \gamma_1 pH, 1)$ equals one such that (9) reduces to

$$E[y] = E[\min(\beta_0 + \beta_1 N, P + v)]. \quad (10)$$

The expectation in (10) defines an integral with respect to v that must be solved numerically to obtain N^*. The approach developed by Tembo et al. (2008) was used to solve the integral, and involves evaluating a univariate normal probability density, and obtaining N^* by marginal analysis. Tembo et al. (2008) showed that the expectation in (10) becomes

$$E[y] = [(1-F)(\beta_0 + \beta_1 N) + F(P - \sigma_v f / F)] \quad (11)$$

where F is the normal cumulative distribution with the argument $\beta_0 + \beta_1 N$, mean P, and variance v; f is the probability density function (pdf) of F, and σ_v is the standard deviation of v. The term $(1-F)$ in (11) is the probability of being above the plateau, and the term $F(P_t - \sigma_v f / F)$ is the contribution to the expected value when below the mean plateau yield.

Substituting (11) into (8), the expected net return function becomes

$$E[NR] = p_y[(1-F)(\beta_0 + \beta_1 N) + F(P - \sigma_v f / F)] - w(N)N - p_l L. \quad (12)$$

The function defined in (12) is concave with respect to N. By differentiating[7] (12) with respect to *N* and setting the derivative equal to zero, N^* is obtained:

$$N^* = \frac{1}{\beta_1}[P_t - \beta_0 + \sigma_v G^{-1}(1 - w(N)/p_y \beta_1]. \quad (13)$$

---

[7] By the chain rule, the first derivative of (12) with respect to *N* is equal to $p_y \beta_1 (1-F) - w(N) = 0$, and the second derivative $-p_y \beta_1^2 f / \sigma_v < 0$ is satisfied.

The term $G^{-1}(1 - w(N)/p_y\beta_1)$ is the inverse standard normal cumulative distribution, which is approximated using *Z* statistical tables or statistical software. When $w(N) = r_n$, a consistent estimate of N^* is obtained directly in (13) by substituting the parameters $\beta_0, \beta_1, P,$ and σ_v by their estimated values, and the input and output prices by their market values. When $w(N) = r_n + [(\eta_2 + \eta_3 N)/\eta_1]p_l$, N^* is found numerically by a graphical grid search.

The profit function in (8) is evaluated using 2010 input and output prices. Input prices for N and lime were taken from fertilizer suppliers located in south-central Oklahoma. The price of N is \$0.99 kg^{-1}, and the cost of liming, including application, is approximately \$.035 kg^{-1} of 100% ECCE. The price of forage is determined as the cost of beef gain per kilogram divided by the kilograms of forage required by a stocker animal to produce a 1-kg gain. Based on the National Research Council (1984), net energy equations used to estimate livestock requirements, Ishrat, et al. (2003) and Krenzer et al. (1996), showed that 1 kg of beef gain requires 10 kg (dry matter) of standing forage. In the southern plains, the cost per kg of gain has ranged from \$0.71 kg^{-1} since 2005 to \$1.21 kg^{-1} in 2010, which is approximately \$0.96 kg^{-1} gain on average. At the cost of beef gain per kg of \$0.96, the price per kg of forage is \$0.96/10=\$0.096.

(d) Estimation of models

The three models (1)-(3) of rye-ryegrass yield response to N and soil pH were estimated using the SAS NLMIXED procedure (SAS Institute Inc., 2003) which maximizes the marginal log-likelihood function. The random error term and intercept year random effect enter the equations linearly, but the plateau year random effect in the stochastic LRP enters the equation nonlinearly. The marginal log-likelihoods of the models have no closed form and can only be approximated numerically. As is common in nonlinear optimization, convergence of the models to global maxima is not guaranteed.

To achieve convergence, three efforts were employed: data scaling, varying starting points, and using different optimization techniques available in SAS. Adaptive Gaussian quadrature was used to approximate the likelihood function integrals, and the function was maximized by the trust region optimization technique. Other optimization techniques that enabled convergence were the Newton Raphson method with ridging and quasi-Newton (SAS Institute Inc. 2003). The linear regression model of soil pH change (equation 4) was estimated using the SAS Mixed procedure using maximum likelihood (SAS Institute Inc., 2003).

Results and discussion

Descriptive statistics

Average annual soil pH changes in limed and unlimed plots during the study period are shown in figure 1. Figure 1 shows that on limed plots, the magnitude and effect of lime application on soil pH varied with initial pH. On plots that received lime, pH increased after lime treatments, and then gradually declined over the study period. Soil pH on the control treatments (no lime) decreased, but the rate of decrease from year to year was slight. Pairwise comparisons based on least significant differences (LSD) showing the years in which soil pH change was significant are presented in Table 1. Changes in the pH of soil samples from year to year confirm acidification progressed.

The relationship between N rate and soil acidification level is shown in figure 2. Figure 2 shows that the pH on both limed and unlimed plots decreased with increasing N fertilization rate. Pairwise comparisons based on LSD show mean pH in limed plots differed significantly (α=0.05) from plots that were not limed for all nitrogen application rates (Table 2). Mean pH in limed (not limed) plots that were fertilized with up to 224 kg ha^{-1} of N was not significantly different (α=0.05) from limed (not limed) plots that received zero N rate.

Average rye-ryegrass yield response to N is shown in figure 3, and the relationship between soil pH levels and rye-ryegrass forage yields is shown in figure 4. Figure 3 suggests that lime treatments influenced forage yield. LSD comparisons (Table 2), however, indicate yields in lime treated and not treated plots were only significantly different (α=0.05) at nitrogen application rates of 224 kg ha^{-1} and above (Table 2). Data presented in figure 4 show increased yield response of rye-ryegrass to soil pH well beyond the current recommendation of 5.5.

Results from the regression of rye-ryegrass yield models

The estimated parameters for the yield functions are reported in Tables 3 and 4. Parameter estimates of N and pH effect on rye-ryegrass yield have the expected signs and are statistically significant (P <0.01) based on the Wald t tests. Parameter estimates of spring and split applications from the yield regression models are not significant (P < 0.05) in the quadratic and stochastic LRP. This result suggests that applying all N prior to planting rye-ryegrass in the fall yielded similar forage yield as split or spring applications of N.

To find the yield functional form that fit the data best, the estimated yield models were compared using the likelihood dominance criterion (LDC) of Pollak and Wales (1991). The LDC provides a rationale to compare two models based on the difference in log-likelihood values, with adjustments for differences in the number of parameters, and for a given level of significance (Pollak and Wales, 1991). Hypothesis testing according to the LDC favors the stochastic LRP model against the non-stochastic LRP model, and the non-stochastic LRP is favored against the quadratic model. A graphical representation of the dataset in Figure 3 provides further evidence of why a quadratic model fit our data poorly. Our conclusions are based on the model that fit the data best, the stochastic LRP.

Results of optimal N and pH are calculated assuming all N was applied in fall. Seasonal N dummy variables shift the slope on N. If we are to consider spring application, or split application, the estimated slope on N would shift by the added parameter of spring or split application. In our recommendations of optimal N and pH from the stochastic linear response plateau model, we do not consider spring or split applications since the estimated parameters are not significantly different from zero.

The estimated soil pH levels (pH^*) for which expected maximum yield can be obtained are different for the models, but within the range of agronomic recommendations for forage grasses. As expected, the estimated pH level necessary to reach maximum yield was highest with the quadratic model. From estimates of the quadratic model, soil pH level of at least 7.19 would be required to obtain maximum yield. With the non-stochastic LRP model, a pH level of at least 6.06 would be required to obtain plateau yield, while for the stochastic LRP, a pH level of at least 5.88 is required to obtain average expected plateau yield.

The Oklahoma Cooperative Extension Service currently recommends lime for forage production when soil pH is below 5.5 (Zhang and Raun, 2006). Yield maximizing soil pH levels obtained in this study suggest higher pH recommendations for rye-ryegrass pasture than the current 5.5.

Results from the regression of soil pH change model

Parameter estimates from the regression of soil pH change model (equation 4) are reported in Table 5. All parameter estimates are statistically significant ($P < 0.05$) except the time trend and intercept parameters. The coefficient of the squared term of N is negative which means the rate of acidification increases as the level of N increases. The coefficient of the interaction of cumulative N^2 and spring N application is negative, meaning applying all N in spring increased acidification due to excess N fertilization. N applied in two splits (spring and fall) reduced soil acidification due to excess N fertilization. Presumably, split application reduced the amount of N lost by leaching.

Equivalent acidity and alkalinity estimates show that 100 kg ha^{-1} of N fertilizer applied as ammonium nitrate (34-0-0) will lower the soil pH by 0.00604 pH units, while 100 kg ha^{-1} of 100% ECCE will raise soil pH by 0.0051 pH units in the long run. Estimates in Table 5 were used in equation (6) to determine the equivalent quantity of agricultural lime (100% ECCE) needed to neutralize acidity produced by applying ammonium nitrate fertilizer. From equation (6), if only 1 kg of N fertilizer were applied annually as ammonium nitrate (34-0-0), 1.2 kg ha^{-1} of 100% ECCE would be required to neutralize the acidifying effect of N. The negative coefficient on the quadratic term for N indicates that proportionally more lime is required for higher levels of N. For example, 173.0 kg ha^{-1} of 100% ECCE is required to neutralize the acidifying effect from 100 kg ha^{-1} of N applied as ammonium nitrate (34-0-0). Model predictions found in this study compare well with findings by Adams (1984) and Pierre et al. (1971) who found that soil acidification due to N fertilizer is about one half of the theoretical estimate.

Estimates of the quantity of lime required to neutralize acidity from various levels of N are presented in Figure 5. From Figure 5, the quantity of lime required to offset acidity from N fertilizer increases nonlinearly as N rate increases. This result suggests that N acidification is more severe with N application amounts above the consumptive potential of the growing plant. This effect may be due to excess nitrates in the soil increasing the potential for leaching. The larger the amount of N fertilizer applied, the larger the percentage lost through leaching and the greater the amount of acidity developed.

Results of this study suggest that minimizing the leaching of NO_3^- by timing and matching fertilizer rates to crop needs during each growing season might substantially reduce acidification due to N fertilization. The cost of liming due to N fertilization was estimated to be $6.74 for 100 kg of applied N, but increases nonlinearly as N increases. In terms of precision agriculture, saving this cost would be an added benefit in addition to the savings in nitrogen fertilizer application or revenues due to yield increase by predicting the nitrogen requirements of the crop in-season using precision sensing systems.

Effect of the cost of lime on nitrogen recommendations and lime requirement

To determine the effect of the cost of liming on the recommended level of N, the expected net return function (equation 8) was solved with, and without, the cost of liming due to N fertilization. Optimal levels of N were noted in both cases, and the effect of the cost of liming on recommendations of optimal levels of N was determined as the difference between the two N levels. Optimal levels of N obtained when the cost of lime is considered are reported in Tables 3 and 4.

With the quadratic model, when the cost of liming is considered, the optimal level of N reduces from 174.1kg ha^{-1} to 156 kg ha^{-1}, which is 10.4% less. With the stochastic LRP model, the optimal level of N reduces by 11.3% from 168 to 149 kg ha^{-1} when the cost of lime is considered. The estimated N^* with estimates of the non-stochastic LRP is 220 kg ha^{-1} with or without considering the cost of liming. That is, at current input and output prices, even when the cost of liming due to N fertilization is considered, the marginal value product (MVP) of N is still greater than the marginal factor cost (MFC) of N. Note that with the nonstochastic LRP, optimal N is either zero (if MVP<MFC) or the level of N required to obtain plateau yield (if MVP>MFC). This means the cost of liming is not large enough to cause MFC>MVP. Current recommendations from the Noble Research Foundation are to apply between 112 to 224 kg ha^{-1}. Based on estimates from the stochastic LRP, optimal N should be 149 kg ha^{-1}.

Optimal levels of N obtained with the specific yield model above were used in (6) to determine the quantity of lime required to keep pH constant at maximum/plateau yield. The lime rates are reported in the respective table of results. Results indicate that with the quadratic model, 318.2 kg $ha^{-1}yr^{-1}$ of lime is required to keep pH constant in relation to annual additions of 156 kg ha^{-1} of N. With the non-stochastic LRP, 526.7 kg $ha^{-1}yr^{-1}$ of lime is required to offset acidity from applications of 220 kg ha^{-1} yr^{-1} of N and keep the pH constant. With the stochastic LRP, the producer will apply 303.8 kg ha^{-1} of lime to offset acidity from annual application of 149 kg ha^{-1} of N. Lime requirements obtained with a stochastic LRP and a quadratic model are very close to the estimates recommended by Bolan et al. (1991).

Conclusion

This study aimed to determine the effect of considering the cost of lime on recommendations about the optimal level of N. To achieve this objective, the study modeled soil pH change in response to N timing and rate, and lime application, and determined the effect of soil pH and N on forage yield.

Optimal levels of N fertilizer and soil pH were greatly affected by the choice of the yield function. The stochastic LRP fit the data best. Considering the cost of lime reduced recommendations about the optimal level of N. At current input and output prices, and based on the stochastic LRP, the optimal level of N was reduced by 11.3 % from 168 kg ha^{-1} yr^{-1} to 149 kg ha^{-1} yr^{-1} by considering the cost of lime due to N fertilization.

Acidification potential due to N fertilizer increased at an increasing rate (nonlinearly) as N rate increased. Nitrogen acidification appears to be more severe with N application amounts above consumptive levels of the crop than with N that is used by the plant. Although the timing of N application had little effect on forage yield, splitting N into two applications for fall and spring may be of benefit by reducing acidification due to excess N fertilization. Minimizing leaching of NO_3^- by matching fertilizer rates to crop requirements would substantially reduce acidification from applying N. Model predictions of N acidification found in this study compared well with theoretical predictions.

Current recommendations of how much N to apply from the Noble Research Foundation for rye-ryegrass pasture are to apply between 112 to 224 kg ha^{-1} yr^{-1}. Based on the estimates of the stochastic LRP, this amount should be adjusted to 149 kg ha^{-1} yr^{-1} with pH at least 5.88.

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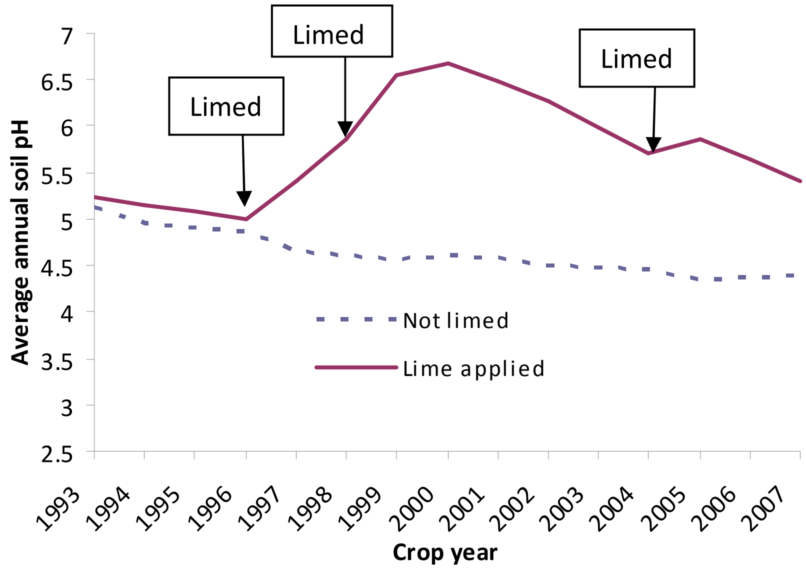

Figure 1. Annual soil pH change over time in limed plots and unlimed plots. Soil pH is the mean of spring and fall measurements averaged over N rate.

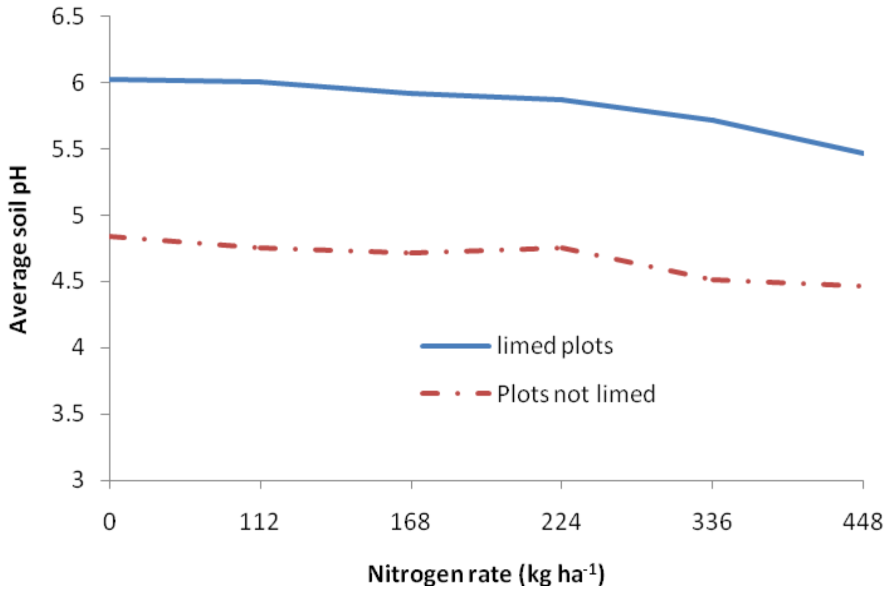

Figure 2. Average soil pH variation with varying levels of applied N fertilizer.

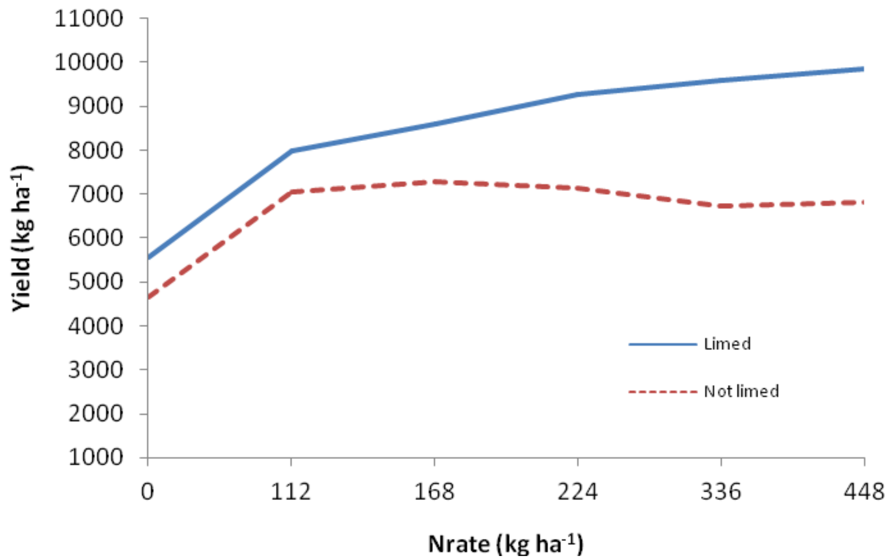

Figure 3. Effect of liming and N fertilization on rye-ryegrass forage yield. Yield is the annual total average over three replications.

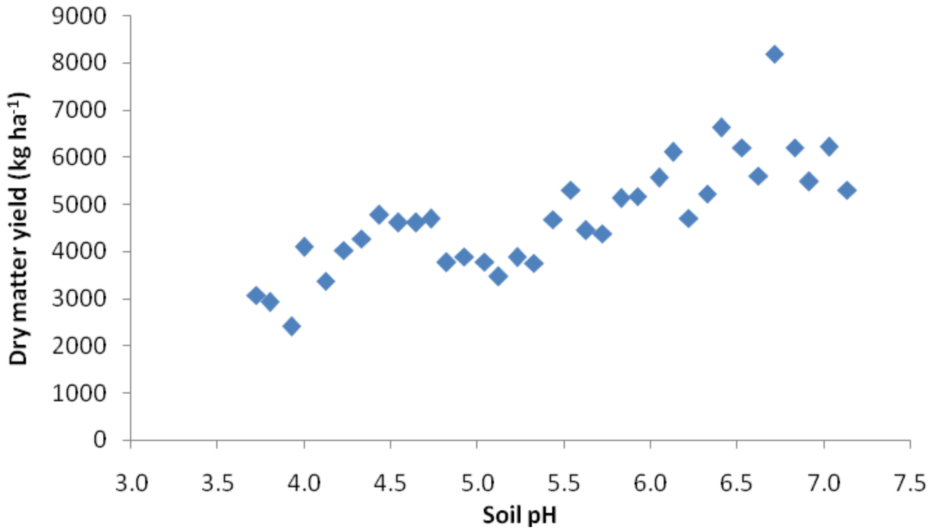

Figure 4. Relationship between annual mean rye-ryegrass forage yield and soil pH.
Note: Soil pH is the mean of spring and fall measurements. Dry matter yield is the annual total average over three replications

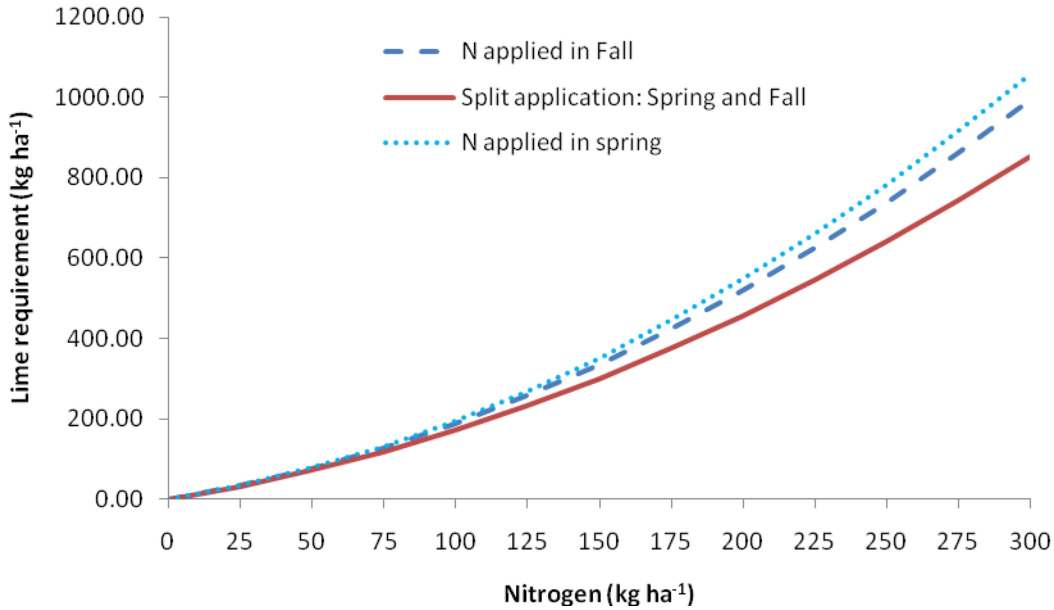

Figure 5. Estimates of quantity of lime needed to neutralize acidity produced by varying levels of ammonium nitrate (34-0-0) fertilizer.

Table 1. Mean estimates of soil pH in limed and unlimed plots across years.

Lime	Crop year									
	1993	**1994**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**
Yes	5.24^{a*}	5.15^{a}	5.08^{b}	5.00^{b}	5.41^{c}	5.85^{e}	6.55^{f}	6.67^{f}	6.48^{f}	6.27^{h}
No	5.12^{a}	4.96^{b}	4.91^{b}	4.86^{b}	4.65^{d}	$4.61^{d,g}$	$4.57^{d,g,m}$	$4.61^{d,g}$	$4.58^{d,g,m}$	$4.50^{g,m}$
	2003	**2004**	**2005**	**2006**	**2007**					
Yes	5.98^{i}	5.70^{j}	5.85^{ek}	5.63^{k}	$5.4^{c,l}$					
No	$4.48^{g,m,n}$	$4.46^{m,n}$	4.35^{n}	4.37^{n}	4.36^{n}					

*Means with a common superscript are not significantly different (α=0.05)

Table 2. Descriptive statistics for effect of N rate, and N rate*lime on pH and yield.

N Rate (kg ha^{-1} yr^{-1})	Lime (kg ha^{-1} yr^{-1})	Soil pH		Forage yield	
		Mean pH (kg ha^{-1} yr^{-1})	SE	Mean yield (kg ha^{-1} yr^{-1})	SE
0	no	4.84^{a*}	0.0705	4646.91^{h*}	527.95
0	yes	6.02^{b}	0.0698	5566.07^{h}	525.04
112	no	4.76^{a}	0.0593	7039.37^{i}	527.95
112	yes	6.01^{b}	0.0593	7974.41^{i,j}	527.95
168	no	4.72^{a}	0.0593	7279.61^{i,j}	527.95
168	yes	5.92^{b}	0.0593	8599.23^{j,k,l}	527.95
224	no	4.75^{a}	0.0491	7130.41^{i}	446.20
224	yes	5.87^{b}	0.0491	9273.71^{k,l}	446.20
336	no	4.52^{c}	0.0498	6729.83^{i}	463.04
336	yes	5.71^{d}	0.0498	9596.97^{l}	463.04
448	no	4.46^{c}	0.0498	6821.7^{i}	463.04
448	yes	5.47^{e}	0.0498	9861.04^{l}	463.04

*Means with a common superscript are not significantly different (α=0.05)

Table 3. Parameter estimates for regressions of rye-ryegrass response to N and soil pH using the linear response plateau (LRP) yield function.

Dependent variable: Yield(1000 kg ha^{-1})		Non-stochastic LRP			Stochastic LRP		
Parameter	Symbol	Estimate	SE	Pr>|t|	Estimate	SE	Pr >|t|
Intercept w/N	β_0	4.51	0.14	<.0001	2.97	0.16	<.0001
N (100 kg ha^{-1})	β_1	1.90	0.21	<.0001	4.29	0.29	<.0001
Intercept w/pH	γ_0	-6.48	0.83	<.0001	-1.00	0.103	<.0001
pH linear slope	γ_1	2.50	0.17	<.0001	0.34	0.02	<.0001
Split N (fall and spring) dummy	β_2	-0.66	0.21	0.0069	-0.48	0.37	0.2119
All N applied in spring dummy	β_3	-0.45	0.21	0.047	-0.54	0.31	0.1042
Plateau yield	P_t	8.69	0.18	<.0001	8.31	0.17	<.0001
Crop year random effect	u_t	13.58	0.37	<.0001	15.23	0.45	<0.0001
Variance of error term	ε_t	3.61	0.14	<.0001	2.61	0.10	<0.0001
Plateau random effect	v_t	-	-		7.01	0.76	<0.0001
Optimal pH	pH^*	6.06	0.12*	<.0001	5.88	0.09	<.0001
Optimal N (100 kg ha^{-1})**	N^*	2.20	0.24	<.0001	1.49		
Optimal Lime (kg ha^{-1} yr^{-1})	L^*	526.68***			303.83		
-2Log likelihood		5286.60			4934.40		

* Standard errors of N^* and pH^* were calculated by the delta method.

**Price of N $0.99 kg^{-1}, cost of liming $.035 kg^{-1}, and price of forage $0.096 kg^{-1}.

***Optimal lime rates were calculated based on N^* obtained for the specific yield function.

Table 4. Parameter estimates for regressions of rye-ryegrass response to N and soil pH using the quadratic yield function.

Dependent variable: Yield (1000 kg ha^{-1})				
Parameter	Symbol	Estimate	SE	Pr>|t|
Intercept	α_0	-18.81	3.29	0.0001
N (100 kg ha^{-1})	α_1	1.91	0.17	<0.0001
N^2	α_2	-0.25	0.03	<0.0001
pH	α_3	7.43	1.22	<0.0001
pH^2	α_4	-0.52	0.11	0.0007
Split N (fall and spring) dummy	α_5	-0.02	0.06	0.7354
All N applied in spring dummy	α_6	0.03	0.05	0.6529
Crop year random effect	u_t	9.20	0.34	<0.0001
Variance of error term	ε_t	4.05	0.18	<0.0001
Optimal pH	pH^*	7.19	0.38	<0.0001
Optimal N (100 kg ha^{-1})	N^*	1.56	0.15	<0.0001
Optimal Lime (kg ha^{-1} yr^{-1})	L^*	318.21		
-2Log likelihood		5367.80		

Table 5. Parameter estimates of the regression of soil pH change.

Dependent variable: ΔpHt				
Parameter	Symbol	Estimate	SE	Pr > |t|
Intercept	η_0	1.068	0.522	0.1776
Cumulative lime (kg ha^{-1})	η_1	5.1E-5	1.9E-5	0.0069
Cumulative N (kg ha^{-1})	η_2	-6.0E-6	2.9E-5	0.0338
Cumulative N^2	η_3	-3.62E-7	0.00000	<0.0001
Time trend	η_4	-0.05	0.052	0.3446
Cumulative N^2*FS	η_5	7.98E-8	0.00000	<0.0001
Cumulative N^2*S	η_6	-3.61E-8	0.00000	<0.0001
Variance of error term	u_t	0.12310		
Year random effect	ε_t	0.23730		
Plot random effect	s_i	0.00412		
-2Loglikelihood value		449.50		

ESSAY III

VERTICAL INTEGRATION IN WEST AFRICA'S COTTON INDUSTRY: IMPLICATIONS FOR PRODUCERS' INCOME AND ECONOMIC EFFICIENCY

Abstract:

This study provides an economic explanation of the preference for vertically integrated monopsonies in the cotton sector of West Africa, and contrasts monopsony with other market structure alternatives in terms of welfare and sector efficiency. Based on a principal agent framework, in the presence of credit and or factor market constraints, as well as capital market failure, the integrator increases sector welfare and efficiency by supplying inputs on credit. Equilibrium outcomes with the principle agent model indicate that under the parastatal vertical integration market structure, growers receive the reservation income to participate in cotton production. Free markets entail more equitable distribution of benefits than with parastatal vertical integration or competition-monopsony market structures. Since most producers are credit constrained, removing the integrated cotton parastatals in favor of competitive market structures would result in little cotton being grown and reduce social welfare. The basic policy implication is that promotion of a competitive market system will not support cotton productivity growth unless stakeholders pursue complementary programs to develop national input supply systems and credit markets.

Introduction

The cotton sector has often been considered a role model for agriculture commercialization and industrialization in West Africa's cotton producing countries: Benin, Burkina Faso, Chad and Mali[8]. The sector was built around public cotton (parastatal) companies that are vertically integrated (Badiane et al. 2002; Tschirley et al. 2009). Historically, vertical coordination between growers and cotton companies took the form of contractual arrangements. Cotton companies provide major non-labor inputs (seed, pesticides, fertilizers, and extension services) and purchase all cotton produced by farmers at guaranteed prices (Badiane et al. 2002). Growers cultivate cotton and deliver the harvest to the cotton company to repay the input credit. The parastatal cotton industry model promoted cotton cultivation and facilitated the sector's growth after independence in the early 1960's (Badiane et al. 2002; Baffe 2007).

Despite the success in promoting cotton cultivation, the state-led contract production model was criticized for being inefficient and for paying producers prices considered to be below the competitive level (Pursell and Diop 1998; World Bank 2000; Badiane et al. 2002). In the early 1990's, these criticisms led to structural reforms[9] supported by the World Bank, International Monetary Fund and other donor institutions (Baffe 2007; Tschirley et al. 2007). Elsewhere in sub-Saharan Africa, the case for reform was made in other cash crop sectors including coffee, cocoa, and cashew that received government support. With a central emphasis on market forces, these reforms have

[8] These countries are often referred to as the West African cotton four (C-4) because of the significance of cotton to their economies. They also utilize a common currency, the CFA franc which is fixed against the euro.

[9] The reforms mainly included reducing government support programs in the input and output markets; developing private-sector based markets and building the technical and commercial capacities of producer associations.

attempted to promote a competitive agricultural sector with less government involvement. Competition is expected to increase producer prices and spur production at the farm level. The nature and pace of implementation of the reforms has varied from country to country, but have mostly been slow and less far reaching, especially in Francophone West Africa (Tschirley et al. 2008, 2009).

West African governments (except Chad[10]) partially liberalized the cotton sectors and allowed the entry of two to three new ginning[11] companies (in each country) operating as monopsonies over geographic cotton producing areas. The parastatal industry structure has, however, been maintained with many of the popular characteristics of the traditional model preserved. The role of government in decision making has been reduced and producers' involvement and share holding in cotton companies increased. Farmers have been organized into regional and national producer organizations to have power when bargaining for cotton prices and other contractual production terms (Poulton et al. 2004; Baffe 2007; Tschirley et al. 2008). The parastatal industry model was maintained because of the benefits it provides, including its ability to reduce producer price risk, credit facilitation, and technology transfer (Kaminski et al. 2009). The recent increase in cotton production within the region has been attributed partly to the implemented reforms (Fadiga et al. 2005; Kaminski et al. 2009). The increase in production may also have been propelled by other factors such as the recent world cotton price increase (Figure 1).

[10] In Chad, the momentum for reform has weakened following the country's discovery of crude oil. Crude oil has displaced cotton as the main source of export revenue for the government, and has caused government energy and attention to focus away from the cotton sector (Baffe 2007).

[11] In Benin, three more companies were recently allowed to operate gins and market cotton.

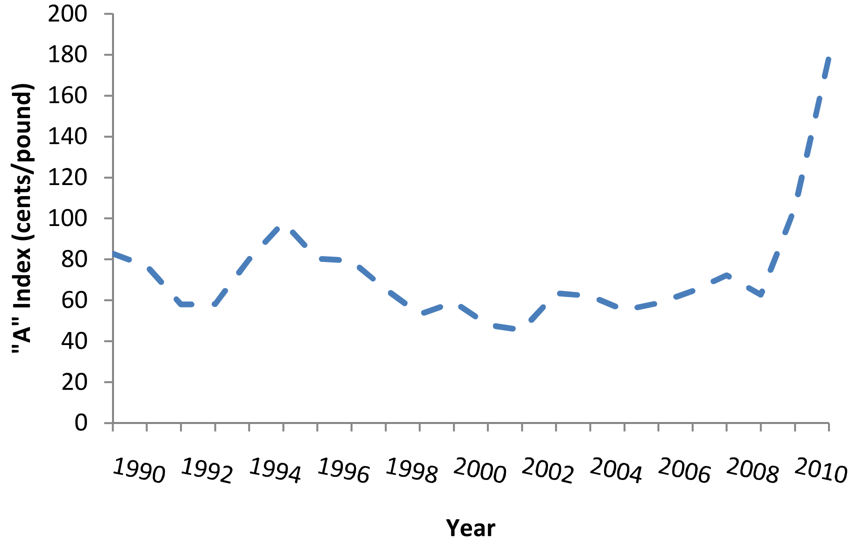

Figure 1. World price of cotton. ("A" Index is a proxy of world price of cotton). Source: National Cotton Council of America, 2011.

Despite the economic reforms, there still remains controversy regarding the parastatal vertical integration industry model. Growers still complain about the level of producer prices received as a percentage of world prices of cotton (Badiane et al. 2002; Fadiga et al. 2005; Sumner 2006; Tschirley et al. 2009), and that the gains from contract arrangements accrue largely to cotton companies while growers receive small returns (Tschirley et al. 2009). Price competition between cotton companies that could ultimately result in better prices for farmers is limited by government regulations. A commonly asked question is whether the parastatal vertical integration industry model is able to align the incentives of industry participants so that market efficiency and welfare of the participants within the sector improves (Tschirley et al. 2008, 2009). Can the current industry organization framework be justified as a viable alternative? Or, would other restructuring alternatives provide more benefits? There is also growing public concern that leaving control of the input market in the hands of cotton companies could potentially 'crowd out' private (commercial) actors which could hinder the development of private input markets and lower overall fertilizer use especially on food crops (Kelly 2006; Xu et al. 2009).

Legislation and policies to overcome some of these concerns are being contemplated or developed in individual countries. One policy option is to break up the vertically integrated cotton parastatal market structure in favor of free[12] markets in the input and output sectors (Tschirley et al. 2008). Another is to allow perfect competition (with imperfect credit and factor markets) in the input market and monopsony in the output market (Tschirley et al. 2009), or to maintain the status quo (Kaminski et al 2009; Tschirley et al. 2008, 2009). The monopoly (input market)–monopsony (output market) market structure[13] is one other possible alternative market structure that could emerge following the removal of the vertically integrated cotton parastatals. These policies may have significant welfare costs or benefits depending on how the current industry model impacts producers' welfare and sector economic efficiency. An important need is research to understand the link between the parastatal vertical integration and producer's net return to determine whether there is an economic basis for public concern regarding the parastatal vertical integration market structure.

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[12] Note that the free market structure alternative being proposed would still be characterized by credit, factor market and institutional constraints inherent in most developing countries.

[13] The monopoly-monopsony market structure could potentially lead to "double marginalization" of producers (See Tirole 1988). Because the monopsonist and monopolist sectors independently engage in noncompetitive pricing behavior, traders in each industry only see the effect of their pricing on their own profits (Tirole 1988). Monopolistic traders have incentives to charge prices that are above competitive levels. This could reduce input demand, lower farm productivity and hence farm supply. The monopsonist would exert market power by lowering producer prices below competitive levels. At the aggregate level, the monopoly-monopsony market structure could reduce social welfare and lead to potential dead weight loss relative to the current parastatal industry model. We do not consider this market structure as a viable alternative to the parastatal market structure and hence do not discuss it further in this study.

This paper provides an economic explanation of why West African countries have selected the existing market organization in the cotton sector. The specific objective is to determine the potential benefits and costs of removing the parastatal vertical integration market structure in favor of the proposed market structure alternatives. The analysis is supported by a conceptual model which takes into account the specific institutional features of the Burkina Faso and Malian cotton sectors, while the analysis and discussion is intended to be broader.

Background

Proponents of liberalization often argue that economic theory suggests that free markets should create positive effects of welfare increase and efficiency improvement in the reformed sectors (World Bank 2000). The basic theoretical argument is that competition should reduce monopolistic traders' profits, increase producer prices and spur production as farmers respond to better prices. A major shortcoming of this argument is that it assumes factor markets work well and that contracts are enforced; that is, there is no market and institutional failures. Perfect competition is best when it is possible and there is no market failure. However, the assumption of no market failures is not realistic in many developing countries, and affects producers' response to price incentives. It is essential to consider market failures in market policy design since they affect how surplus is created and distributed among sector agents.

Liberalization policies advocated by donor institutions and governments often center on "getting prices right" by aligning domestic commodity prices with world prices with a view of gaining efficiency (World Bank 2000). This policy objective has changed over time, largely in response to poor economic performance in most developing countries (Timmer 1995). Institutional and structural barriers in many developing economies do not allow price policies to work well. These barriers have refocused development efforts on the need for good institutions to pave the way for price policies. According to Timmer (1986), price liberalization policies require good institutions to work well.

Empirical evidence on the effects of market reforms in sub-Saharan Africa is mixed. In countries where competitive spot markets have emerged following liberalization (e.g. Uganda, Tanzania and Ghana), increased output prices and significant reduction in production have been observed (Poulton et al. 2004; Winter-Nelson and Temu 2002; Gorex 2003; Makdissi and Wodon 2005). Field data from these countries suggest production fell due to declining input use, and lack of extension services which affected farm productivity (Tschirley et al. 2009; Winter-Nelson and Temu 2002). Empirical evidence indicates farm productivity is higher among West Africa's C-4 countries compared to countries that completely liberalized such as Uganda, and Tanzania (Figure 2).

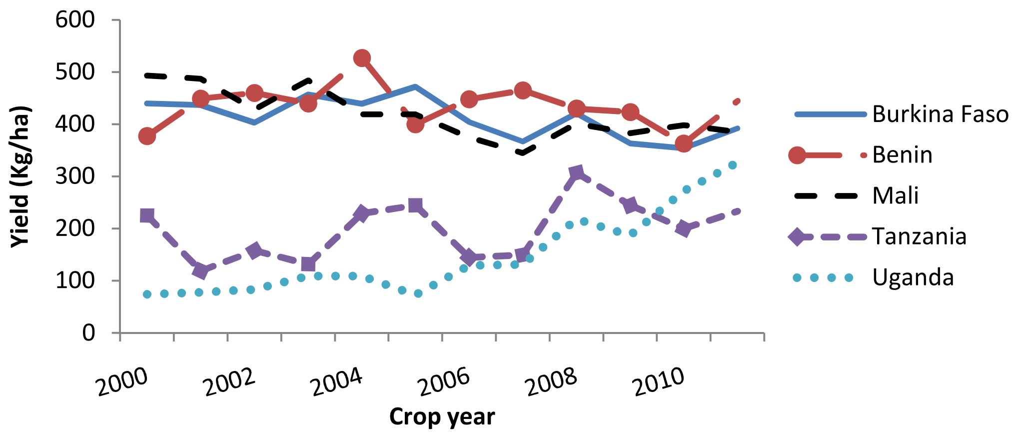

Figure 2: Farm productivity in selected countries. Yield is expressed in lint equivalent. Data is from USDA Foreign Agriculture Services

Declining input use has largely been attributed to constraints in factor markets, especially credit constraints and or missing input markets (Goreux 2003; Poulton et al. 2004). While input markets are in general not all together missing in rural West Africa and sub-Saharan Africa, high transport costs, price risk, unfavorable weather, and illiteracy in the farming community limit participation. Even cotton farmers who have the money to purchase inputs may find it difficult to obtain them when aggregate local demand is not sufficient to attract private traders to remote locations. This is especially true when demand is spatially dispersed and unpredictable-a typical case in sub-Saharan Africa.

Soil scientists point out that nutrients in African soils are being depleted because of continuous cropping without proper soil husbandry (Voortman, Sonneveld, and Keyzer 2000; Yanggen et al. 1998), suggesting the need to use inorganic fertilizers if agricultural productivity is to be increased or to even maintain current productivity levels. Cotton, in particular, requires significant investments for profitable and sustainable production. Investment is required to provide inputs on an annual basis, in the medium term to provide credit for farm equipment, and in the long run for research and development (R&D) to maintain productivity and improve land husbandry. Producers' ability to purchase inputs in competitive spot markets is weak because of high poverty levels, especially in rural areas. There is also evidence that risk aversion towards production and price risks inherent in agricultural production reduce producers' incentives to make significant investments in input use (Ellis 1992). Evidence from the field confirms a much lower use of inputs and technology in cereal crops that are privately financed, yet field trials indicate that economic returns to fertilizer, when combined with improved seed and better farming techniques can be high for most food staples (Yanggen et al. 1998; Kelly 2006).

Farmers' capacity to save income from crop sales this season and use it to purchase inputs for next cropping season is weak due to heavy financial obligations. Farmers need money to pay school fees, medical costs, taxes, and sometimes finance family ceremonies such as weddings. The financial obligations pressuring farmers at harvest time are so perverse that staple food prices usually collapse at harvest time in many developing countries. These financial needs also prevent farmers from storing their crop even though returns to storage are known to be high for most cereal crops in sub-Saharan Africa (Stephens and Barrett 2011).

Formal financial lending is nearly non-existent or expensive in many rural areas of West Africa (and generally in most developing countries). Farmers are especially unable to obtain credit because: a) their assets (collateral) are inflexible – held almost exclusively in the form of family land; (b) most farms are relatively small to act as collateral; and c) information asymmetries between growers and lenders lead to problems of adverse selection, moral hazard, or costly verification (Blancard et al. 2006). These problems make borrowing expensive. Moreover, the farmer cannot pledge his future harvest as security to a formal or informal credit institution because of the riskiness of the harvest value.

The private sector has been unwilling or lacks incentives to provide long term investments in the input supply system and in R&D. In 2000 for instance, private-sector investment made only 1.7% of total agricultural R&D spending in sub-Saharan Africa (Pardey et al. 2006). In West Africa, a key disincentive for private agents to provide inputs is anticipation that competitors will free ride on inputs provided (Baffe 2007; Delpierre 2010), which is due partly to the existence of weak (or lack of) institutions for formal contract enforcement in most developing countries (Poulton et al. 2004; Tschirley et al. 2008; Delpierre 2010). The private sector is often guided by short-term profit interests: without long-term vested interests in a sector, traders are unlikely to make the required investments to develop and sustain a sector. Pray, Oehmke, and Naseem (2005) argue that investments in R&D require a certain degree of market power so that companies that invest can reap the benefits from the innovation.

Globally, vertical integration has emerged as a response to growers' credit constraints and in some cases as a way to provide long term investments in sector development and sustainability (Vukina 2001; Sexton et al. 2007; Swinnen and Vandeplas 2010; Ciaian and Swinnen 2009). In West Africa, though criticized, cotton companies have been successful in providing input credit and making long term investments in R&D. Alongside input provision and innovation, institutional organization is also important. Contract vertical integration enables efficient coordination along the production, processing and marketing chain.

Vertical integration is also emerging in the agricultural sectors of many developing countries as a means to provide quality and cost advantages. Evidence suggests integrated cotton companies in West Africa have outperformed other market structures in the sub-Saharan region in terms of lint quality (Tschirley et al. 2009). Lint quality is associated with price premiums and thus increases the prices that integrated cotton companies can pay producers. Monopolies can have cost advantages when there are economies of scale that may reduce transaction costs (Swinnen, Sadler, and

Vandeplas 2007; Ciaian and Swinnen 2009). Swinnen and Vandeplas (2010) observe that if monopoly or monopsony structures contribute to reducing market failures and if transaction costs are substantially lowered, efficiency gains may result from concentrated market structures.

Other studies conclude that oligopsony market structure can be economically efficient for industries that exhibit high transportation costs, large investment into specialized equipment, and specialized needs of processors (Richards, Patterson, and Acharya 2001). In West Africa, economic surplus generated by cotton parastatals has been an engine of economic development, particularly in rural areas. The construction of schools, roads and hospitals and the provision of agricultural extension services have benefited from financial resources provided by cotton parastatals (Tschirley et al. 2009; Vitale et al. 2009).

Despite these benefits, some scholars argue that the linkages associated with concentrated vertical market structures present conditions conducive for monopoly firms to cheat growers through unfair pricing of output and or inputs, or through other contract terms (see Sivramkrishna, and Jyotishi 2008; Swinnen, Sadler, and Vandeplas 2007). These claims are also being made in many emerging and developed countries in the food sector where expansions of supply chains are affecting growers and society as a whole (Reardon et al. 2009). In West Africa, the poor incentive system is said to contribute to allocative inefficiencies and to the persistence of poverty in rural areas. This has led to persistent calls for deeper reforms in the cotton sector with a view to counter the perceived market power of cotton companies. In view of these contrasting outcomes, contradictory policy advices are found in many developing countries. Additional theoretical and empirical insights are needed to guide policy and address some of the current controversies.

Theoretical framework

We develop a theoretical framework based on the fact that small scale producers in developing countries face credit and or factor market constraints. The role played by cotton companies in alleviating these constraints and welfare effects (including distribution) are examined within a principal agent framework. After presenting some theoretical considerations, we calibrate the theoretical model to provide empirical evidence. First we develop producers' response functions.

Producer response functions

Consider a farm household that is endowed with land, $\bar{A}$, labor, $\bar{L}$, and capital, K, available for financing input purchases. A typical farm household in West Africa's C-4 allocates farm resources to the production of crops which mostly are maize, millet, sorghum and cotton. Maize and cotton are usually found in the same cropping system because they require similar levels of rainfall and soil nutrients (Coulibaly 1995; Vitale et al. 2009), yet growers do not necessarily grow both crops. In practice, cotton requires a crop rotation to maintain an adequate soil nutrient balance and to minimize pest pressure. Maize benefits from this rotation by deriving residual benefits from fertilizers applied on cotton. West African farmers typically use a three-year rotation of cotton-maize-maize (Vitale et al 2009; Coulibaly 1995). We do not consider rotation constraints in our framework. For simplicity we consider the two crops: maize and cotton. Let A_i be the acreage allocated to the i^{th} crop (i = c if crop is cotton and i = m if crop is maize),

$q_i = f_i(\boldsymbol{x}_i, l_i)$ the per acre production function with $f_i(.,.)$ a concave function of $\boldsymbol{x_i}$ and l_i, l_i is labor and $\boldsymbol{x}_i$ is a vector of non-labor inputs (including seed, fertilizer, pesticides, and herbicides) used on the i^{th} crop.

The producer's farm profit maximization is:

$$\max_{\boldsymbol{x}_i, l_i, A_i} \pi = \sum_i \{p_i f_i(\boldsymbol{x}_i, l_i) - r\boldsymbol{x_i} - wl_i\} A_i \tag{1}$$

s.t.

$$\sum_i r\boldsymbol{x_i} \leq K$$

$$\sum_i A_i \leq \bar{A}\,;\ \sum_i l_i \leq \bar{L}$$

where p_i is unit price of the i^{th} crop output, w is the wage rate, and $\boldsymbol{r}$ is the price vector of $\boldsymbol{x}$. We assume that the farm household's decisions in (1) are made sequentially: first is to choose input levels and then allocate land, i.e. variable input and land allocation decisions are separable. The maximization in (1) has three constraints that affect producer's responses. First is the credit constraint which restricts payments of purchased inputs to the household's cash on hand, K. The second constraint is land. With competitive markets and regular nonjoint technologies, individual producers choose the profit-maximizing allocations of land subject to the land constraint. The third constraint is labor. This constraint restricts total labor use to the available household labor, $\bar{L}$. The formulation indicates that households are not credit constrained with respect to labor- a typical case in West Africa since farm households rely on family labor. For simplicity, assume that the labor constraint is not binding. Assuming the usual regularity conditions on (1), such as strict concavity hold, solutions to (1) may be obtained.

Focusing on the effect of credit constraints and or factor market constraints, we establish the equilibrium without credit constraints as the reference point. Producer response functions are derived from (1) by Hotelling's lemma. The first order conditions for optimality with respect to $\boldsymbol{x_i}$ and l_i are: $p_i f_{i\boldsymbol{x}} = r$ and $p_i f_{il} = w$, respectively. The first order conditions and the land constraint determine factor demands with a non binding credit constraint obtained in the form: $\boldsymbol{x}_i^* = \boldsymbol{x}_i(p_i, r, w, \bar{A})$, and $l_i^* = l_i(p_i, r, w, \bar{A})$, with supply $q_i^* = q_i(p_i, r, w, \bar{A})$. The maximization in (1) with no credit constraints ensures that inputs are allocated or applied to the level where their marginal value products are equal to their respective market prices. This is the neo-classical equilibrium, and assumes that credit and or factor markets work perfectly.

With credit constraints, the farm profit function is represented by the Lagrangean:

$$L = \sum_{i=1}^{2}\{p_i f_i(\boldsymbol{x}_i, l_i) - r\boldsymbol{x}_i - wl_i - \lambda_i[r\boldsymbol{x}_i - K] + \eta[\bar{A} - \sum_{i=1}^{2} A_i]\} \qquad (2)$$

where λ_i is the shadow price of the credit constraint assuming that *K* makes the credit constraint binding (λ_i> 0), and η the shadow price of land. The shadow price of the credit constraint is crop specific. It is higher for input intensive crops like cotton than for crops like maize that require relatively less purchased inputs. When λ_i >0, the first order conditions in (2) for optimality with respect to $\boldsymbol{x_i}$ and l_i become: $p_i f_{i\boldsymbol{x}} = r(1 + \lambda_i)$ and $p_i f_{il} = w$, respectively. Unlike the case of unconstrained maximization, the first order conditions with a credit constraint indicate that the marginal value product of $\boldsymbol{x}$ (the credit constrained input) is higher than its market price by the value of λ_i. With credit constraints, demand for $\boldsymbol{x}$ and output supply are functions of available capital: $\boldsymbol{x}_i^* = \boldsymbol{x}_i(p_i, r, w, K, \bar{A})$ and $q_i^* = q_i(p_i, r, w, K, \bar{A})$. The household can potentially increase farm profits by increasing the use of inputs up to the point where $p_i f_{i\boldsymbol{x}} = r$, but is prevented by the credit constraint. Credit constraints have an effect of tightening input use while missing input markets may tighten availability. It follows that

$$\boldsymbol{x}_i^* = \boldsymbol{x}_i(p_i, r, w, K, \bar{A}) < \boldsymbol{x}_i^* = \boldsymbol{x}_i(p_i, r, w, \bar{A}) \qquad (3)$$

$$q_i^* = q_i(p_i, r, w, K, \bar{A}) < q_i^* = q_i(p_i, r, w, \bar{A}) \qquad (4).$$

That is, the more producers are credit constrained, the less inputs they apply, and the less the productivity. Field observations indicate (3) and (4) are consistent with empirical studies and reality[14]. In West Africa, this implies that a competitive input market system will not support productivity growth unless stakeholders pursue complementary programs to develop credit markets and the national input supply.

To complete the producer's decision process, we examine the land allocation decision. When both maize and cotton are grown, optimal land allocation is determined by:

$$\frac{\partial \pi_c(p_c, r, w, K, \bar{A})}{\partial A_c} = \frac{\partial \pi_m(p_m, r, w, K, \bar{A})}{\partial A_m} \qquad (5)$$

which are the first order conditions of (1) involving the indirect profit function. Equation (5) indicates that the fixed input, land, is allocated across cropping activities to equalize their shadow prices. Chambers and Just (1989), and Shumway, Pope, and Nash (1984) show that when corner solutions exist, equation (5) still holds, but is replaced by an inequality. This means that the shadow price of land for crops receiving a zero allocation must be less than the shadow price of land for crops receiving a positive allocation. The outcome discussed in (3) through (5) provides incentive for firms such as cotton companies to either provide credit or inputs to producers.

The input subsidy provided by the cotton company relieves the binding credit constraint for cotton growers which allow them to apply inputs at optimal levels. At the farm level, this has the effect of increasing land productivity and the marginal value

[14] The aggregate analogues of the response functions in (3) and (4) can be obtained by integrating farm level responses over all producer types and regions in a given country.

product of land. We assume here that the input credit and technology provided by the cotton company relaxes the constraints for cotton production, but the constraints may be binding for maize production. Generally, the input package provided by cotton companies in West Africa is issued under strict guidelines and cannot be used on other crops. According to Ellis (1992), input subsidies also reduce the risk[15] perceived by farmers especially in circumstances where farmers' limited knowledge about the optimal level of inputs causes them to limit expenditure on inputs. Apart from providing purchased inputs and institutional organization, cotton companies guarantee producer prices. This shifts price risk away from cotton producers. Price stabilization may stimulate investment and innovation especially for small scale risk averse farmers thereby generating higher output. Abruptly

Hueth and Ligon (1999), and Key and Macbride (2003) use different methods and models in the tomato and hog industries in the United States and prove the argument that production contracts providing a low risk environment for growers lead to increased production over the no contract alternative farmers. Contract producers were associated with a substantial increase in factor productivity, and technological improvement over independent producers. Ammani et al. (2010) also find that liberalization of the fertilizer market in Nigeria significantly reduced fertilizer use and aggregate maize yield. A study by Theriault (2011) in Benin, Burkina Faso and Mali cotton sectors also finds strong evidence that farms with access to inputs are more productive.

The discussion above provides a basis for making observations about market policy alternatives in the input market. First, imperfections in credit and or factor markets

[15] Note that risk aversion can be an alternative explanation of why farmers might apply less than optimal inputs.

make spot markets non-optimal for organizing the input market. Secondly, credit and or factor market constraints, and weak (or absence of) institutions to enforce contract terms create a market failure that can be addressed by a market structure that ties together input and output. Due to the lack of contract enforcement mechanisms, recovering the input loan could be problematic if private traders supply inputs on credit. Under concentrated market structures, in the absence of alternative output buyers and input sellers, the gain from defaulting is low compared to the cost of exclusion from the input scheme.

The framework above illustrates that farm supply (and hence aggregate supply) as well as social welfare can be higher under parastatal vertical integration market structure relative to the competitive market structure in the presence of credit and or factor market constraints. Social welfare increase arises primarily from improvements in resource allocation and bringing production (closer) to its optimal level. An issue of concern, however, is the question regarding who benefits from the welfare increase: the cotton company, producer or both? A related question is whether other market structure alternatives can do better relative to the parastatal vertical integration market structure. These are questions that we explore in the sections that follow by comparing producer prices and grower’s income across the proposed market structure alternatives: parastatal vertical integration (current market structure), competition input market-monopsony output market and perfect competition in both input and output markets. In the next sub sections, we briefly describe these market structures and the equilibrium concepts that characterize each.

Parastatal vertical integration market structure

Contract production in agriculture is often studied using principal-agent theory (Goodhue 1999; Hueth and Ligon 1999; Vukina 2001; Swinnen, Sadler, and Vandeplas 2007). The principal agent framework is used here to investigate how the cotton company could determine input and output prices. Under the principal-agent framework, the cotton grower can be viewed as an agent of the cotton company (principal, here also called integrator or parastatal). The standard principal-agent problem is one where a principal is seeking a contract with an agent that will maximize the principal’s expected utility or profits. In the West African cotton sector, contracting is aimed at combating credit and or factor market constraints, enabling technology transfer and risk sharing. Generally, cotton companies bear price risk while growers bear yield risk. Typically, a grower has a production contract to use the cotton parastatal’s technology and inputs, but on the grower's land. It is assumed that both the integrator and the grower act in an individually rational way to maximize individual expected utilities or profits.

There are two constraints involving the grower, typical in a traditional principal agent problem as discussed by Varian (1992) and Anderhub et al. (2002). First, the participation constraint (PC) assumes that the producer has a reservation level of income, and the cotton company must ensure that the farmer gets at least this reservation income in order to be willing to participate. Typically, the reservation level of income is determined by the farmers’ alternative option- the grower’s expected income without contracting. The second constraint is the incentive compatibility constraint (ICC), which in this context, gets the grower to use the level of inputs that the cotton company considers optimal. It is assumed here that the cotton company has information regarding the profit maximizing input level and or growers cost structure and actions. One argument to motivate this assumption is that cotton parastatals have gained knowledge of the farming system through the provision of extension services and R&D. However, there is noise in the system since the relationship between input and output cannot be known with certainty. The cotton company must design an incentive schedule that does well on average. More generally, the PC is necessary to guarantee that the grower agrees to the contract, while ICC is necessary to align the interests of the cotton parastatal and the grower (Anderhub et al. 2002).

Based on the assumptions established above, the cotton company's profit function, π_c^g, is specified as:

$$\text{Max}_{r_g,p_g}\, E\pi_c^g = \left(p_w - p_g\right) q_c\left(p_g, r_g, w, \bar{A}\right)$$

$$-(r_c - r_g)\boldsymbol{x}_c^*(p_g, r_g, w, \bar{A}) - Z(q_c) \quad (6)$$

$$\text{s.t. } E\pi_f(p_g, p_m, r_g, r_m, w, \bar{A}|\text{contract}) \geq$$

$$E\pi_f\left(p_g, p_m, r_g, r_m, w, K, \bar{A}\middle|\text{no contract}\right) \quad \text{PC}$$

$$\boldsymbol{x}_c^* \in \text{argmax}\, E\pi_f(p_g, p_m, r_g, r_m, w, \bar{A}|\text{contract}) \quad \text{ICC}$$

where p_w is the world price of lint cotton, p_g is the producer price (lint equivalent[16]) set by the cotton company, q_c is cotton farm supply (lint equivalent), $\boldsymbol{x}_c^*$ is the optimal input package determined by the integrator for cotton production, r_c is the unit price at which the cotton company procures $\boldsymbol{x}_c^*$ from the competitive input market, r_g is the price at which the cotton company charges producers for $\boldsymbol{x}_c^*$, Z is the variable processing,

[16] Lint is obtained after ginning seed cotton that farmers produce. If we need to compare world prices and farm gate prices at a one to one level, then we would multiply world prices at the ginner's gate by the ginning efficiency ratio. Within the region, ginning efficiency ratio is estimated to be 42% (Kelly et al. 2010; Tschirley et al. 2009).

transportation and marketing costs, p_m is the price of maize, r_m is the price of $\boldsymbol{x}_m$ the quantity of non-labor inputs used for maize production. Note from (6) that ginners are price takers in the world lint market. Production from West Africa' s C-4 accounts for about 3% of world cotton production and only about 8% of world exports. Cotton demand is presumed to be perfectly price elastic. Equation (6) states that the cotton company's profits equals the price margin multiplied by lint quantity, less input and processing costs. The quantity of seed cotton ginned is influenced by the price of seed cotton and input prices the company offers in the contract.

The question of interest regards the design of the optimal contract and the resulting welfare effects. Varian (1992) demonstrates that if the principal has full information regarding the agent's production technology (and or utility), the ICC would not be binding on the principal's maximization. The principal designs an incentive structure that maximizes the optimal choice or minimizes production costs. Conceptually, the principal's need to provide an incentive compatible contract drives a wedge between its costs and the agent's utility/profit-maximizing (and or production cost minimizing) production decisions (Goodhue 2000; Varian 1992). Consequently, in the optimal solution, the agent only receives the minimum rent necessary to accept the contract. Thus a cotton company ultimately exerts market power on labor and land, but not on purchased inputs. Under the current market arrangement, the cotton company does so by subsidizing inputs to avoid producer's capital constraint and taxing output by lowering prices to meet the reservation level of income.

Experimental research and empirical studies, however, show that agents' often reject contractual offers that imply unfair surplus sharing (Anderhub et al. 2002; Fehr and

Schmidt 1999), and that principal's contractual offers imply less unequal surplus sharing than predicted by standard agency theory (Keser and Willinger 2000; Anderhub et al. 2002). In practice, agents' choice to accept contractual relationships also depends on aspects outside the participation constraint and ICC. Such aspects that may influence contract terms include agents' bargaining strength, reciprocal effort choices (Anderhub et al. 2002; Fehr and Schmidt 1999), and government regulations that set price ceilings and floors. Although the agency theory suggests that parastatal market structure in the West African cotton sector may foster the formation of market power, whether in fact it arises and in what form are empirical questions.

Competition input market-monopsony output market

Under the competition-monopsony market structure, it is proposed that cotton producers procure inputs from competitive spot markets, but cotton parastatals be maintained as regional monopsonies. In reality, reform measures in the input market will only be partially successful in getting competitive prices to cotton farmers because credit constraints and imperfections in factor markets will still remain. Input prices are likely to lie somewhere between monopolistic and perfect competition. Focusing on the effect of monopsony buyer power, standard economic theory predicts that the key to monopsony rents is restricting output supply and driving prices down below competitive levels. In West Africa, cotton parastatals have no incentive to restrict output because cotton demand in the export market is perfectly elastic.

The question is whether competition-monopsony market structure would be any better than vertical integration in the West African cotton sector in terms of price competitiveness and or economic benefits. As noted, producers maximize profits from farming through land allocation decisions: cotton area and production will decline when cotton prices decline or costs of production increase relative to maize, the other crop option. Abstracting from the principal agent framework described in the preceding subsection, the monopsony ginner's profit function is specified as

$$\max_{p_g} E\pi_c^g = \left(p_w - p_g\right) q_c\left(p_g, r_c, w, K, \bar{A}\right) - Z(q_c) \quad (7)$$

s.t.

$$E\pi_f(p_g, p_m, r_g, r_m, w, K, \bar{A}|\text{contract}) \geq$$

$$E\pi_f\left(p_g, p_m, r_g, r_m, w, K, \bar{A}\middle|\text{no contract}\right) \quad \text{PC}$$

where r_c is the price of $\boldsymbol{x}_c$ in the competitive input market. The monopsony would exercise market power by choosing output price, but the maximization is constrained by the grower's maximization through land allocation decisions. Maximization of (7) establishes the equilibrium in the output market. Input demand function with credit constraints derived from equation (1) is $\boldsymbol{x}_c\left(p_g, r_c, w, K, \bar{A}\right)$. The market equilibrium under perfect competition is determined at a point where demand equals supply which is perfectly price elastic[17]. Assuming a downward sloping input demand function, the equilibrium input demand would be obtained according to

$$\boldsymbol{x}_c\left(p_g, r_c, w, K, \bar{A}\right) = r_c. \quad (8)$$

Note that input prices are exogenous to the monopsonist's objective function. If demand and supply functions are known, equation (7) and (8) can be solved jointly to determine the equilibrium outcomes using either analytical or mathematical programming methods.

[17] Dead weight loss would occur if input supply is not perfectly elastic

Free market (input and output markets)

A free market is the most efficient type of economic organization in the absence of credit and or factor market constraints. In West Africa's C-4, the proposed free market structure alternative would still be characterized by market failures in capital markets and institutional constraints. In a free market, it is assumed that the input market is dominated by many private suppliers and ginning companies have no monopsony control over farmers; cotton prices paid to farmers are determined competitively using world cotton prices. Creating competition is not an easy task. For instance, in Ghana, Tanzania, and Uganda, private input suppliers and ginners did not step in as quickly or as effectively as desired following liberalization of the input and output markets (Poulton et al. 2004; Winter-Nelson and Temu 2002).

With a free market, producer prices are linked to world lint prices. An increase (or decrease) in the cotton company's variable costs and world prices is transmitted through the marketing system to producers. Under the current pricing system in West Africa's C-4, the ex ante negotiation of producer prices annually means that market price shifts are transmitted with a lag, and temporary movements may not be transmitted at all. The market equilibrium under a free market is determined at a point where demand equals supply.

As noted above, the equilibrium input demand with credit constraints would be determined from $\boldsymbol{x}_c\left(p_g, r_c, w, K, \bar{A}\right) = r_c$, while if no credit constraints, equilibrium input demand is determined from $\boldsymbol{x}_c\left(p_g, r_c, w, \bar{A}\right) = r_c$. We consider both cases for comparison purposes. In the output market, the market equilibrium is established as

$$p_w = p_g + Z'(q_c)$$

(9)

where $Z'(q_c)$ is the marginal cost of transportation, ginning and marketing. Hence, output price can be obtained analytically from $p_g = p_w - Z'(q_c)$ if the parameters are known. Note that the equilibrium prices must solve the grower's participation constraint; otherwise farmers would grow no cotton.

Empirical model

To illustrate the potential magnitude of welfare effects of market policy, we solve equations (6)-(9) for a specific empirical example. To conduct the optimizations, it is necessary to establish specific functional forms for the input demand and farm supply functions specified in general form in equations (3) and (4). Cotton is assumed produced using one composite[18] input (seed, fertilizer, insecticide and herbicide) according to the law of the minimum (LoM) production technology. This formulation has been found to provide a reasonable representation of yield functions (Paris 1992; Lanzer and Paris 1981).

To simplify the analysis, we make the following assumptions: First, output from each crop depends only on the amount of inputs allocated to it-non joint production technology, and that the household's cash on hand is sufficient to purchase enough inputs to plant all land to maize. Second, assume that under the current market structure, there are no private seed cotton buyers[19], which means growers have no option to produce

[18] This assumption is made for analytical convenience, but the argument developed is valid with multiple inputs. The assumption also implies if the production process requires that the non-labor inputs be used in fixed proportions.
[19] Generally, private seed cotton markets are absent because of government regulations that restrict entry.

cotton other than under contract with the cotton parastatal. The second assumption is relaxed when considering liberalization alternatives that allow perfect competition. These assumptions imply that growers' land allocation decisions can be analyzed as a discrete choice. That is the grower chooses either to plant all land to cotton or all land to maize. A grower will contract with the cotton parastatal to allocate his/her land to cotton production as long as the expected income/utility from cotton production exceeds that from the alternative option-maize.

Let $q_i = \min\,(a_i + bx_i, Y_i)$ be the per ha production function for the i^{th} crop (*i* = *c* if crop is cotton and *i* = *m* if crop is maize), a_i is a constant (intercept) representing yield if no input *x* is applied; *b* is the input productivity parameter and Y_i is the expected plateau (average) yield. Generally, the use of purchased inputs on maize is low and farmers can still harvest maize even if they do not apply purchased inputs (Coulibaly 1995; Vitale et al. 2009), which means $a_m > 0$, but the same is not true for cotton, i.e. a_c is close to zero. Since cotton production is more input intensive than maize, it requires more capital per acre to produce. Letting *r* be the price of *x*, the variable cost of cotton production per ha is rx_c**.** The producer's profit function is specified as

$$\max_{x_c} \pi = p_c \min\,(a_c + bx_c, Y_c) - r_c x_c. \qquad (10)$$

Equation (10) will exhibit constant positive marginal product when $Y_c > a_c + b\boldsymbol{x}_c$ and indicates that $\boldsymbol{x_c}$ should be applied until its marginal value product (MVP) is equal to its marginal factor cost (MFC).

With the law of the minimum (LoM) production technology, optimal input use is either the level required to reach the plateau or zero depending on the input-output price ration. However, assuming$a_c = 0$, equation (10) indicates that with zero input use, no cotton production occurs. Hence optimal production will require the level of x_c necessary to reach the plateau:

$$x_c = Y_c/b \tag{11}$$

Under contract cotton production, the cotton company will provide the optimal input amount or price incentives to enable producers to apply the optimal amount. Substituting (11) into the production function, farm supply is obtained.

Without a contract, the farmer obtains inputs from private (free) input markets and faces credit constraints. The farm profit maximization is represented by the Lagrangean:

$$L(x_c, \lambda) = p_c \min\,(a_c + bx_c, Y_c) - r_c x_c + \lambda(K - r_c x_c) \tag{12}$$

where λ is the shadow price of the credit constraint. With an active credit constraint, the marginal value product (MVP) of *x* is higher than its market price by a value of the shadow price of the credit constraint, i.e. $p_c \min(a_c + bx_c, Y_c) = r_c(1 + \lambda)$. Input use under credit constraints is determined by

$$x_c = \frac{K}{r_c} \tag{13}$$

which is the F.O.C of the credit constraint.[20]

The response functions in (11) and (13) are used to parameterize the empirical models for each of the market structure scenarios described in equations (6) to (8). Our results are, of course, sensitive to the choice of functional form of the production technology used, but nonetheless, useful in identifying and quantifying some potential effects that might flow from liberalization.

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[20]Ciaian and Swinnen (2009) and Just, Hueth, and Schmitz (2004) use a similar approach.

Data

For world cotton price, we use the Cotton A index price, which is the world reference cotton price, obtained from the National Cotton Council of America reported in US$/lb and transform it to US$/kg. The world price used is the average world price for the period 1999/2000 -2005/2006 (Table 1). The estimated average price for the period 1999/2000 - 2005/2006 is $1.22/kg lint equivalent (Table 1). A sensitivity analysis is conducted by varying the price to see the effect of price changes on equilibrium outcomes. Estimated ginning, transport and marketing costs for the period 1999/2000 -2005/2006 are included in Table 1. An examination of costs in Table 1 indicates that the average variable cost for the ginning company is $0.46/kg of lint exported.

Table 1. Ginning and FOB-to-CIF Costs for 1999/2000-2005/2006

Crop Year	World Price ($/kg)	Exchange Rate (f/$)	Domestic Transport (f/kg)	Ginning Costs (f/kg)	Sea Freight ($/ton)	Marketing Costs ($/ton)
1999/2000	1.2	649	60	230	65	36
2000/2001	1.27	731	65	245	60	38
2001/2002	0.97	731	70	225	55	29
2002/2003	1.16	648	71	220	60	35
2003/2004	1.47	555	72	215	55	38
2004/2005	1.23	524	73	220	55	32
2005/2006	1.24	535	75	225	60	32
Average	1.22	624.71	69.40	225.71	58.57	34.29

Source: Tschirley et al. (2009).

The average estimated cost of purchased inputs for cotton and maize (excluding labor) is included in Table 2. The estimated total cost for cotton production technology is approximately $172.98/ha, while for maize it is $87.69/ha. With this technology and in a normal season, average seed cotton yield in the region is approximately 1200 kg/ha, or

504 kg/ha lint equivalent (Vitale et al. 2007; Baquedano and Sanders 2008), which means the producer's cost of purchased inputs per unit produced is $0.144. The high value crop-cotton requires more capital to produce than maize. We assume the household's cash on hand, *K*, is sufficient to purchase inputs used for maize production, i.e. *K*=$87.69. Field surveys in this region indicate average maize yield is approximately 1500kg/ha (Yanggen et al. 1998; Baquedano and Sanders 2008). Maize price used is average producer prices in Burkina Faso for the period 1999-2005 as reported by FAOSTAT. The price of maize is US$0.16/kg. We do a sensitivity analysis by varying these prices to US$0.24/kg which is the average 2008/2009 season prices as reported by FAOSTAT.

Table 2. Average Cost (US $/ha) of the Technology Package

Crop	NPK (kg/ha)	Urea (kg/ha)	Seed	Fertilizer	Insecticide	Herbicide	Total
Cotton	150	50	49.42	72.54	36.67	14.35	172.98
Maize	100	50	3.19	58.19		26.31	87.69

Source: Baquedano and Sanders (2008) and Tschirley et al. (2009).

In sub-Saharan Africa, research approximating technical coefficients is generally scarce. There are few case studies that can be used to guide empirical analysis. Using surveys, Theriault (2011) measured input productivity in the West African cotton sector and found purchased inputs (seeds, fertilizers, pesticides, and insecticides) elasticity coefficient to be ~0.7 in Burkina Faso, and ~0.57 in Benin. Other studies report for individual factor inputs especially for nitrogen. Kelly (2006) reported that 1kg of nitrogenous fertilizer increased cotton yield by 7kg in Mali. Ruben and van Ruijven (2001) estimated that in southern Mali, 1kg of nitrogen fertilizer increased cotton yield by 0.09%. The study by Theriault (2011) is a useful example to guide our empirical analysis since they also consider purchased inputs as a composite package. The input productivity parameter (b in equation (10)) is assumed to be 0.7, and is varied to 0.57 to show the effect of technology on model outcomes.

Procedure

The maximization in (6)-principal agent problem- is solved analytically. The problem objective function to be maximized is

$$\max_{p_g, r_g} \pi = (p_w - p_g) * \min(a_c + bx_c, Y_c) - (r_c - r_g)x_c$$
$$-Z * \min(a_c + bx_c, Y_c) \qquad (14)$$

Constraints:

$$p_g * \min(a_c + bx_c, Y_c) - r_g * x_c \geq p_m * Eq_m - r_m * x_m$$

$$x_c = \left(\frac{Y_c}{b}\right)$$

$$r_g x_c = K$$

where Eq_m is the expected (average) maize yield per hectare in the region, Y_c is the average cotton yield, and r_c is the price at which the cotton parastatal procures x_c in the competitive input market, and Z is the unit variable processing and marketing cost. The estimated market price of purchased inputs is approximately \$0.144 per unit. The choice variables for the cotton parastatal are grower output price (p_g) and input price (r_g). Note that the solution for the maximization of (14) is not unique. Any input and output price combination that maximizes (14) and solves the participation constraint is optimal. The input price reported in this analysis is the highest price the principal (integrator) can charge and satisfy the agent's credit constraint: $r_g = K/x_c$ where $x_c = Y_c/b$. Under this formulation, growers have to use all of their cash on hand (*K*) to purchase inputs from the integrator. The input price r_g is then substituted into (14) and the problem solved analytically to obtain a producer price p_g that maximizes the principal's objective function and satisfies the participation constraint. Equilibrium outcomes are reported in the results section.

The maximization problem in the competition-monopsony structure is solved analytically as in (14) above. For comparison purposes, the problem is solved under two scenarios: with and without credit constraints. With a credit constraint, the problem is set up as:

$$\max_{p_g} \pi = \left(p_w - p_g\right) * \min(a_c + bx_c, Y_c)$$

$$-z * \min(a_c + bx_c, Y_c) \qquad (15)$$

Constraints:

$$p_g * \min(a_c + bx_c, Y_c) - r_c * x_c \geq p_m * Eq_m - r_m * \boldsymbol{x}_m$$

$$x_c = K/r_c$$

where r_c is the competitive price of purchased inputs used for cotton production. With no credit constraint, $x_c = K/r_c$ is dropped from (15) and input use becomes $x_c = \left(\frac{Y_c}{b}\right)$. Note that the participation constraint must be solved in order for grower's to participate in cotton production.

The solution to the free market structure is obtained analytically. For comparison purposes, the problem is solved under two scenarios: with and without credit constraints. To obtain the price received by the grower (lint equivalent) under free market (p_g), average domestic transportation cost (*D*), sea freight cost (*F*), insurance and marketing cost (M) of lint cotton are subtracted from the world cotton price. This gives a proxy for the world cotton price at the ginners' gate or FOB price. We then subtract average ginning costs (G) to obtain the domestic price in lint equivalent:

$$p_g = p_w - D - M - G - F. \quad (16)$$

Deflating p_g by the ginning efficiency ratio will give domestic prices in seed cotton equivalent of world price. Given the producer's response functions with and without credit constraints as derived above, economic effects of a free market in the input and output markets on producer are determined analytically. Results for the market structure alternatives are considered in the next section.

Simulated results and discussion

Results from the principal agent model

The solution is not unique. The highest input price that the principal can charge and satisfies the grower's capital constraint is $0.12/unit of input. With $0.12 input price, the principal pays agents $0.48/kg lint cotton equivalent to satisfy the agents' participation constraint (Table 3). This solution suggests that the principal subsidizes input prices to ensure producers purchase the optimal amount, but extracts the entire surplus above the grower's reservation income (Table 3). The reservation income level is determined by the maize market, and is $152.31/ha.

Note that the assumed functional form of the grower's (agent's) production technology and input productivity parameter affects the optimal level of the input selected by the principal, and hence the price charged for inputs. For instance, if the grower's production technology is assumed to be a Cobb-Douglas type production technology, prices received by growers could decrease as the world price increases. In the optimum, the principal provides more inputs as world prices increase. Production increases because input demand increases under this production technology as world price increases. Growers, however, receive only their reservation income and any increase in surplus created through increased production is extracted by the principal. When the input productivity parameter is changed from 0.7 to 0.57, more inputs would be needed to achieve the maximum potential yield. The principal provides more inputs or reduces the price charged for the inputs for agents to purchase what is considered the optimal input amount.

Under the cost structure stated above, empirical results suggest that cotton production is possible if world lint price is at least $1.10/kg (Table 3). Below, $1.10/kg and with the participation constraint active, no cotton is produced because the integrator must ensure the grower gets the reservation income level. Results indicate that as world price increases, the principal keeps all of the added surplus as predicted by standard principal agent theory. Experimental research shows, however, that the principal shares more of the surplus than predicted by the theoretical model (Anderhub et al. 2002; Keser and Willinger 2000). In West Africa, parastatals adjust their pricing strategies to varying market conditions including changes in the participation constraints. It is also often observed that producer prices increase as world prices increase suggesting that the supply function is less perfectly inelastic than implied by the model.

Results suggest that economic surplus is maximized when the principal provides inputs at a price cheap enough to avoid the credit constraint. The principal could also provide inputs for free and receive rents from output. In practical terms, the cotton company must charge a small price for its inputs to limit usage to the level considered optimal. This controls the risk of inefficient input use (over application), diversion on other crops, or even resale on the secondary market. Goodhue (2000) argues that the principal increases profits by controlling input use.

Table 3. Equilibrium Economic Outcomes from the Vertical Integration Model

World Price ($/kg)	Producer Price[a] ($/kg)	Input Price $/unit	Grower's Income ($/ha)	Parastatal Profit ($/ha)	Total Surplus[b] ($/ha)
1.00	0.48	0.12	152.31	0.00	-
1.10	0.48	0.12	152.31	11.13	163.44
1.20	0.48	0.12	152.31	61.53	213.84
1.22	0.48	0.12	152.31	71.61	223.92
1.30	0.48	0.12	152.31	111.93	264.24
1.40	0.48	0.12	152.31	162.33	314.64
1.50	0.48	0.12	152.31	212.73	365.04
1.55	0.48	0.12	152.31	237.93	390.24
1.65	0.48	0.12	152.31	288.33	440.64

[a]Output prices depend on the price the principal charges for the inputs
[b]Total surplus generated per ha is the sum of grower's income and parastatal's profit

Reducing the price of cotton relative to the price of maize increases the importance of maize production to cotton, suggesting producers are likely to shift to maize production. Increasing price of maize increases the producer's reservation income level, and hence increases the price the cotton company must pay producers to participate in cotton production. For instance, when price of maize increases from $0.16/kg to $0.24/kg, the reservation income (participation constraint) increases from $152.31/ha to $272.31/ha.

At the aggregate level, producers are heterogeneous. Farmers differ in terms of their farm size, income sources, resource endowment, and management abilities. These differences can affect the aggregate outcomes realized with production contracts. For cotton production among the West Africa's C-4, field studies indicate that some growers consistently perform better than the average while others consistently perform worse (Theriault 2011). If the cotton parastatal knows growers' types and can restrict each type to their reservation income or utility level, the parastatal could potentially price discriminate and increase profits and hence social welfare by designing different contracts for the different grower types. However, such discrimination would increase the parastatal's market power. There could also be information costs for search of optimal contracts for agent types. Contracts that do well on average reduce information costs for search, but may be inefficient. Perhaps the best way to discriminate in the context of cotton production in West Africa's C-4, is by establishing regional pricing strategies. Grower variability is likely less within a region than between regions in a given a country. Production contracts designed based on a more homogeneous region could be more efficient than an average production contract designed for heterogeneous regions in a country, but could increase the market power position of the cotton parastatal.

Results from competition-monopsony market structure

Equilibrium outcomes indicate that the objective function of the monopsony is maximized when the cotton company pays growers a reservation price that solves the participation constraint. Equilibrium outcomes for competition-monopsony market structure are presented in Table 4. For producer's not credit constrained, the reservation price that solves the participation constraint is $0.51/kg and the world cotton price has to be at least $1.10/kg for the monopsony cotton company to remain economically viable. For growers credit constrained, the reservation price that solves the participation constraint is $0.56/kg and the world price has to be at least $1.20/kg (Table 4).

The price that solves the participation constraint for credit constrained growers depend on the grower's cash on hand. If producers' cash on hand is less than the assumed K=87.69, the participation price would have to be higher than $0.56/kg. The result demonstrates that output price has to be higher for credit constrained growers to participate in cotton production than for producers not credit constrained under the competition-monopsony market structure. Under credit constraints, there is potential welfare loss due to production not being optimal. The credit constraint leads to lower input use and hence less than what is optimal is applied and or not all land will be planted. This leads to less farm supply. In the case of West Africa, credit constrained farmers are the majority of the farmers implying aggregate welfare could suffer. Note also that our model imply a perfectly inelastic supply function at the farm level and dictates that there is no dead weight loss associated with the pricing behavior of the monopsonist. In reality, the supply function is less inelastic than implied by our model which means the equilibrium under the competition-monopsony market structure would be associated with some dead weight loss.

Results from the competition-monopsony market structure suggest that surplus due to increasing world prices would accrue to the monopsonists while the grower receives only the reservation income. It appears competition-monopsony market structure would not be any better than the parastatal vertical integration market structure in terms of welfare distribution among sector agents, and could potentially lead to social welfare loss in the presence of grower's credit constraints.

Table 4. Economic Outcomes from Competition-Monopsony Model[a]

	With Credit Constraints				Without Credit Constraints			
World Price ($/kg)	Producer Price[b] ($/kg)	Grower Income[b] ($/ha)	Parastatal Income ($/ha)	Total Surplus	Producer Price ($/kg)	Grower Income ($/ha)	Parastatal Income ($/ha)	Total Surplus
0.90	0.51	152.31	-			152.31	-	
1.10	0.51	152.31	11.13	163.44	0.56	152.31	-	
1.20	0.51	152.31	61.53	213.84	0.56	152.31	28.55	180.86
1.22	0.51	152.31	71.61	223.92	0.56	152.31	37.08	189.39
1.30	0.51	152.31	111.93	264.24	0.56	152.31	71.18	223.49
1.40	0.51	152.31	162.33	314.64	0.56	152.31	113.80	266.11
1.50	0.51	152.31	212.73	365.04	0.56	152.31	156.43	308.74
1.55	0.51	152.31	237.93	390.24	0.56	152.31	177.75	330.06
1.65	0.51	152.31	288.33	440.64	0.56	152.31	220.37	372.68

[a]The model assumes that cotton producers procure inputs from competitive spot markets, but cotton parastatals be maintained as regional monopsonies. The model is solved with the participation constraint active.
[b]Grower's income is the per hectare revenue less input costs for cotton production.

Results from free market (input and output markets) model

Equilibrium outcomes for the free market in the input and output sectors are included in Table 5. Equilibrium prices presented in Table 5, suggest that producers would benefit more from increasing world cotton prices than with other market structure alternatives. Note that with a free market, producer prices are linked to world lint prices. An increase (or decrease) in the cotton company's variable costs and world prices is transmitted through the marketing system to producers.

Farm incomes for producers with and without credit constraints under the free market structure are included in Table 5 (last two columns). Results suggest that producers not credit constrained would benefit most in a free market structure alternative (Table 5). Producers without credit constraints apply inputs at optimal levels, attain the maximum production potential, and hence benefit from increased world cotton prices through increased revenue per ha. Input use for credit constrained farmers is constrained by the household's available capital.

Results suggest that free input and output market structure would guarantee cotton production for credit constrained farmers if world lint prices are $1.20/kg and growers receive $0.63/kg (Table 5). Below $0.63/kg, the grower's participation constraint is not solved; suggesting farmers are likely to shift to maize production. For producers not credit constrained, the participation constraint is solved if world lint prices are $1.10/kg and growers receive $0.53/kg (Table 5). The result demonstrates that output prices have to be higher for credit constrained growers to participate in cotton production than for producers not credit constrained. In the context of West Africa's C-4, farmers' are likely even more credit constrained than assumed in this study.

Total surplus generated under vertical integration (Table 3) is the same as the grower's income under free market without credit constraints (Table 5). This result demonstrates that the monopoly/monopsony firms do not always lead to inefficient production due to price-setting behavior. Under a free market, economic profits for the cotton company would be zero. Surplus gains (losses) due to increasing (decreasing) world cotton prices accrue to the producer. Results demonstrate that gains from the free market relative to vertical integration would be distributional rather than welfare enhancing. Free markets allow the surplus captured by the cotton company under monopolistic/monopsonistic conditions to be transferred to growers.

The perfectly inelastic supply function implied by our analytic framework dictates that dead weight loss associated with imperfect markets is zero. In reality, the supply function is less inelastic which means the equilibrium under the competition-monopsony and parastatal vertical integration market structures would be associated with some dead weight loss. Since dead weight loss is eliminated under free market structures, total surplus generated under a free market could potentially be higher than with other market structures. Surplus generated under the free market with credit constraints (Table 5) is less than surplus generated under vertical integration (Table 3). This demonstrates that in the presence of credit constraints, the integrator increases sector welfare and efficiency by controlling or supplying inputs. Varian (1992) points out that the comparison between monopoly and competitive output levels under similar cost structures may be flawed, because a monopolist/monopsonist can only exist in an imperfect market. The monopolist/monopsonist may have a different cost structure, including a downward-sloping marginal cost curve, from that of the (long run) total cost structure of the perfectly competitive market. This suggests that the efficiency advantages of parastatal vertical integration market structure relative to a free market structure with credit constraints may be under estimated.

Table 5. Economic Outcomes for Free Market Structure

World Price ($/kg)	Producer Price ($/kg)	Grower's Income[a] ($/ha)	Grower's Income[b] ($/ha)
0.77	0.20	-2.99	-2.44
0.8	0.23	12.13	10.35
1.00	0.43	112.93	95.61
1.10	0.53	163.33	138.23
1.20	0.63	213.73	180.86
1.22	0.65	223.81	189.39
1.30	0.73	264.13	223.49
1.40	0.83	314.53	266.11
1.50	0.93	364.93	308.74
1.55	0.98	390.13	330.06
1.65	1.08	440.53	372.68

[a]Grower's income without credit constraints.
[b]Grower's income with credit constraints. Assumes some land is not planted due to credit constraint.

Conclusions and final remarks

This study provides an economic argument for the importance of vertical integration market structures in the cotton sector of West Africa, and contrasts vertical integration with other market structure alternatives in terms of welfare and sector efficiency. Based on a principal agent framework, in the presence of credit constraints, the vertically integrated firm increases social welfare by subsidizing inputs to overcome the producer's credit constraint. The negative impacts of cotton parastatals in West Africa seem overstated by opponents of the parastatal vertical integration market structure given the credit constraints for most producers.

Equilibrium outcomes indicate that under the principal agent framework, growers receive only the reservation income necessary for growing cotton to be preferred to growing the alternative crop, corn. In practice, however, the principal will share more of the surplus than predicted by theory. One way to ensure the integrator provides more equitable contract terms is by empowering growers by strengthening producer organizations to be able to demand more equitable contract terms. Thus, current efforts by West Africa's C-4 cotton producers' to form producer organizations and strengthen them should be supported by policy makers. The other way is financial participation by increasing the share holding of producers (or producer organizations) in cotton companies. This would provide an opportunity to reduce managerial slack and to initiate external audits aiming at controlling the management.

Removing the integrated cotton parastatals in favor of competitive market structures could impact negatively on the income of growers who are credit constrained, but would benefit growers without credit constraints. Since the bulk of the farming households in West Africa are credit constrained, social welfare may suffer if the vertical integration market structure is removed in favor of the free market structure. Competition-monopsony market structure will not be any better than the parastatal market structure in terms of benefit to producers. In the presence of credit constraints, competition-monopsony market structure is welfare reducing relative to the parastal market structure. Under a free market with no capital market failures, surplus captured by cotton companies would be transferred to growers.

The basic policy implications follow: Imperfection in the credit and or factor markets make spot markets non-optimal for organizing the input market. Credit and or factor market constraints, and weak (or absence of) institutions to enforce contract terms create a need for a concentrated market structure that ties together input and output. Promotion of a competitive input market system will not support cotton productivity growth unless stakeholders pursue complementary programs to develop national input supply systems and credit markets.

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VITA

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Scope and Method of Study:
This dissertation consists of three essays: The first essay determines the optimal level of N fertilizer for rye-ryegrass pasture using yield functions estimated with different functional forms that assume parameters are either nonstochastic or stochastic. Three yield functions were estimated: linear response plateau, quadratic, and Spillman-Mitscherlich.

The second paper determines the effect of considering the cost of lime on recommendations about optimal levels of N. Yield response and soil pH change functions were estimated and used to determine the optimal levels of N and lime. The study also developed a new version of a linear response plateau function that allows the yield plateau to vary by year with respect to nitrogen but not soil pH.

The third paper provides an economic explanation of the existence of parastatal vertical integration market structures in the cotton sector of West Africa, and contrasts it with other market structure alternatives in terms of welfare and sector efficiency.

Findings and Conclusions:
In the first essay, nonstochastic models are rejected in favor of stochastic parameter models. The stochastic models lead to smaller recommended levels of N, but the economic benefits of using fully stochastic models are small since expected profit functions are relatively flat for the stochastic models.

In the second essay, considering the cost of lime reduced the optimal level of N by as much as 11.3%. Acidification potential due to N fertilizer increased nonlinearly as N rate increased. N acidification appears to be more severe with N application rates above consumptive potential of the crop than with N that is used by the plant.

In the third essay, due to credit and or factor market constraints, vertical integrated cotton parastatals increase sector welfare and efficiency by supplying inputs to overcome credit constraints. Surplus sharing between the grower and the integrator is significantly shifted towards the cotton company. Removing the integrated cotton parastatals in favor of a free market structures would result in little cotton being produced.

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