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Economically Optimal N Fertilizer Rates for Maize Produced on Vertisol and Inceptisol Soils under No-Till Management: A Case Study in Maphutseng, Lesotho

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Authors' contributions

This work was carried out in collaboration between all authors. Authors NSE, FRW and MM designed and implemented the study. Author IBC wrote the first draft of the manuscript. Author DML assisted with the economic analysis. All authors read and approved the final manuscript.

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ABSTRACT

Aims: To determine differences in maize yields, optimal nitrogen (N) rates, and profitability on contrasting soil types and no-till and till management.
Study Design: Randomized block design field trials involving no-tillage and tillage practices were conducted on contrasting soil types (vertisols and inceptisols) to investigate the effect of N fertilizer rates on maize (*Zea mays*) grain yield.
Place and Duration of Study: Mohale's Hoek District, Maphutseng, Lesotho over the 2012/2013

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agricultural year.
Methodology: Maize response to N was estimated with a linear response plateau function. Economically optimum N rates were estimated for both soil types and tillage practices assuming typical corn and N fertilizer prices for the 2012/2013 agricultural marketing year.
Results: The economically optimal N rates were estimated at 141 kg of N ha^{-1} with a predicted maize grain yield of 7.75 tons ha^{-1} for no-till vertisol maize system, 150 kg of N ha^{-1} with a predicted maize grain yield of 4.90 tons ha^{-1} for no-till inceptisol maize system, and 73 kg of N ha^{-1} with a predicted maize grain yield of 7.37 tons ha^{-1} for the till vertisol maize system. A Monte Carlo analysis suggests these findings are robust to N cost, maize prices, and sampling uncertainty.
Conclusion: Findings of this study suggest that if other production factors remained constant, farmers in Lesotho - a country where access to commercial fertilizer is limited and average fertilizer N use is less than 25 kg ha^{-1} - would need to increase significantly their N fertilizer rates to meet their food needs.

Keywords: Lesotho; inceptisols; vertisols; no-till; maize; nitrogen.

1. INTRODUCTION

The Kingdom of Lesotho is a low income, food deficit country with about 86% of its resident population working as subsistence farmers [1]. Presently less than a quarter of the country's total food demand is produced internally. As a result, the Basotho - e.g. the Basotho people, the native population of Lesotho - depend on food assistance and rely on imports, mainly from South Africa, to meet their food needs [2]. Maize (*Zea mays*) is a major food crop and forms an important part of the Basotho diet, making up about 54% of their average daily caloric intake [3]. Nevertheless, maize imports have increased considerably in recent years with an approximate 11% increase reported from 2011 to 2013 marketing year [1].

Maize is still widely grown throughout the country and occupies about 60% of the total crop land, but the major maize producing areas are the fertile lowlands that cover the western parts of the country [3]. Maize is mainly grown for subsistence by small scale, resource poor farmers using simple technologies and tools such as a hand hoe. Maize is usually planted from mid-November to mid-January at the onset of the rainy season and harvested from May to July of the following year [4].

The major factors limiting food production - especially maize - are land degradation and erratic rainfall. The latter has also been reported in neighboring countries in southern Africa with excessive and heavier rains becoming even more frequent in recent years [4]. Heavy and excessive rainfall events contribute to erosion, soil fertility decline, and consequently low agricultural yields. According to the Ministry of Agriculture and Food Security (MAFS) and Ministry of Finance and Development Planning (MFDP) of Lesotho, the total arable land decreased by approximately 20.1% from 1999/2000 to 2009/2010 due mainly to an increased frequency of heavy rains coupled with fragmented soil cover. This loss of cover becomes increasingly important as households counter firewood scarcity with animal dung collection and utilization as a heat source for home cooking. From 1999-2009, overall maize production decreased by approximately 54% [1].

To address this issue, the Government of Lesotho has taken positive steps in designing and implementing policies to tackle food insecurity by improving farmer access to fertilizer and seed. Yet, maize yields remain low and are typically less than 1 ton ha^{-1} (~10 to 20 % of typical yields across the border in South Africa). Low yields are also attributed to poor weed, pest and nutrient management practices, low plant population, inefficient fertilizer and water use, continuous maize mono-cropping and intensive tillage. Conversely, despite the prevailing low yields, the *Agricultural Situation Report of Lesotho 2010-2011* [4] pointed out that the country has experienced an increase of 46.3% in maize production in 2009/2010. This increase was attributed mainly to an increase in land area planted to maize from 137,585 ha in 2001/2002 to 151,717 ha in the same period, 2009/2010 [4]. This increase in arable land area coupled with combined interventions from the government of Lesotho and NGOs helped support smallholder farmers by increasing agriculture productivity and ensuring food security by providing seed vouchers and subsidizing agricultural inputs [5]. Despite the increased maize production, the overall economic performance of Lesotho's agricultural sector has decreased over the last decade. The agricultural sector's gross domestic product moved from 11.2% in 2000 to 7.8% by 2009, with horticulture witnessing the greatest decrease from 4.7% to 1.8% [4].

This study was a collaborative research effort between Growing Nations (a local NGO), National University of Lesotho and The University of Tennessee with funding from the United States Agency for International Development's Sustainable Agriculture and Natural Resource Management - Collaborative Research Support Program (SANREM-CRSP) to investigate strategies that could be used to sustainably increase maize yields in Lesotho. The study examines the effect of N fertilizer rates, and contrasting soil types and tillage practices on maize grain yield over the 2012/2013 cropping season. An economic analysis of optimal N rates is determined for different soil types (vertisols and inceptisols) and tillage techniques; specially no-till and conventional tillage practices.

Soil management for maize production is comprised of many factors including fertilizer management, crop rotation, and crop residue utilization. Crop residues play an important role in the Basotho culture and have high economic value both to the agronomic system as well as for livestock feed due to increasing communal grazing pressure. According to the FAO [3], besides farming, Basotho also use residues for construction leading to increased exposure of fragile arable land to weather. As Derpsch et al. [6] indicated, residues also serve as a nutrient storage vehicle in tropical regions due to the low cation exchange capacity of tropical soils. Thus, if kept on fields, residues could increase the efficiency of mineral fertilizers. Thierfelder et al. [7] reported significant yield benefits from a combination of reduced tillage, permanent soil cover, and crop rotation plus fertilizer over conventional tillage treatments. The study was conducted over seven cropping seasons. Initially, significant differences were hard to detect, but changes in soil fertility became more evident four years after the study was initiated. Thierfelder et al.'s results suggest that there is a buildup of organic matter over time and more nutrients are eventually mineralized for plant uptake. Most fertilizer recommendations account for N needed to break down high carbon residues; similarly, farmers that transition to no-till often add additional N because of the N that is immobilized in the new crop residues will not mineralize in the first cropping season. As a result, fertilization rates can be reduced gradually in no-till after a few years to rates common in intensive tillage systems. In another study, the merits of the long-term rain-fed maize-legume cropping systems under conservation agriculture were analyzed in Mozambique. Dias and Nyagumbo [8] reported significant maize yield benefits from incorporating fertilizer together with cover crops, residues, and reduced tillage practices in the first year of the study. These findings suggest that the benefits of incorporating minimum tillage and residue management into maize production systems can be immediate.

Bloem et al. [9] collected data from demonstration plots at Belvedere, Dumbarton and Lusikisiki in South Africa. Their studies found that integrating legumes into the maize production system by either planting maize after or in combination with a legume resulted in fodder and grain yield benefits similar to applying high N fertilizer rates (54 kg at planting and 54 kg N as top dressing ha^{-1}). Benefits of incorporating these practices into maize production were also reported in Zimbabwe. Mapfumo et al. [10] obtained a 22% increase in maize yield from a field where pigeon pea (*Cajanus cajan*) was previously cultivated. These yield increases suggest that there is potential to augment the agricultural productivity of old and degraded soils characterizing much of Lesotho. Soil fertility enhancement can be achieved through implementation of integrated approaches which can address low soil fertility issues and provide smallholder farmers an alternative to exotic, expensive synthetic fertilizers. The findings above are consistent with those of the FAO's [3] research in Lesotho where benefits were obtained from the *likoti* system, a planting basin method that reduces tillage, establishes a crop residue management protocol, and uses very site-specific but low rate fertilizer applications [11]. This conservation agriculture management system provides advantages that include (1) improved input use efficiency, (2) increased agricultural productivity, and (3) output or yield stability. The same study also showed that tilling the soil causes further degradation and decreases soil productivity, thus increasing farmer dependence on fertilizer inputs. Despite the very well-known advantages of *likoti* [3], digging basins is not an easy task especially if the soil is compacted or has a heavy texture.

Investigating the effect of contrasting soil types, alternative tillage systems, and fertilization rates is therefore important to improve the current maize yields and reduce Lesotho's dependence on imports of such a major staple. The objectives of this study were to: 1) compare optimal N rates, yield, and profitability generated by tillage and no-till methods on vertisol soils, and 2) compare optimal N rates, yield, and profitability of no-till of inceptisol and vertisol soils in the Mohale's Hoek District of Lesotho. The null hypotheses are: 1) till and no-till yields on vertisol soils will not be different, and 2) no-till yield on inceptisol soils will not be different from no-till yields on vertisols.

2. MATERIALS AND METHODS

Field experiments were conducted in the southwest lowlands of Mohale's Hoek District (latitude: 30°8'60S and longitude: 27°28'0E) in the village lands area of Maphutseng, Lesotho, to assess the effect of N, P and K fertilizer rates on maize grain yield under rain fed conditions. The experimental site is located at an elevation of 1553 meters above sea level, and receives an average low and high annual temperature of 8.9°C and 22.8°C, respectively, and rainfall of 811 mm [4]. The fertilizer experiments were conducted on two contrasting soil types classified by Soil Taxonomy [12] as a vertisol and an inceptisol. The former belongs to the Phechela soil series which has a taxonomic classification of a Typic Pelluderts (Phechela fine montmorillonite mesic typic Pelluderts). The other site had a soil classified as the Matela soil series which has a taxonomic classification of a Dystic Eutrochrept.

2.1 Experimental Design

Each site was planted to maize only. Planting was completed under different tillage systems – till and no-till – in combination with different N, P, and K fertilizer rates. Limestone ammonium nitrate (LAN), single super phosphate (SSP) and potassium chloride (KCl) were used as N, P and K sources, respectively. There were four replicates in each N treatment. N application rates were 0, 50, 100, 150 and 200 kg ha^{-1}. Phosphorus and K were applied uniformly at 120 and 80 kg ha^{-1}, respectively. The P and K rates were applied at these levels to ensure their availability would not be a limiting factor in plant growth and increase the likelihood that plant response to N could be detected.

Fertilizer was broadcast over the row immediately following planting and the treatments were laid out in a randomized complete block design (RCBD) with four replicates each. Each plot had 5 rows of maize, planted at 44,444 plants ha^{-1} at a row spacing of 90 cm.

After physiological maturity, the maize was allowed to dry for approximately 3 to 4 weeks. Grain yield was determined by manually harvesting the three center plot rows at the end of the cropping season. Measurements were converted to equivalent yield (tons ha^{-1}) at 15.5% moisture.

2.2 Yield Response Estimation

Plant yield response was estimated by fitting a regression model using crop yield as the response variable (y), and the fertilizer rate as the predictor variable (N), with a linear response plateau (LRP) function [13]. The LRP model is:

$$y_j = min\{\beta_{0,j} + \beta_{1,j} \cdot N_j,\ M_j\} + u_j, \qquad (1)$$

where y_j is maize grain yield (metric tons ha^{-1}) for a tillage method/soil type j = no-till/vertisol, no-till/inceptisol, and till/vertisol; N is the rate of N fertilizer in kg ha^{-1}; M is the maize yield plateau; and u_j is an independent and identically distributed error term with mean zero and a constant variance. The coefficient β_0 is the expected yield when no N is available to the plant. The maize yield plateau is the maximum obtainable yield given plant genetics and growing conditions. Maize yield increase at the constant rate β_1 with respect to N until some other nutrient is limiting [14]. The closed-form solution for biologically optimal N rates, treatment j, is:

$$N_j^* = \frac{M_j - \beta_{0,j}}{\beta_{1,j}}. \qquad (2)$$

Biologically optimal yields (BOY) are determined by evaluating equation 1 at N^*. Note there are two possible yield optima. When $M_j > \beta_{0,j}$, $N_j = N_j^*$, otherwise $N_j = 0$ because of some other limiting factor.

2.3 Economically Optimal Yield, Fertilizer Rates, and Profit

Based on the LRP model, the decision to apply N fertilizer depends on the ratio of the per-unit cost of elemental N (r), prevailing maize prices (p), and the linear response of maize to N (β_1). Accordingly, when the trigger $r/p < \beta_1$, then N_j^* is applied to maximize profit; otherwise, profit is maximized by not applying N:

$$N_j^{EONR} = \begin{cases} N_j^* \; if \;\; r/p < \beta_1 \\ 0, otherwise \end{cases}, \tag{3}$$

where EONR is the economically optimal rate of nitrogen. Profit (π, USD$ ha^{-1}) for treatment *j* is:

$$\pi_j = p \cdot y_j - r \cdot N_j - k_j, \tag{4}$$

where *p* is the maize price (USD $0.26 kg^{-1}, survey reported by Bisangwa [15]), *r* the elemental N cost (USD $1.79 kg^{-1}), and k_j other costs of production ($ ha^{-1}). N costs were collected during site visits to agricultural equipment vendors near the research site. Other operating costs include seed, planting, chemicals (fertilizer, pesticides, and herbicides), labor (e.g., harvesting, planting, weeding), no-till planter depreciation, and chemical application costs (Table 1).

Table 1. Operating costs for no-till and conventional maize systems (US$ ha^{-1})

Activity	No-till	Conventional
Seed	109	135
No-till planter depreciation	8	
Fertilizer application	20	20
Planting	7	29
Hand weeding	3	
Herbicide	13	24
Pesticide	14	23
Harvesting	82	82
Additional labor	84	84
Management overhead	333	333
Total	674	730

These costs were collected during the growing season for conventional and no-till planted plots. Cost other than N were $674 ha^{-1} and $730 ha^{-1} for no-till and tillage operations, respectively. Maximized profit (EOP) is calculated by evaluating equations 2 and 3 at the EONR.

2.4 Statistical Analysis

Univariate statistical analyses of maize grain yield were performed using the SAS Mixed Model Procedure [16]. Means were compared using a least significant difference (LSD) test, with a Type I error rate of 5%.

The parameters β_0, β_1, and *M* were estimated with a nonlinear programming algorithm. White's [17] heteroskedastic robust covariance matrix was used to estimate standard errors of the coefficients. Significance of the regression coefficients were calculated using T-tests. T-tests were also calculated for yield plateaus, EONRs, and profitability evaluated at the regression estimates.

2.5 Monte Carlo Sensitivity Analysis of Optimal N Rates, Maize Yield, and Profit

Sensitivity of biologically and economically optimal N rates, corresponding yields and profits to uncertainty in N costs, and maize prices, and the sampling variability of the estimated model parameters was conducted with a Monte Carlo analysis. Model parameters, maize prices, and N cost were assumed to be random variables drawn from different distributions. At each *m* = 10,000 new realization of the parameter vector, $\theta = \left(\beta_{0,j}^*, \beta_{1,j}^*, M_j^*, p^*, r^*\right)$, *ex ante* optimal N rates, yields, and profits were recalculated.

The distribution of the yield response coefficients ($\beta_{0,j}$, $\beta_{1,j}$, M_j) was simulated as multivariate normal (MVN) random variables,

$$\begin{bmatrix} \beta_{0,j}^* \\ \beta_{1,j}^* \\ M_j^* \end{bmatrix} \sim MVN \left(\begin{bmatrix} \beta_{0,j} \\ \beta_{1,j} \\ M_j \end{bmatrix}, \begin{bmatrix} \sigma_{0,j}^2 & \sigma_{0,j}\sigma_{1,j} & \sigma_{0,j}\sigma_{M,j} \\ \sigma_{0,j}\sigma_{1,j} & \sigma_{1,j}^2 & \sigma_{1,j}\sigma_{M,j} \\ \sigma_{0,j}\sigma_{M,j} & \sigma_{1,j}\sigma_{M,j} & \sigma_{M,j}^2 \end{bmatrix} \right) \tag{5}$$

where the 3 by 3 matrix of $\sigma_{i,j}$'s is the robust covariance estimator of the regression parameters in equation 1, and "*" indicates a random draw from the distribution (Appendix). Maize price was simulated as a log normal random variable,

$$p^* \sim Log\ Normal\left(\mu_p, \sigma_p^2\right) \tag{6}$$

where μ_p and σ_p are the mean ($216.83 Mt^{-1}) and standard deviation ($33.85 Mt^{-1}) of maize prices (Mt ha^{-1}). N prices ($ kg^{-1}) were simulated with a triangular distribution,

$$r^* \sim Triangular(r_{min}, r, r_{max}) \tag{7}$$

where r_{min} = 0.82 kg^{-1}, r_{max} = 3.95 kg^{-1}, and *r* = $1.79 kg^{-1}. The minimum and maximum prices were reported by Moore [18].

3. RESULTS AND DISCUSSION

Maize grain yields were affected by soil type and N fertilizer rates. On the vertisol plots, grain yields ranged from 4.6 to 8.2 tons ha^{-1}, while on the inceptisol plots grain yields were relatively lower ranging from approximately 1.0 to 5.4 tons ha^{-1} (Figs. 1.1 and 1.2). These findings indicate that maize yield did not increase significantly as N fertilizer rates were increased from 50 to 100 and from 150 to 200 kg ha^{-1} in either soil types (Figs. 1.1, 1.2, and 1.3), thus suggesting that high maize grain yields could be maintained without any yield penalty by reducing N fertilization rates from 200 to 150 kg ha^{-1} in both soil types (vertisol and inceptisol). However, the increased yield trend with increasing N fertilization below 150 kg ha^{-1} is consistent and notable but was not statistically significant. This 25% reduction translates to a $25 savings on fertilizer cost assuming that a 50 kg bag of LAN costs 270 Maloti and $1 = 10.93 Maloti. When N fertilizer was not applied, the yields at the inceptisol site were less than a quarter of those on vertisol plots, thus suggesting that the former is deprived of nutrients (Figs. 1.1 vs 1.2).

Grain yields did not differ significantly as the N fertilization rate was increased from 0 to 50 kg ha^{-1} in the no-till vertisol experiment (Fig. 1.1) compared to the no-till inceptisol (Fig. 1.2) and the tilled vertisol experiment (Fig. 1.3). The highest grain yield increases were observed on the no-till inceptisol, with an increase in yield estimated at 1.8 (>150%) and 2.1 (>50%) tons ha^{-1} as N fertilization rates were increased from 0 to 50 and from 100 to 150 kg ha^{-1} (Fig. 1.3), respectively, thus suggesting that the inceptisol soil was more responsive to N fertilizer.

The site with vertisols had relatively higher yields than the site with inceptisols. The vertisol yields ranged from approximately 4.5 tons ha^{-1} to more than 8.5 tons ha^{-1}. On the inceptisol soil, yields ranged from 1.0 ton ha^{-1} to approximately 6.5 tons ha^{-1}. These results may be attributed to the degree of weathering of these soils. Unlike vertisols, the inceptisols at this site are relatively older and nutrient-poor. As a result, because of their generally poor fertility and acidity, the inceptisols cannot sustain high crop yields without soil amendments [3]. An inceptisol, by definition, usually suggests that the soil age is younger - relatively speaking - but in this case the parent materials were highly weathered. This observation agrees with the present experimental results. Side by side comparison between Figs. 1.1 and 1.2 indicates that a rate of 150 kg of N applied ha^{-1} on the inceptisol site is required to achieve the same yield benefit as that obtained at an N application rate of 50 kg ha^{-1} on the vertisol site. Moreover, it was observed that significantly higher yield benefits resulted at relatively higher N fertilizer rates (Figs. 1.1 and 1.2) and that this was somehow affected by the tillage component. Taking Figs. 1.1 and 1.3 as an example, a side by side comparison between the tillage systems indicates that it took double of the amount of fertilizer N applied under tilled vertisol plots (50 kg ha^{-1}) to get the same or approximately the same yield benefits under non-tilled plots of the same soil type (100 kg ha^{-1}). According to Derpsch et al. [6], tilling the soil may benefit crops in the short-term. However, continuous tilling of soils over time leads to a decline in soil fertility due to soil erosion, loss of soil organic matter, soil nutrient leaching, and alteration of soil physical properties.

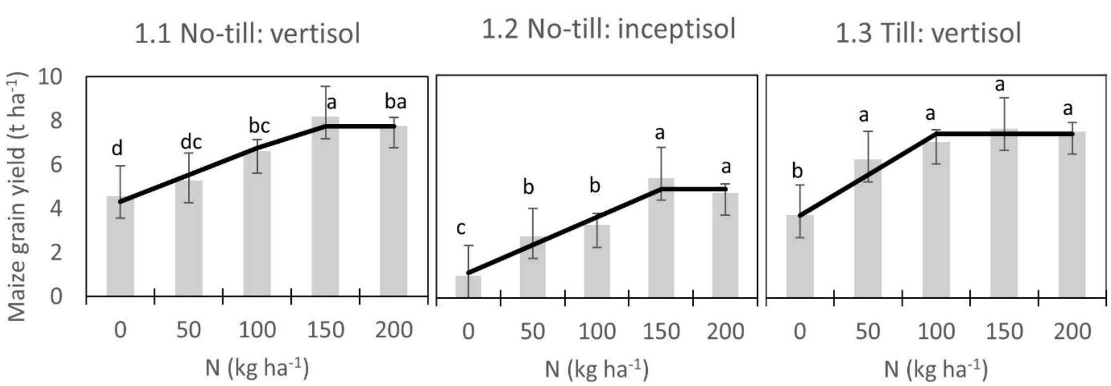

Fig. 1. Maize grain yield response to N fertilizer rates, soil type and tillage systems in the southern lowlands of Mohale's Hoek District, Lesotho

Bars are means with ± 90% confidence intervals. Bars with the same letters are not different at the 5% level. Solid lines are linear response plateau predicted yields based on the regression estimates of Table 2

3.1 Economically Optimal N Rates, Yield, and Profit

The adjusted R^2's ranged between 0.70 (till + vertisol) to 0.75 (no-till + vertisol), suggesting the LRP model explained at least 70% of the variation in the experimental data (Table 2). The estimated LRP parameters for each trial were significant at the 5% level. As implied by the graphical analysis (Fig. 1), maize yield response to N was greatest under the till + vertisol treatment relative to the no-till experiments. For every additional kilogram of N applied, maize yield increased by 0.05 Mt ha^{-1}. Yield response on the no-till treatments was about 50% that of the till + vertisol treatment. This may be partly associated with the type of soil and the short term benefits associated with tillage.

Yield plateaus were similar for the vertisol treatments (7.75 for the no-till trial, 7.37 for tilled plots), and about 50% higher than the yield plateau of the no-till + inceptisol maize yield (Table 2). For all treatments the decision rule trigger – apply N if $r/p - \beta_1$ (or $0.0083 - \beta_1$) – was significantly less than zero, suggesting that profit is maximized when N is applied (Table 2). Economically optimal N rates were similar for the no-till treatments (141 and 150 kg ha^{-1} for the vertisol and inceptisol soils, respectively). For the till + vertisol treatment the EONR was about 50% less than the no-till treatments. The EONR's suggest that about 27.5% 36% of the 200 kg ha^{-1} of N applied as LAN was lost to the environment.

Ex-post estimated profits from the no-till and till vertisol trials were significantly different from zero at the 5% level (\$754.54 ha^{-1} and \$737.96 ha^{-1}, respectively) (Table 2). Economic profit for the no-till + inceptisol treatment was about 84% less than the profit associated with the vertisol soils (Table 2). The net returns point estimate for this treatment was not different from zero (P = 0.16, Table 2). Owing to its inherent characteristics, vertisols are more likely to sustain relatively higher yields than inceptisols by providing more nutrients (particularly N) to the crop in short, medium and long term. These physical properties of vertisols would translate into higher short-term profits, as observed in this analysis. The results of this work on these contrasting soil orders suggests that the soils with the greater intrinsic fertility (vertisols) will usually provide greater and more sustainable profits than lesser developed inceptisols that lack soil properties to consistently support high yields.

3.2 Monte Carlo Simulation of Yield Plateaus, EONR, and Profitability

The simulated yield distributions approximate the parametric fit of the yield data. There is more variability in terms of EONR for the no-till treatments. There were only 4 data points associated with 0-N rates for the till + vertisol treatment. This occurs because the marginal yield response to N is 50% larger than the N response rates estimated for the no-till treatments.

The *ex post* N rate, plateau, and profit estimates appear to be robust. N cost and maize price uncertainty, and sampling variability associated with the trials appear only to slightly affect the EONR, yield plateaus, and profitability point estimates calculated above (Fig. 2). Simulated EONR's are remarkably close to those reported in Table 2. The simulated EONR distributions were skewed right, pulling the Monte Carlo mean EONR estimates to the right of the *ex-post* estimates. In 2% of the simulation cases, 0 kg ha^{-1} N were applied in the no-till + vertisol treatment. For the till + vertisol and no-till + inceptisol trials EONR was greater than zero in more than 99% of the Monte Carlo trials.

Yield plateaus and profit are driven by EONR. *Ex-post* yield plateaus of the no-till treatments (Table 2) appear overstated in the vertisol treatments according to the simulated means (Fig. 3).

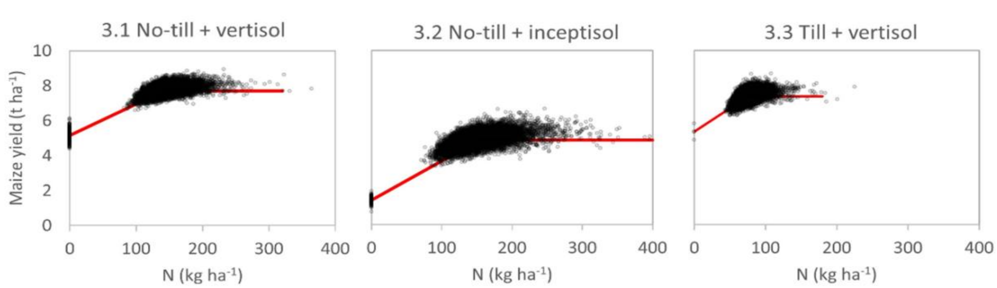

Fig. 2. Simulated maize yields

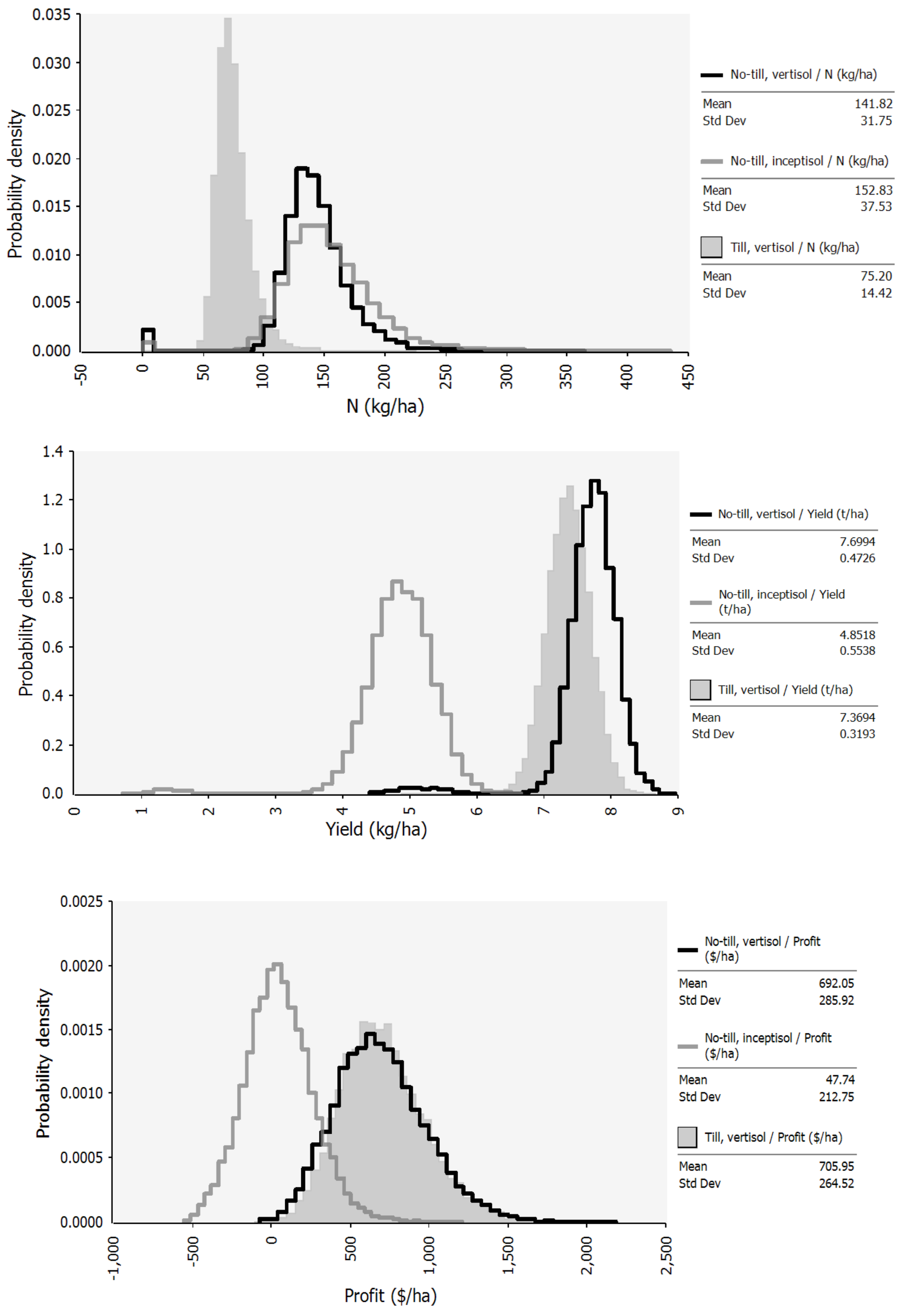

Fig. 3. Monte Carlo simulation (10,000 iterations) of applied N, maize yield, and profits for till and no-till N trials

The *ex-post* profits reported in Table 2 also appear to be overstated relative to the simulated profits. However, in all cases, comparison of the *ex-post* point estimates with the means and standard deviations of their *ex-ante* distributions suggests that these differences are trivial (Fig. 4).

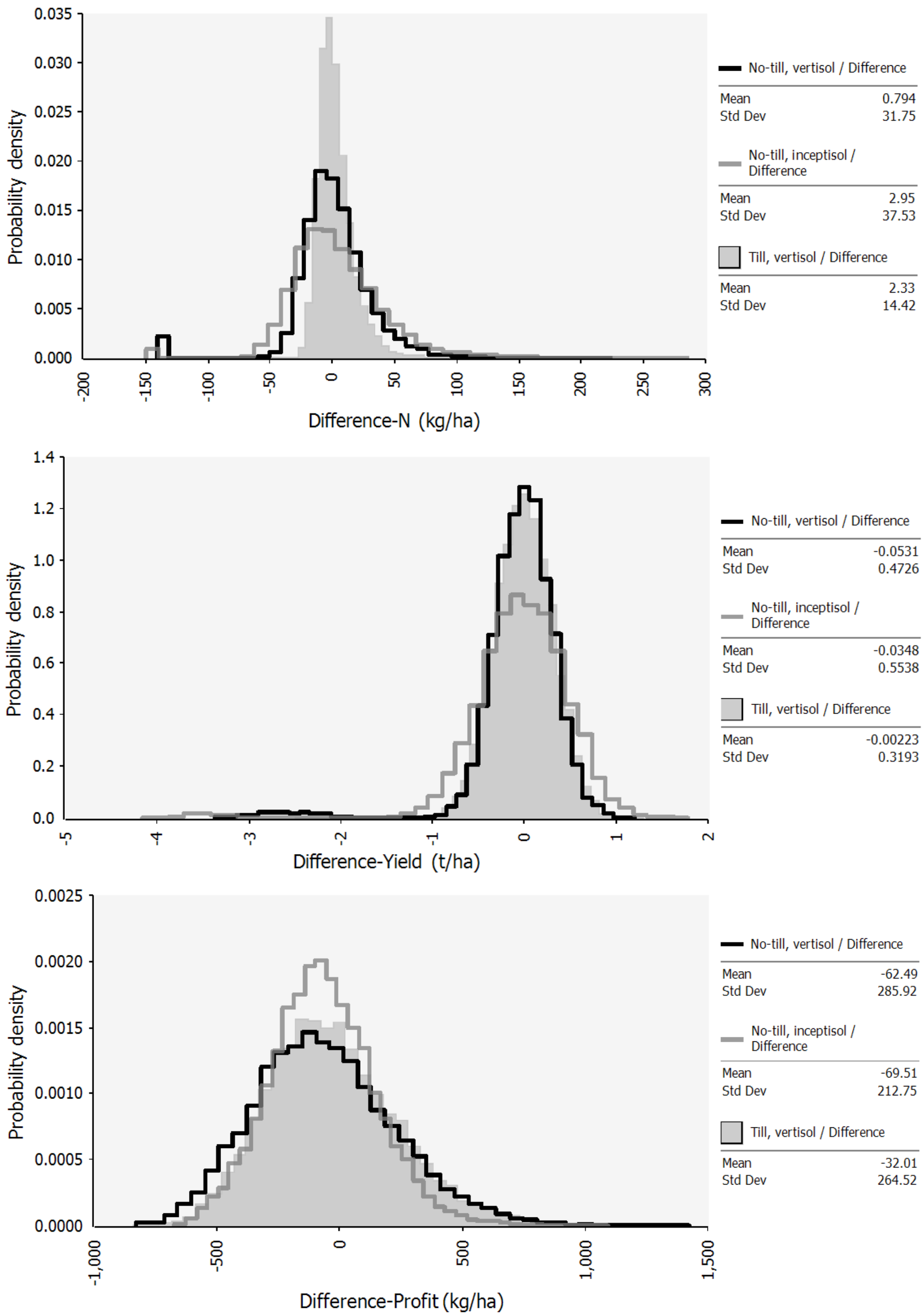

Fig. 4. Differences between point estimates (Table 2) and Monte Carlo simulated values

Table 2. Linear response plateau estimates of maize response to N

	No-till + vertisol	No-till + inceptisol	Till + vertisol
R^2	0.75	0.73	0.70
N	20	20	20
β_0	4.32	1.13	3.71
(t value)	9.10	5.56	7.11
β_1	0.0243	0.0250	0.0503
(t value)	4.23	4.90	4.17
Trigger, r/p - β_1 1/	-0.0161	-0.0168	-0.0420
(t value)	-2.79	-3.29	-3.48
EONR (kg ha^{-1})	141.02	149.88	72.87
(t value)	6.45	4.79	6.17
Yield plateau (tons ha^{-1})	7.75	4.89	7.37
(t value)	26.39	11.09	23.02
Profit (USD ha^{-1})	754.54	117.25	737.96
(t value)	14.18	1.48	12.16

Notes: 1/ Negative values of this function indicate it is profitable to use N, given the prevailing N cost (r) and maize price (p). In other words, the incremental increase in yield from applying an additional kilogram of N is sufficient to cover the cost of an extra unit of N.

4. CONCLUSION

The most important difference across all studies was due to soil type, followed by fertilizer rate and then tillage. Soils classified as vertisols had relatively higher grain yields across the N trials, thus suggesting that the vertisols were more efficient in providing nutrients to maize compared with the inceptisol, a result that emphasized the low fertility status of the highly weathered inceptisol. The findings suggest that N is indeed a major limiting nutrient to maize production in Maphutseng, though it is a well-known fact that most African soils are poor in P. Maximum maize yield was obtained at N rates ranging between 73 and 150 kg ha^{-1}, thus suggesting that applying 200 kg of N ha^{-1} (the highest fertilizer rate tested) under similar conditions is not cost effective. Unlike the non-tilled vertisol and inceptisol conditions, applying 50 kg of N ha^{-1} under tilled vertisol resulted in yield benefits statistically insignificant as compared to applying 100, 150 or 200 kg ha^{-1} of N.

Despite the very well-known impacts of tillage on soil physical, chemical and biological properties, the yield benefits of no-till over tillage practices on vertisols were not evident in this study. Our findings lead us to accept the hypothesis that till and no-till yields on vertisol soils will not be different. We reject the hypothesis that no-till yield on inceptisol soils will not be different from no-till yields on vertisols. However, this observation may be attributed to time. As Thierfelder et al. [7] concluded, it takes at least 4 to 5 years before the yield benefits from combining no-till or reduced tillage practices along with permanent soil cover and crop rotation into maize production become evident. Therefore, the benefits of incorporating one or just a portion of these components per se, e.g. no-till, would take longer to manifest. This assessment agrees with Thierfelder and Wall [19], who observed that significant benefits in maize yield cannot be expected immediately if soil moisture is not a major limiting factor. Based on these results, a similar pattern may be expected if till-inceptisol was tested and compared against no-till of the same soil type.

From an agronomic perspective, it is suggested that 140 to 150 kg N ha^{-1} could be recommended as the N fertilizer rate for both the inceptisol and vertisol no-till maize systems in Maphutseng. On vertisols, and using conventional tillage methods, the optimal N rate is closer to 75 kg ha^{-1}. These N levels assume P and K are not limiting factors. These benefits may be temporary if an integrated nutrient management approach is not adopted. It is also noteworthy that no-till maize nutrient requirements on both highly eroded inceptisols and highly productive vertisols in southern Africa are similar to no-till maize nutrient requirements on more fertile soils in North America. However, it is unclear if the 75 kg ha^{-1} rate on the intensively tilled vertisol would provide consistent and sustainable yields over a longer period.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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APPENDIX

Covariance matrices for the Linear Response Plateau estimates

No-till + vertisol treatment:

$$cov(\beta_1, M, \beta_0) = \begin{bmatrix} 0.0058 & 0 & -0.0466 \\ 0 & 0.2938 & 0 \\ -0.0466 & 0 & 0.4754 \end{bmatrix}$$

No-till + inceptisol treatment:

$$cov(\beta_1, M, \beta_0) = \begin{bmatrix} 0.0051 & 0 & -0.0203 \\ 0 & 0.4405 & 0 \\ -0.0203 & 0 & 0.2241 \end{bmatrix}$$

Till + vertisol treatment:

$$cov(\beta_1, M, \beta_0) = \begin{bmatrix} 0.0121 & 0 & -0.0688 \\ 0 & 0.3203 & 0 \\ -0.0688 & 0 & 0.5221 \end{bmatrix}$$

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