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Abstract
The profitability of fertilizer-N use can be optimized using N response functions specific to climate-based technology extrapolation domains (TED). Crop growth simulation can complement field research for targeting of response functions. The objective

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of this study was to target maize (*Zea mays* L.) N response functions to seven TED in Ethiopia through CERES-Maize simulation of continuous maize over 30 yr. The complete factorial set of treatments included seven levels of N in 25 kg ha^{-1} increments under no-till (NT) and conventional tillage (CT) systems. The CERES-Maize simulated experiments were done for two or three sites per TED. Nitrogen response functions were generated for each TED with tillage-specific functions for three TED with tillage × N interactions. The N rate responses for all TED fit curvilinear to plateau functions but with differing magnitudes and shapes of response. The mean yield with NT was 6% less than with CT, but the difference declined with increased N rate. The economically optimum N rate (EONR) ranged from 65 to 179 and 103 to 243 kg ha^{-1} for high and low-cost fertilizer-N, respectively. The EONR was 6% less and the profit cost ratio was 11% higher with CT compared to NT, indicating greater fertilizer-N need with NT than with CT. The application of N for maize was highly profitable for all TED. The EONR from CERES-Maize were higher than past field research results. This suggests that the CERES-Maize N response functions were most appropriate for well-managed crop production situations in Ethiopia.

Abbreviations:

CP, cost/price ratio, or the ratio of fertilizer N use cost to grain price
CT, conventional tillage
EONR, economically optimal N rate
NT, no-till
PCR, profit cost ratio
TED, technology extrapolation domain

Core Ideas

- CERES-Maize was used to target N response functions in Ethiopia.
- Maize response to N was consistently curvilinear to plateau.
- Maize monoculture under no-till required more fertilizer-N than with tillage.
- The economically optimal N rates differed by technology extrapolation zone.

1 Introduction

The farming systems of Ethiopia are very ecologically diverse with a range of tropical to temperate conditions (GYGA, 2016; HarvestChoice, 2010). Maize (*Zea mays* L.) production is primarily done by smallholder farmers and is very important to food security. National average maize yield potential under rainfed production conditions was estimated to be 12.4 Mg ha^{-1} (GYGA, 2016). However, harvested mean maize yield was 3.4 Mg ha^{-1} for the 5 yr ending in 2016 (FAO, 2018), with yield constrained by soil water deficits and other abiotic, biotic, and management constraints (Admassu, Getinet, Timothy, Waithaka, & Kyotaliyme, 2013; Liben, Midega, Tufa, & Wortmann, 2020; Shiferaw, Prasanna, Hellin, & Banziger, 2011). Nitrogen deficiency is an especially important constraint (Demissie & Bekele, 2017; Shiferaw et al., 2011; Tesfaye et al., 2015a), and therefore fertilizer-N is widely used, but at a low mean rate. Ethiopian farmers are mostly financially constrained in fertilizer use and need high returns on investments with little risk. Optimization of financially constrained fertilizer use for high profitability and low risk needs to consider the farmer's land allocation to different crops, the responses of these crops to applied nutrients, the value of the produce, the costs of fertilizer use, and the money available for fertilizer use (Kaizzi, Mohammed, & Nouri, 2017). Information on maize response to N specific for major technology extrapolation domains (TED) is important for fertilizer use decisions (Van Wart et al., 2013).

Nitrogen response functions can mathematically represent crop response to fertilizer-N, typically with maize yield increasing in a curvilinear manner with increased fertilizer- N rates until the response reaches a peak or plateau (Kaizzi et al., 2017). However, maize response to fertilizer-N is dependent on the local climate, soil characteristics, and crop management practices (Demissie & Bekele, 2017; Liben, Wortmann, & Tirfessa, 2020; Tesfaye, Jaleta, Jena, & Mutenje, 2015b).

Ethiopia has a complex topography and heterogeneous agroecology (FAO, 1978; HarvestChoice, 2010) requiring TED-specific N response functions and other good agronomic practices. The TED were determined to facilitate rapid evaluation and scaling out of currently available and emerging practices (Rattalino Edreira et al., 2018). Essentially, a TED is an area that has sufficiently similar conditions where comparable responses to given management practices can be expected. The TED were defined for Ethiopia using a crop suitability approach that considers the ratio of annual precipitation relative to annual potential evaporation, the annual rate of growing degree day accumulation, and variation in mean monthly temperature during the year (GYGA, 2016; Van Wart et al., 2013). Crop simulation model or field experiment results obtained within a TED are expected to be applicable throughout that TED. There are currently only two maize N recommendations based on field research for Ethiopia, despite many heterogeneous zones in Ethiopia (Demissie & Bekele, 2017). Therefore, it is important to obtain TED-specific fertilizer-N response functions for profitable and environmentally sound fertilizer use optimization in Ethiopia.

Conducting field research to develop robust N response functions and adapting it for the diverse maize growing conditions of Ethiopia would require much researcher time and cost. Geospatial crop growth simulation modeling may be useful for developing TED-specific crop N response functions (Jones et al., 2003; Rezzoug, Gabrielle, Suleiman, & Benabdeli, 2008). For example, in a recent comparison of potential and actual maize yield across a range of cropping systems and environments, Van Ittersum et al. (2013) concluded that use of model simulation with a long-term weather database can provide a more robust estimate than field research because simulation better accounts for climatic variation over the long term. Successful geospatial modeling for the development of N response functions can reduce research cost and shorten the time-lag between development and well-targeted transfer of N recommendations to farmers.

Therefore, the objectives of this study were to (a) to simulate the effect of fertilizer-N on maize grain yield and to generate N response functions targeted to seven TED with and without tillage in Ethiopia where maize is an important crop, (b) determine the economically optimal N rates (EONR) and profit to cost ratios (PCR) for seven TED, and (c) compare EONR derived from the simulation with EONR derived from field results.

2 Materials and methods

2.1 Environmental characterization

Nitrogen response functions were determined for seven TED in Ethiopia with each TED representing >15,000 ha yr^{-1} of maize production. The responses to fertilizer-N were determined for at least two sites per TED and a total of 16 sites representing about 251,700 ha yr^{-1} and >72% of maize production in Ethiopia (Table 1). The TED commonly consisted of two or more dispersed land areas separated by areas of other TED (Liben et al., 2020).

The seasonal rainfall amounts and their inter-seasonal variability were less for sites in TED 7201 which had a relatively short growing season compared with higher rainfall sites in the other TED (Figure 1; Table 1). Sites in TED 7201 were considered to represent low potential

Table 1 Targeted technology extrapolation domains (TED), selected sites in each TED, their dominant soil texture class and order, coordinates, and area of maize production represented by each site in Ethiopia (GYGA, 2016; Jones et al., 2013). A map of these TED was published in Liben et al. (2020)

TED	*Study site*	*Soil texture, order*[a]	*Long.*	*Lat.*	*Elevation* m	*Area* ha
5501	Ambo	L, PHha	37.84	8.96	2,100	17,295
5501	Kulumsa	L, VRha	39.15	8.00	2,200	9,172
6301	Haramaya	SCL, LVcr	42.03	9.40	1,980	3,680
6301	Arsi Negele	L, VRha	38.68	7.35	1,578	10,533
6501	Bako	CL, NTum	37.03	9.07	1,650	10,272
6501	Waliso	C, VRha	37.97	8.55	2,060	17,696
6501	Walkite	C, VRha	37.78	8.27	1,880	27,492
6601	Bahirdar	CL, LVha	37.38	11.58	1,790	20,428
6601	Debremarkos	C, VRha	37.74	10.33	2,470	14,541
6801	Jimma	CL, VRha	36.43	7.84	1,750	39,956
6801	Nekemte	CL, NTum	36.54	9.09	2,110	18,046
7201	Harar	SCL, LVcr	42.10	9.31	1,840	7,878
7201	Melkassa	L, ANsn	39.33	8.40	1,550	26,626
7201	Shire Endasillase	SCL, LPli	38.33	14.10	1,920	10,065
7401	Areka	CL, VRha	37.45	7.04	1,801	10,706
7401	Gelemso	CL, CMcr	40.53	8.81	1,810	7,337
Total						251,723

a. C, clay; CL, clay loam; L, loam; SCL, sandy clay loam; PHha, Haplic Phaeozems; VRha, Haplic Vertisols; LVcr, Chromic Luvisols; NTum, Umbric Nitisols; LVha, Haplic Luvisols; ANsn, Silandic Andosols; LPli, Lithic Leptosols; CMcr, Chromic Cambisols.

maize production areas due to frequent occurrence of soil water deficits and a short growing season, whereas sites in the other higher-rainfall TED represented various relatively high potential maize production areas (Admassu et al., 2013).

2.2 Experimental design

A complete factorial experiment of 14 treatments was simulated for maize over 30 yr with the same treatments on the same land area each year. The response to N was determined for conventional tillage (CT) and no-tillage (NT) with fertilizer-N rates of 0, 25, 50, 75, 100, 125, and 150 kg ha^{-1}. Nitrogen was split-applied with 50% at planting and 50% at

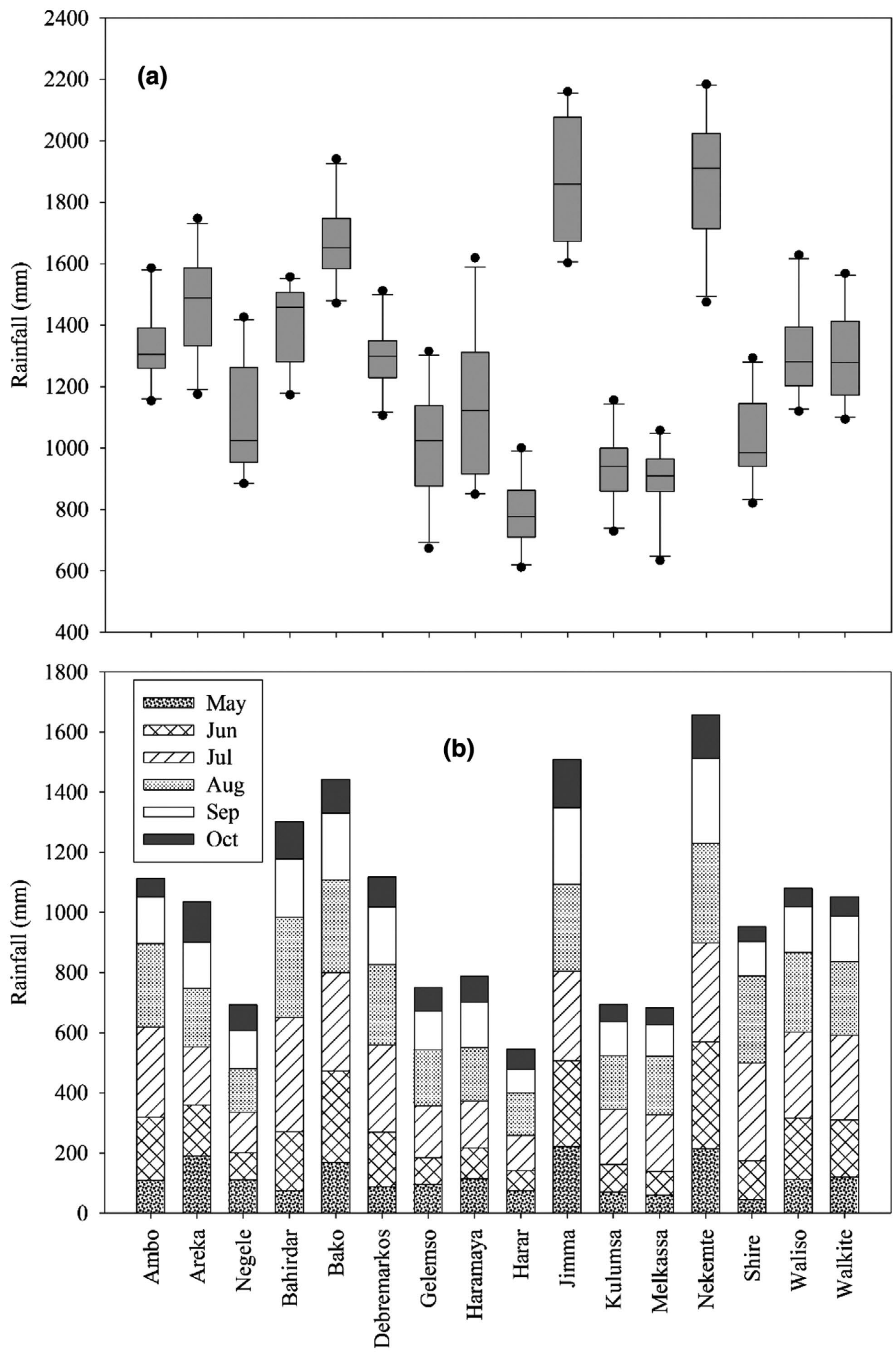

Figure 1 Inter-annual variability (a) and mean seasonal monthly distribution (b) of rainfall at the 16 study sites in Ethiopia. The inter-annual variability and mean monthly distribution were based on 10-yr rainfall data (1998–2007). Negele and Shire are the Arsi Negele and Shire Endasillase sites, respectively.

60 d after planting (Demissie & Bekele, 2017). The CT had three passes with an animal-drawn ard (plow) with <5% residue retention which was incorporated into the soil. The NT had no tillage, with 30% residue retention on the soil surface and hand-planting with a stick to open holes for seed placement. The N rates and tillage practices were designed to represent maize production by smallholder farmers under conventional and conservation agriculture systems in Ethiopia.

2.3 Model selection and description

The Decision Support System for Agro-technology Transfer (DSSAT 4.6) connects several crop and soil simulation models within a decision support system including the Cropping System Model CERES-Maize (Jones et al., 2003). The CERES-Maize simulates the effects of daily weather, soil, and management on maize growth, development, and yield. The DSSAT has sub-modules for simulating the effects of fertilizer-N rate, crop residue cover, tillage, and other practices on soil water, and N and C dynamics, and maize growth and development are simulated with CERES-Maize (Hoogenboom et al., 2019). The CERES-Maize has been extensively calibrated, validated, and used for making decisions in N fertilizer management across diverse environments in sub- Saharan Africa (Liben et al., 2018a; Liben et al., 2020; Ngwira, Aune, & Thierfelder, 2014; Thornton et al., 1995; Thornton, Jones, Ericksen, & Challinor, 2011).

The CENTURY model is an optional component of DSSAT that accounts for the effects of crop residue decomposition on soil organic C turnover and nutrient mineralization. It accounts for the effects of crop residue retention and tillage on runoff, surface albedo, evaporation, surface roughness, and soil texture (Corbeels, Chirat, Messad, & Thierfelder, 2016; Porter et al., 2010). Therefore, CERES-Maize can be used to determine and extrapolate maize N response functions for heterogeneous TED.

2.4 Soil and weather dataset

Evaluation of the treatments designed in this simulation study required long-term daily rainfall, minimum and maximum temperatures, and solar radiation, plus soil profile information for each of the 16 study sites. Measured soil profile data descriptions were incomplete for most study sites and soil profile descriptions from the Global High-Resolution Soil Profile Database for Crop Modeling Applications were used (HarvestChoice, 2015). This soil profile database was formed by combining SoilGrids and ISRIC-AfSIS soil profiles at a 1-km resolution to develop a set of DSSAT compatible soil profiles on a 5 arc-min grid for the globe. The uncertainty associated with the data were reported (HarvestChoice, 2015). The soil profile for each of the 16 simulation sites was taken based on the latitude and longitude of their geographic grid (Table 1).

In preparation for this simulated experimentation, different weather generators and generated weather datasets were evaluated for the complex topography and heterogeneous agroecology of Ethiopia, and the performance and uncertainty associated with generated datasets were reported (Liben et al., 2018a). Data generated with WeatherMan corresponded with measured weather data for Ethiopia (Liben et al., 2018a; Van Wart et al., 2013). WeatherMan was then used to generate 30-yr daily rainfall, maximum and minimum temperature, and solar radiation for the target sites based on 5 yr of observed daily weather data from each of the 16 study sites. These generated daily weather data were used to run CERES-Maize.

2.5 Genetic coefficient and model evaluation

The CERES-Maize was calibrated and validated using field experimental data generated at Bako and Melkassa Agricultural Research Centers in Ethiopia. The two centers represent two different important maize growing agroecologies in Ethiopia. The CERES-Maize parametrization and evaluation (Table 2; Liben et al., 2018a) was done using measured soil profile and daily weather data from the research centers and using results of past field research. These results included grain yield data from 6 yr of field experiments on conservation practices and fertilizer-N rates, 10 yr of maize variety testing and other fertilizer experiments (Liben et al., 2017; Liben et al., 2018b; Mesfin, 2017; Tadesse & Kim, 2015).

2.6 Model setup and simulation

In the CERES-Maize simulation of maize response to fertilizer-N and tillage effects under rainfed condition in Ethiopia, the genetic coefficients for maize cultivar Melkassa- II were used for TED-7201 and cultivar

Table 2 Soil profile properties by depth including lower soil water limit (LL), drained soil water upper limit (DUL), saturated upper limit (SAL), bulk density (BD), organic C (OC), total N (TN), P, pH in water, cation exchange capacity (CEC), clay and silt content of the soils used in DSSAT simulations. LL, DUL, and SAL were calculated using DSSAT 4.6 CSM

Depth	*LL*	*DUL*	*SAT*	*BD*	*OC*	*Clay*	*Silt*	*TN*	*P*	*pH*	*CEC*
cm		*cm³cm⁻³*		*g cm⁻³*		*g kg⁻¹*			*mg kg⁻¹*		*cmol kg⁻¹*
Bako Agricultural Research Center											
15	0.244	0.371	0.446	1.13	25.4	409	244	0.9	27.2	5.6	43
30	0.259	0.385	0.455	1.16	19.4	435	234	0.7	17.1	5.7	51
60	0.272	0.399	0.463	1.21	12.4	458	223	0.6	21.2	5.9	52
100	0.273	0.399	0.462	1.27	7.2	459	216	0.8	22.4	6.0	37
200	0.264	0.389	0.455	1.32	4.1	444	213	0.9	16.5	6.2	27
Melkassa Agricultural Research Center											
15	0.094	0.343	0.393	1.19	10.6	201	452	1.2	17.3	7.3	33
30	0.188	0.337	0.387	1.23	10.4	194	471	1.6	12.4	7.5	32
60	0.162	0.348	0.398	1.24	10.3	192	493	2.1	10.1	7.6	34
100	0.186	0.352	0.401	1.25	10.1	183	513	2	7.4	7.8	34
200	0.209	0.378	0.428	1.24	10.1	185	511	1.6	6.6	7.9	34

BH546 were used for the remaining higher potential TED (Liben et al., 2018a; Table 3). Urea (46–0–0) was the N source. Crop management information, soil properties, and crop residues measured at the start of field experiments conducted previously at Melkassa and Bako research centers were used as input to run CERES-Maize. Reported information from Melkassa was used for TED-7201 and information from Bako was used for the other TED (Liben et al., 2017, 2018b). Soil organic matter content was initialized in the CENTURY model following the procedure of Porter et al. (2010), in which antecedent simulations were run until predicted soil organic C reflected the measured soil organic C at the start of the actual experiment (Liben et al., 2017, 2018b).

The CERES-Maize simulations were conducted for rainfed continuous maize with 45,000 maize plant ha^{-1} for TED 7201 and 43,000 plant ha^{-1} for all other sites. Planting times and other practices were according to the recommendations for each site (Fantaye, 2016; Liben et al., 2018b). Full control of weeds, diseases, and insect pests and adequate supply of all essential nutrients other than N were assumed. Attainable yields were simulated for water and N limited conditions in the seasonal analysis mode over 30 yr using the WeatherMan generated daily weather data and HarvestChoice soil profile information for the target sites in each TED.

Table 3 Calibrated genetic coefficients for maize cultivars adapted to high (BH546) and low (Melkassa-II and MHQ138) potential technology extrapolation domains in Ethiopia. Adapted from Liben et al. (2018a). PD, photothermal day.

Coefficient	*Definition*	*BH546*	*Melkassa-II*	*MHQ138*
P1	Thermal time from seedling emergence to the end of the juvenile phase (PD)	248	180	280
P2	Extent to which development is delayed (expressed as days)	0.70	0.80	0.30
P5	Thermal time from silking to physiological maturity (PD)	958	675	720
G2	Maximum possible kernel plant^{-1}	436	675	668
G3	Kernel filling rate during the linear grain filling stage (mg d^{-1}).	12.35	5.50	6.50
PHINT	Phylochron interval (PD)	49.0	50.0	38.9

2.7 Data and analysis

2.7.1 Model validation

Normalized deviations values [(Yi − Xi)/Xi, where Xi is observed and Yi is simulated data] were calculated to determine the overall performance of CERES-Maize (Mitchell, 1997). A plot of normalized deviation against the observed variable was used to detect patterns in the predictive ability of the model (Bonifas & Lindquist, 2006; Mitchell, 1997). The average of the normalized deviations provides an estimate similar to a coefficient of variation (Lindquist, 2001). Therefore, the smaller the average of the normalized deviations, the greater the accuracy in predicting observations. The plus–minus sign (±) of the average of the normalized deviations indicates whether the model over- or under-predicts observations (Bonifas & Lindquist, 2006).

2.7.2 Maize N response function

An analysis of variance (ANOVA) combined across TED was applied to CERES-Maize grain yield to test the main and interaction effects of N application rate, tillage system, sites, and TED using R software v3.2.5 (https://cran.r-project.org/bin/windows/base/old/3.2.5/). Percent variation for each treatment-associated source of variance was determined to indicate the agronomic importance of each main effect or interaction as the ratio of sum of squares for the source of variation to total sum of squares associated with treatments multiplied by 100. Significant sources of variation that accounted for ≥0.3% of the total variation in yield were considered to be agronomically important and therefore described and interpreted.

The N response functions were generated separately for NT and CT tillage for three TED that had N rate by tillage interaction effects, but only one response function combined over tillage practices was generated for the other TED. Asymptotic functions were fitted using R software v3.2.5 for curvilinear to plateau response to N rate: $Y = a - bcr$, where Y is yield (Mg ha^{-1}), a is yield at the plateau (Mg ha^{-1}), b is the maximum potential yield increase due to application of N (Mg ha^{-1}), c is a curvature coefficient, and r is the N application rate (kg N ha^{-1}).

2.7.3 Fertilizer-N economic analysis

A partial budget analysis was limited to fertilizer-N use costs and farmgate values of increased maize grain production which fluctuate greatly within and across years in Ethiopia (Demissie & Bekele, 2017). Therefore, determinations of EONR and PCR were done with urea-N use cost to grain price ratios, hereafter called cost/price ratios (CP), of 5, 10, and 15 kg kg^{-1} (cost of 1 kg of N use in terms of the value per kg of maize grain). For example, the partial budget analysis of Demissie and Bekele (2017) used a maize grain farmgate value of 5 Ethiopian birr (ETB) kg^{-1} and a fertilizer-N use cost of 43 ETB kg^{-1} N for a CP of 8.6. Mean EONR and PCR were also determined for each TED and compared to EONR derived from field research and to current N recommendations (Demissie & Bekele, 2017).

The curvilinear to plateau N response functions were used to calculate EONR for N rates of 0 to 200 kg ha^{-1}. To obtain PCR, profit was calculated as the value of the yield increase minus the cost of fertilizer-N use with this difference divided by the cost. Both EONR and PCR were determined either for TED or by tillage within TED where the N by tillage interaction was significant.

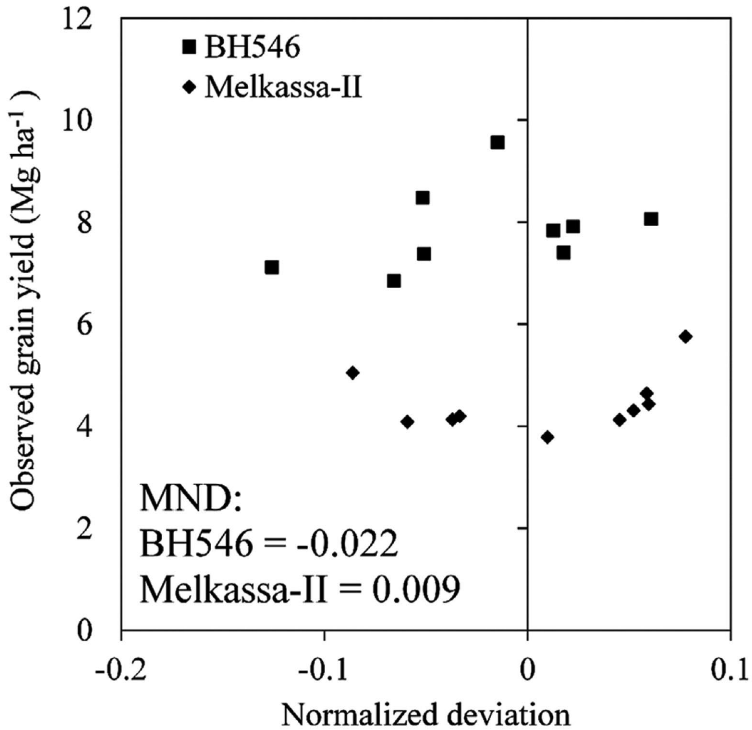

Figure 2 The normalized deviation and its mean (MND) to compare simulated with observed grain yield of maize cultivar BH546 for high potential areas (9-yr maize grain yield data) and maize cultivar Melkassa-II for low potential areas (10-yr maize grain yield data). Simulations were with 73 and 41 kg ha^{-1} N rates for BH546 and Melkassa-II, respectively.

3 Results

3.1 Model performance evaluation

Model evaluation based on 10 yr of data from the national variety experiments illustrated more than 95% of predictions were within ± 10% of observations (Figure 2). The means of normalized deviations (MND) were −0.022 for BH546 and 0.009 for Melkassa-II. CERES-Maize acceptably predicted the effects of fertilizer-N rates and of tillage with −0.05 < MNR <0.05 (Figure 2, 3). Therefore, CERES-Maize was used with confidence to simulate maize response to N rates under different tillage systems.

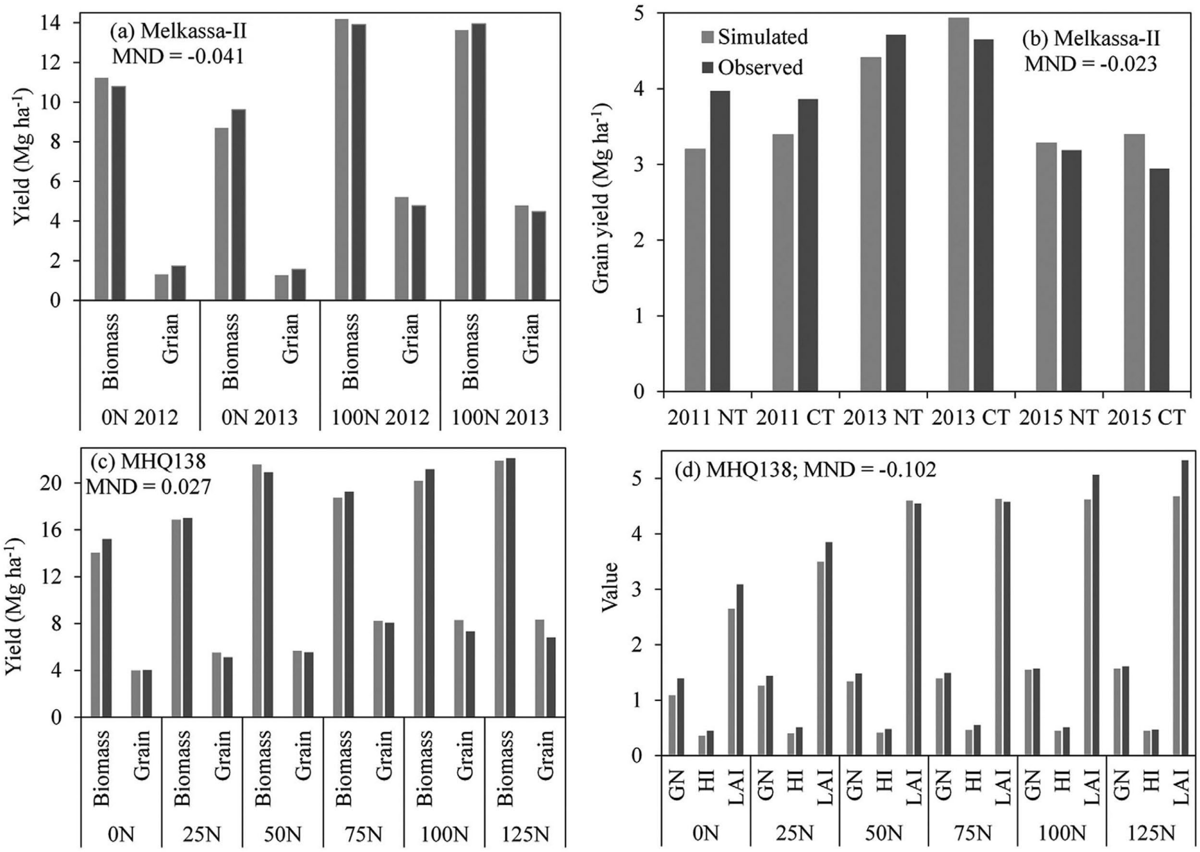

Figure 3 Mean of normalized deviation (MND) for simulated compared to observed maize grain yield (Mg ha^{-1}), aboveground biomass (Mg ha^{-1}), grain N (GN, %), harvest index (HI), and maximum leaf area index (LAI) at maturity. The conventional tillage (CT) consisted of three passes with an animal-drawn ard (plow) with <5% residue retention and NT had no tillage and 30% residue retention on the soil surface with a stick used to open planting holes. The simulations were with maize cultivar Melkassa-II and MHQ138.

3.2 Simulated maize grain yields

The mean yield increase with 150 compared with 0 kg N ha^{-1} was 5.89 Mg ha^{-1} and 150% (Table 4, 5; Figure 4). The three-way interaction of site × tillage × N rate was not significant for any TED (Table 4). The site × N rate interaction was significant for six TED and accounted for >0.3% of the treatment-related variation in five TED. The grain yield increase with 150 compared with 0 kg N ha^{-1} was 65% greater at Kulumsa than with Ambo for TED 5501, 27% greater at Bako than with Waliso and

Table 4 Main and interaction effects on simulated maize grain yield in Ethiopia of tillage (T), N rate, and technology extrapolation domain (TED). The agronomic importance is indicated as the percent of total variation due to treatment-related effects for each source of variation (SV). Reported values indicate the probability of significant effects

		TED						
SV	*df*	*5501*	*6301*	*6501*	*6601*	*6801*	*7401*	*7201*
					%V			
Site (S)	1	***	***	***	***	***	***	***
T	1	3.1***	3.7***	0.3***	1.0***	0.1***	1.9***	0.7***
N rate	6	89.1***	95.9***	97.3***	97.9***	99.4***	97.0***	93.7***
S × T	1	2.4***	0.3***	0.0*	0.0ns	0.0ns	0.9***	0.1*
T × N	6	0.1ns	0.0ns	0.1**	0.1*	0.0ns	0.1ns	0.4***
S × N	6	5.2***	0.1ns	2.3***	1.0***	0.4***	0.1ns	4.9***
S × T × N	6	0.1ns	0.1ns	0.0ns	0.0ns	0.0	0.0ns	0.2ns
Error	812							
ANOVA combined across TED								
TED	6							
T	1	1.3***						
N	6	93.3***						
TED × T	6	0.4***						
T × N	6	0.1*						
TED × N	36	5.0***						
TED × T × N	36	0.0ns						
Error	6622							

* Significant at the .05 probability level;
** Significant at the .01 probability level;
*** Significant at the .001 probability level; ns, not significant.

Walkite for TED 6501, 20% greater for Bahirdar than with Debremarkos for TED 6661, 8% greater for Nekemte than with Jimma for TED 6801, and 46% greater for Harar than with the mean for Melkassa and Shire Endasillase for TED 7201.

The tillage × N rate interaction affected grain yield for TED 6501, 6601, and 7201 but accounted for ≤0.4% of the treatment-related variation in grain yield in these TED. These interactions were due to greater yield response to N with NT than with CT (Table 4; Figure 4). The yield advantage of CT relative to NT decreased with increasing N application but was not affected by years since the start of the simulation. Across all TED, there was a mean yield advantage of 6.1% or 0.47 Mg ha^{-1} with CT compared with NT, but the TED by tillage interaction accounted for 0.4%

Table 5 The N response function coefficients and the coefficient of determinations obtained using the CERES-Maize simulated maize grain yield response to N rates under the two tillage systems which were used to maximize profit per hectare. The numbers in the first column are code for the targeted technology extrapolation domains (TED) in Ethiopia

TED	*Tillage*[a]	*ab*	*b*	*c*	r^2
5501	CT and NT	10.285	6.174	0.986	.68
6301	CT and NT	14.665	9.073	0.990	.78
6501	CT	10.835	6.238	0.981	.92
6501	NT	10.836	6.657	0.982	.93
6601	CT	12.983	7.851	0.990	.70
6601	NT	12.946	8.407	0.990	.71
6801	CT and NT	12.046	8.739	0.988	.95
7201	CT	5.227	3.500	0.971	.94
7201	NT	5.284	3.928	0.976	.86
7401	CT and NT	12.978	8.435	0.988	.80

a. CT, conventional tillage with three passes with animal-drawn ard with <5% residue retention; NT, no-till and 30% residue retention on soil surface with planting using a stick to open holes for seed placement.

b. The coefficients *a*, *b*, and *c* are for the asymptotic function of $Y = a - bc^r$. *Y*, yield; *a*, yield at the plateau (Mg ha^{-1}); *b*, the maximum yield increase due to application of the nutrient (Mg ha^{-1}); *c*, a curvature coefficient; *r*, the nutrient application rate (kg ha^{-1}).

of the treatment-related variation in grain yield (Table 4). The site × tillage interaction was significant for five TED but accounted for >0.3% of the treatment-related variation in grain yield for TED 5501 only where tillage had little effect at Ambo but grain yield was 21% greater with CT than with NT at Kulumsa.

3.3 Response functions and economically optimum N rates

There was a yield response to applied N for all TED with N rate accounting on average for > 93% of the treatment-related variation in yield (Table 4). The significant TED by N rate interaction accounted for 5% of the treatment-related variation in yield and was due to differences in magnitude and shape of responses (Table 5; Figure 5). The coefficient of determinations (R^2) for the fitted N response functions were > 0.7 for all TED. The TED 6301 had a near-linear response with a large b coefficient. The yield increase at 150 compared with 0 kg N ha^{-1} was greatest in TED 6801 and least in TED 7201 with CT. The EONR was greater for NT than

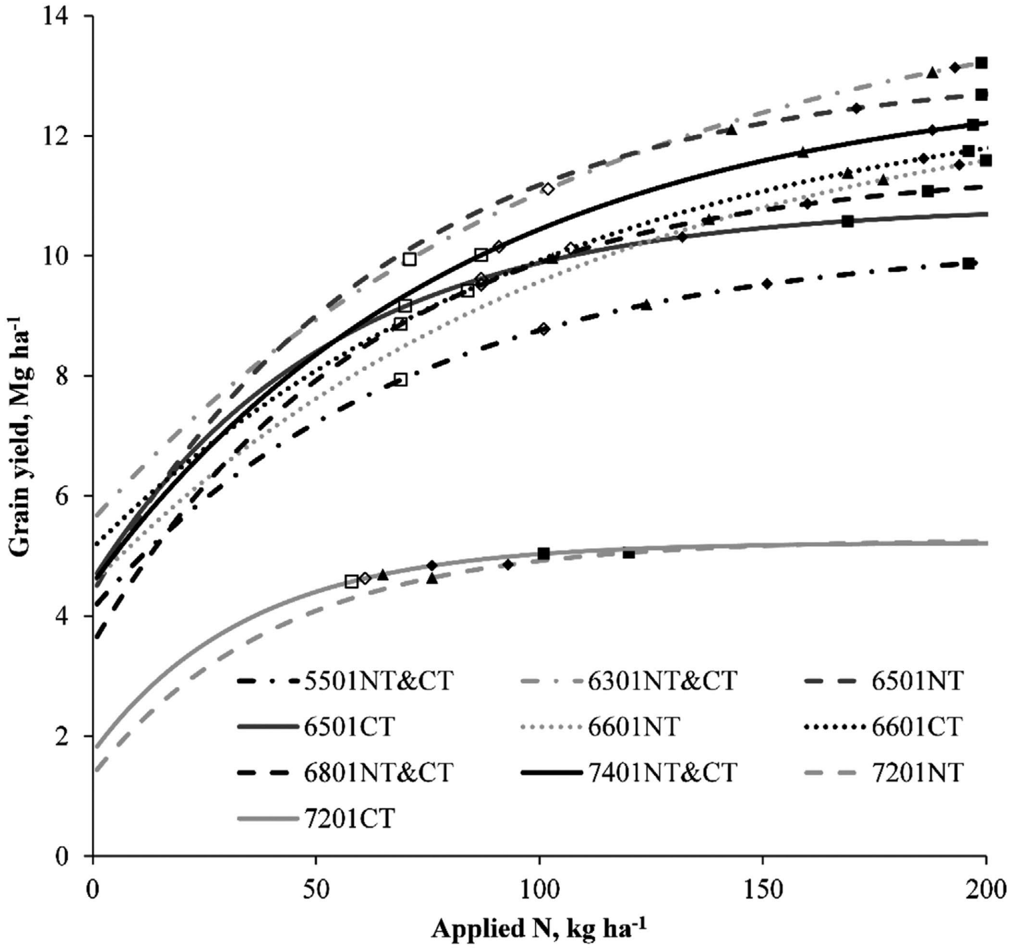

Figure 4 The CERES-Maize simulated yield responses to applied N for the seven technology extrapolation domains (TED) in Ethiopia, accounting for significant N rate × tillage interactions in TED 6501, 6601, and 7201. The economically optimum N rate (EONR) based on simulated results for fertilizer-N cost to grain price ratios of 5, 10, and 15 was represented by the black filled square, diamond, and triangle markers, respectively. The EONR generated from field research results were represented by open diamonds and the recommended N rates were represented by the open squares (Demissie & Bekele, 2017). Conventional tillage (CT) consisted of three passes with an animal-drawn ard with <5% residue retention. No-till (NT) had no tillage and 30% residue retention on the soil surface with a stick used to open planting holes

CT at all TED where the tillage by N rate interaction was significant (Figure 5). For the current CP of 8.58, EONR was greater with CERES-Maize simulation compared to the EONR determined solely from field research results and to the current recommended N rates for CT (Demissie & Bekele, 2017). The CERES-Maize EONR compared to EONR from field research and to the current recommendation N rate were, respectively:

30 and 51% higher for TED 5501; 44 and 61% higher for TED 6301; 30 and 43% higher for TED 6501; 41 and 58% higher for TED 6601; 41 and 42% higher for TED 6801; 51 and 52% higher for TED 7401; and 14 and 15% higher for TED 7201 (Figure 5).

3.4 Fertilizer nitrogen economics

Net returns on investment in fertilizer-N were determined for the current CP of 8.58 (Figure 5), and also for CP of 5, 10, and 15 for TED with significant N rate × tillage interaction (Figure 6). The *x*-axis gives the

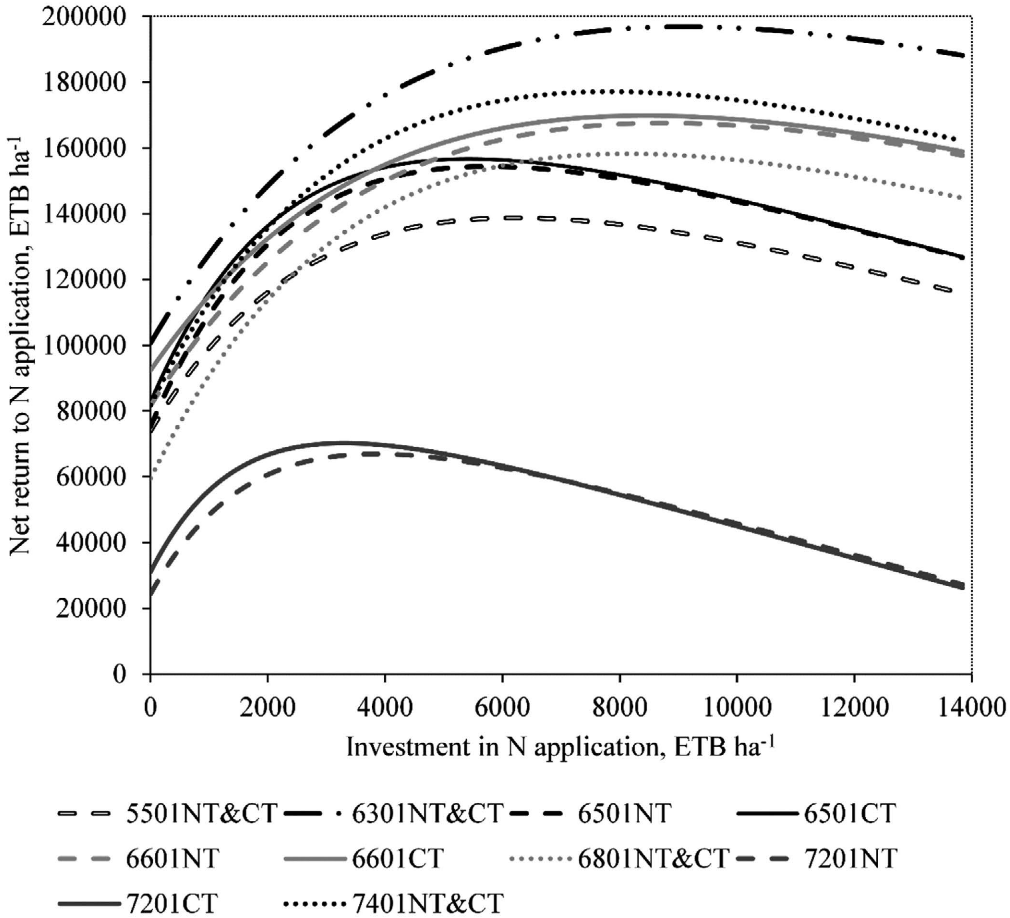

Figure 5 Net returns to investment in fertilizer-N based on CERES-Maize grain yield responses for seven technology extrapolation domains in Ethiopia with the current cost of one kg of fertilizer-N use cost equal to the value 8.58 kg of grain. The N rate by tillage interaction was addressed for TED 6501, 6601, and 7201. The CT consisted of three passes with an animal-drawn ard with <5% residue retention and NT had no tillage and 30% residue retention on the soil surface with a stick used to open planting holes.

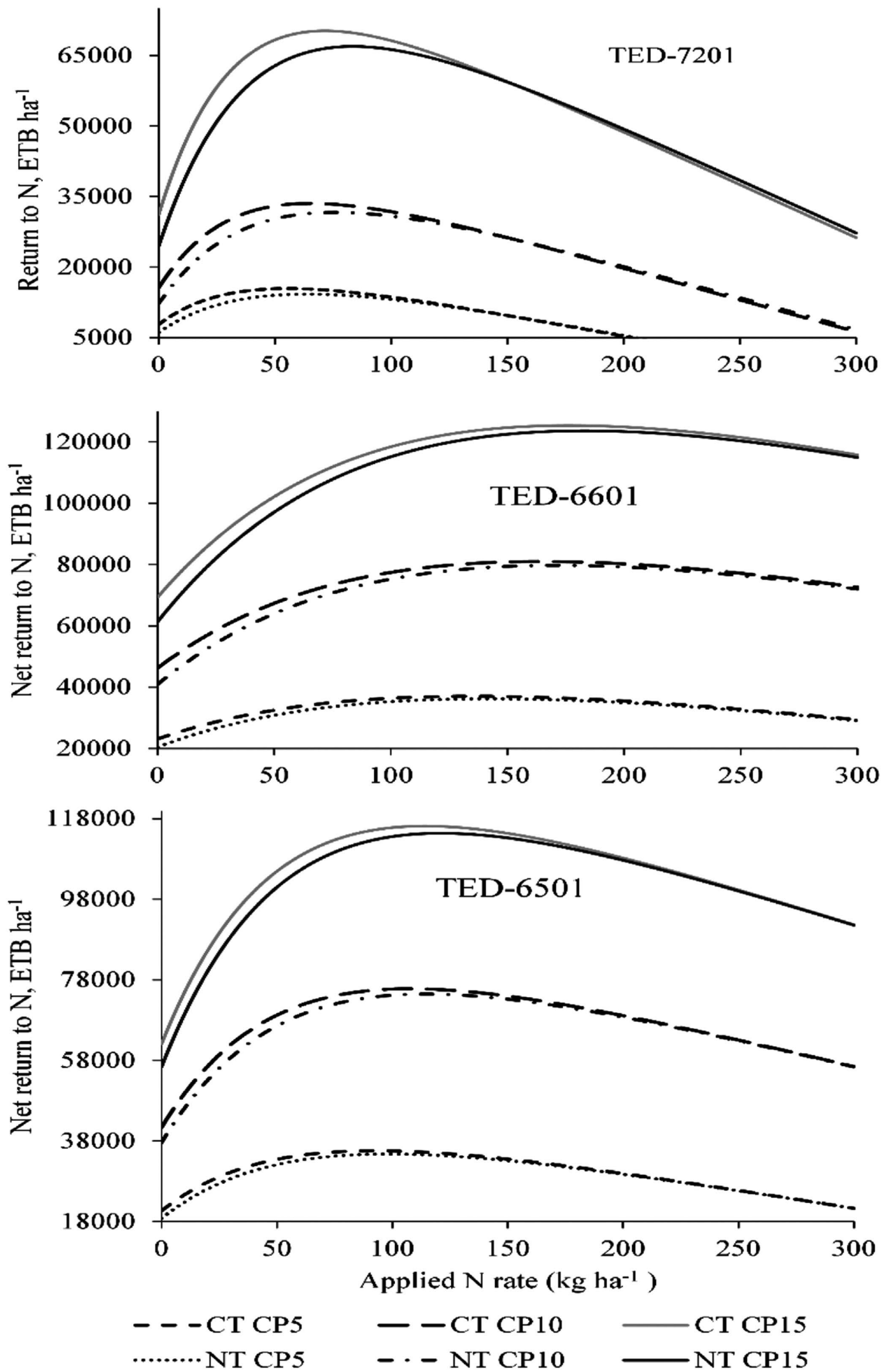

Figure 6 Net return to N rates for CERES-Maize grain yield under conventional tillage (CT) and no-till (NT) systems for the cost of fertilizer-N use to 5, 10, or 15 times the grain price (kg kg^{-1}; CP5, CP10, and CP15). The N rate by tillage interaction was significant for technology extrapolation domains (TED) 6501 and 6601 but not for TED 7201. The CT consisted of three passes with an animal-drawn ard with <5% residue retention and NT had no tillage and 30% residue retention on the soil surface with a stick used to open planting holes

investment in applied N (ETB ha^{-1}). The *y*-axis gives net returns on investment in N application. When the slope of the curve is steeply positive, net returns to investment are very high. As the amount invested increases (the *x*-axis) the slope decreases but if still upward, profit is increasing. The N rate, CP, and TED were the major determinants of the PCR of N with much less effect due to tillage. Nitrogen application was profitable for all CP evaluated. Net returns at EONR were greater with CT than with NT for TED where the N × tillage interaction was significant. Net returns to applied N were more sensitive to the N rate as CP increased, and the returns to N were greater with CP = 15 than CP = 5 or 10 across the TED for both tillage types. The EONR, averaged across CP, was 6% greater with NT than CT, but mean PCR was 11% higher with CT than NT (Table 6). The lowest and highest EONR were with TED 7201 and 6301, respectively. The PCR ranged from 2.47 to 10.74 and 2.09 to 10.07 for CT and NT, respectively. The lowest PCR were at TED 7201 with NT and at TED 6801 with CT. The highest PCR was at TED 6501.

Table 6 The economically optimal N rate and profit cost ratio for the three fertilizer cost/grain price ratios (CP, kg N kg^{-1} grain) determined from CERES-Maize simulated maize grain yield for seven technology extrapolation domains (TED) in Ethiopia

	TED											
	5501	*6301*	*6501*		*6601*		*6801*	*7201*		*7401*	*Overall mean*	
CP	*Mean*	*Mean*	*CTa*	*NT*	*CT*	*NT*	*Mean*	*CT*	*NT*	*Mean*	*CT*	*NT*
Economically optimal N rate, kg ha^{-1}												
5	199	243	166	175	229	242	232	103	121	239	199	210
10	151	219	129	137	206	212	195	77	93	188	164	174
15	123	179	108	115	165	172	162	65	76	156	135	143
Profit to cost ratio												
5	8.05	9.40	10.74	10.07	8.65	8.09	7.91	7.82	6.39	8.54	8.93	8.15
10	4.39	4.22	5.99	5.51	3.82	3.64	3.75	4.32	3.24	4.49	4.58	4.02
15	3.03	2.89	4.20	3.80	2.64	2.44	2.45	2.83	2.09	3.06	3.14	2.70

a. CT, conventional tillage of three passes with animal-drawn ard with <5% residue retention; NT, no-till with 30% residue retention on soil surface and planting using a stick to open holes for seed placement.

4 Discussion

4.1 Effect of tillage types and nitrogen rates

Overall, CERES-Maize simulated grain yield was 6% less in NT than with CT (Table 4), and the difference declined with increased N rate agreeing with the results of Mupangwa et al. (2019) and Diaz-Zorita, Duarte, and Grove (2002). This could be due to the increased N supply offsetting the N immobilization in a mulched soil (Liben et al., 2018b; Mupangwa et al., 2019). It suggests value in rotating maize with a legume crop versus maize monoculture in NT systems. Based on field research, Liben et al. (2017, 2018b) reported mixed results when comparing maize yield and yield response to fertilizer- N in NT versus CT in Ethiopia. Others have reported much greater yield benefits of using NT or conservation agriculture over CT (Laborde, Wortmann, Blanco-Canqui, Baigorria, & Lindquist, 2020; Pittelkow et al., 2015). The tillage effect in the current study was likely smaller than that reported elsewhere because the CT tillage with an animal-drawn ard used in our study was less aggressive than tillage with a tractor-drawn plow or disk. Although simulation was for three ard passes, the ard tillage is shallow and slow moving with soil slowly pushed to the sides in a manner not likely to be very destructive of soil aggregation. Moreover, the NT practice with retention of only 30% of crop residues might have diminished NT yield versus 100% residue retention (Laborde et al., 2020). We used the smaller retention value because smallholder farmers in Ethiopia value crop residue for livestock feeding, and acceptance of greater residue retention is not likely. Given these circumstances it appears that realistic use of NT has minimal yield benefit over CT in Ethiopia, which agrees with results reported for South Africa (Mupangwa et al., 2019).

The simulated maize grain yield response to N applied varied greatly among TED (Table 4, 5; Figure 4). The site× N rate interaction accounted for ≥2.3% of the treatment-related variation in yield for three of the seven TED, indicating that either a site did not fit well within a TED or that some TED need to be more narrowly defined. For such TED, the main effect of N rate accounted for 17 to 42 times as much variation in yield response versus the site × N interaction effect. This validates the use of TED while realizing that some TED might be better defined.

4.2 Response functions and fertilizer-N profitability

CERES-Maize showed a large yield increase with increasing N at low rates and a declining rate of yield increase at higher N rates until yield reached a plateau (Figure 4; Table 5). Such response curves are typical and provide a basis for profit optimization from fertilizer use (Jansen, Wortmann, Stockton, & Kaizzi, 2013; Kaizzi, Wortmann, & Jansen, 2013; Liben et al., 2020). Fertilizer N use was profitable at all TED (Table 6). The response functions can be used for maize production that is not financially-constrained to determine the EONR for the current CP (Figure 4). Financially constrained farmers can optimize returns on their limited investment in fertilizer-N by operating at a relatively steep part of the response curve and applying to more land at less than EONR (Figure 5).

The EONR and PCR decreased with increased CP. The PCR >1 suggests that financially constrained farmers of all TED are likely to find fertilizer-N application to maize to be sufficiently profitable to justify the investment (Wortmann & Ssali, 2001). The PCR for TED 6501 revealed especially high profit potential. The effect of CP on the profitability of fertilizer use suggests a need to adjust N rates according to CP as others have reported (Kaizzi et al., 2012a, 2012b; Liben et al., 2020; Wortmann et al., 2018). The CP might be reduced by storing grain to sell later at higher prices more efficient marketing, improved access to credit, more efficient fertilizer supply, and agricultural subsidies (Heisey & Mwangi, 1996). The N response coefficients determined from CERES-Maize data could be applied to generate other economic variables in addition to EONR and PRC, such as value/cost ratios, with the same or other CP.

Compared with CT, NT did not improve the economics of fertilizer-N use for maize in Ethiopia. The slightly higher EONR with NT compared with CT for the three CP indicated that NT, requires on average, 10 kg ha^{-1} more N application to maximize profit ha^{-1} (Table 6; Figure 5). However, the tillage × N rate interaction was significant in only three of seven TED, and accounted for <0.5% of the treatment-related variation in grain yield, indicating that separate N rate recommendations for CT and NT are not justified (Table 4). Despite the greater yield stability and low risk under NT as reported in different findings (Liben et al., 2017, 2018a) and the potential soil conservation benefits of NT, the mean 6% yield reduction with NT may hinder its adoption in Ethiopia.

4.3 Comparison of simulated and observed ONR and its implication

The CERES-Maize based EONR were consistently higher than the recommended N rates and EONR determined solely from field research results at all TED (Demissie & Bekele, 2017; Liben et al., 2020). For comparable N rates, mean CERES-Maize yields in this experiment were similar to the mean yields used for model calibration and validation (Figure 3, 4). However, the experimental N rates reached far above the N rates used in experiments which were the source of calibration and validation data (Liben et al., 2018a). Therefore, CERES-Maize may have overestimated maize response to the higher N rates. Also, the simulations were for attainable yields with only water and fertilizer-N limitations. The crop growth constraints encountered in the experiments used for CERES-Maize calibration were likely many more than N and water-related constraints, and these may not have been fully accounted for in model calibration, especially for high simulated yields. The EONR determined with CERES-Maize are likely to be most valid for high levels of management that adequately mitigate biotic and abiotic constraints to crop growth and less valid for financially constrained management by typical smallholders.

Any N application at lower rates than the simulated EONR implies less than maximum potential profit per ha to fertilizer-N use but rates of less than EONR give higher PCR. The higher simulated EONR with NT than with CT showed that more fertilizer-N was required to maximize profit per hectare under NT, but the extra N had a low PCR. The PCR is an especially important consideration to financially constrained farmers who need high returns on their small investments. They can optimize profit by applying a limited amount of fertilizer-N at less than EONR to more land than applying at EONR to less land.

5 Conclusions

Nitrogen management is critical to maximizing the profitability and productivity of maize with sustainable soil productivity. Nitrogen response functions can be generated with CERES-Maize specific to TED assuming adequate mitigation of other constraints to maize growth. Response functions depended on tillage type for some of the TED. The N response functions determined from simulated results can be applied to determine EONR and PCR to optimize N use in well-managed maize production situations. The EONR and profit potential from fertilizer-N varies greatly with TED. Grain value relative to the cost of fertilizer-N use greatly affects EONR and PCR. Net returns to financially constrained investments in fertilizer-N use can be greatly increased by applying the limited fertilizer at less than EONR to more land. The profitability of fertilizer N use could be further improved through subsidization of fertilizer N use and by enabling farmers to use stored grain to obtain credit and delay grain sales for more favorable prices.

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