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Narrowing crop yield gaps in Ethiopia under current and future climate: A model-based exploration of intensification options and their trade-offs with the water balance

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ABSTRACT

In the Central Rift Valley of Ethiopia (CRV), actual productivity of most cereals is less than 3 t ha^{-1} associated with low input use and poor crop management. After calibrating and validating the Agricultural Production System Simulator (APSIM) using experimental data, we explored and prioritized promising intensification options for rainfed maize and wheat that enable to narrow prevailing yield gaps in the CRV, and quantified trade-offs with the water balance and gross margins. We set up a factorial simulation experiment combining Genetic x Environment x Management factors that influence crop yield and water use at field scale to simulate yield and water balance components under current and future climate scenarios (pessimistic scenario for mid-century). Varietal selection and nitrogen (N) fertilization were the most important factors contributing to yield gap closure. Although yields were maximized with N application rates up to 250 kg^{-1} in most soils and varieties, maximum gross margin and maximum water use efficiency (WUE) were attained at lower N rates, associated with a small yield reduction compared to the maximum. There was a trade-off between intensification and increased absolute water use through transpiration, while the water use per kg product was decreased. However, location-specific N application rates that allow producing at least 80% of the water-limited potential yield (Yw) of maize and wheat resulted in high water use efficiencies as well as favorable cost-benefit ratios. Climate change was projected to lower yield as it advanced maturity, and to result in decreased drainage and increased soil evaporation across all variety, location and management combinations for both crops. Climate change reduced crop yield by 15–25% for wheat and 2–30% for maize. We conclude that the locally-calibrated APSIM model could be used to derive key lessons from the genetic, environment and management interactions, and generate information on sustainable intensification pathways that combine narrowing yield gaps with maximizing WUE and gross margins.

1. Introduction

In the recent past, increased food production in the Central Rift Valley (CRV) of Ethiopia was the result of an increase in the cultivated area (Meshesha et al., 2012; Biazin and Sterk, 2013). Agriculture expanded to marginal areas with low land productivity, mainly related to erosion and poor inherent fertility (Yimer and Abdelkadir, 2011). These land use changes affected the hydrological balance of the CRV, which is manifested through the declining water levels of rivers and lakes (Legesse et al., 2004; Getnet et al., 2014).

In the CRV, more than 70% of the area is already cultivated whereas most of the remaining land is unsuitable for agriculture because of steep slopes and land covered by lakes, settlements, and highly degraded lands. Therefore, future agricultural development should focus on increasing the productivity per unit area instead of expanding the agricultural area. However, the effects of agricultural intensification on the catchment hydrology should be taken into account to maintain ecosystem services that are already under pressure due to current agricultural land expansion (Getnet et al., 2014).

Although some increase in cereal productivity has been observed over the past years (Van Dijk et al., 2020), the current productivity of most cereals in the CRV is still less than 3 t ha^{-1}, while the population

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increases with 2–3% per year (IFPRI, 2006, 2017), underlining the challenge to feed the population from the currently cultivated land (Van Ittersum et al., 2016). However, there is potential for intensification in the CRV given the large yield gap between on the one hand current farmers' yields and on the other hand experimental and simulated yields (Kassie et al., 2014; Van Ittersum et al., 2016). This yield gap is mainly attributed to low input use (Assefa et al., 2020) and poor crop management, including suboptimal nutrient application (Kenea et al., 2021), and technological limitations in variety selection, planting date and density, crop residue management and control of weeds, pests and diseases (Silva et al., 2021). Given the variation in available biophysical and socio-economic resources and conditions across the CRV, the yield gaps differ across crops, farming zones, soils and climate.

Improving input use and management can narrow yield gaps, but the lack of information on spatially explicit best-bet combinations of input use and crop management options impedes tailored and effective decision making towards yield gap closure. This is mainly because multifactorial experimentation, taking into account Genetic x Environment x Management (G x E x M) interactions, is costly in terms of time and finances.

Improving crop management in an effort to narrow yield gaps influences the water balance of cropping systems at field scale (Eastham and Gregory, 2000). For example, intensification may result in a more efficient use of precipitation (Farahani et al., 1998; Badra et al., 2012) but may result in trade-offs of decreased downstream water availability due to reduced runoff and deep percolation. For the CRV, the impacts of intensification on the components of the water balance are expected to differ by location, soil type, crop type and management, but are poorly understood.

Agricultural system models are being used worldwide to explore options and solutions for enhanced food production and climate change adaptation. The Agricultural Production System Simulation (APSIM) model is one of the agricultural system models that has evolved over many years of research and has been applied to understand G x E x M effects on yield under current changing climate scenarios (Probert et al., 1998; Asseng et al., 2002; Keating et al., 2003; Holzworth et al., 2014).

In this paper, we explored a range of crop management options to narrow the prevailing yield gaps for rainfed maize and wheat at field scale in the CRV using the APSIM model. We exploited the capacity of APSIM to run a large number of simulations in a factorial setting to analyze the effects of many G x E x M combinations on crop yield and the soil water balance. To address the trade-off between crop yield and water use, we identified fertilizer application rates that maximize water use efficiency and economic gross margins. To assess the possible effects of climate change, all analyses were done for the present and a future climate scenario. With respect to future climate, we focus on temperature change only as projections of precipitation changes for the study area are highly uncertain (Admassu et al., 2013; Kassie et al., 2013; Mekasha et al., 2014). We derived key lessons from the factor interactions and generate hypotheses about intensification scenarios that can be used in future research addressing the relationship between crop intensification and basin hydrology.

2. Materials and methods

2.1. Description of the study area

The study was conducted for the Central Rift Valley (CRV) of Ethiopia, approximately between 38° 81′ and 39°8′ E, and 7°10′ and 8° 30′ N. The CRV shows a remarkable diversity in altitude, temperature, rainfall and farming systems associated with differences in biophysical and socio-economic conditions. Therefore, we used the three relatively homogenous farming zones (HFZs), i.e., Eastern highlands (EH), Central lowlands (CL) and Western highlands (WH) (Getnet et al., 2015). The EH and WH are characterized by a higher altitude (about 3000 m.a.s.l), higher rainfall (1600 mm yr^{-1}) and lower average temperature (16 °C) compared with the CL at a lower altitude (1600 m.a.s.l), lower rainfall (600 mm) and higher temperature (21 °C) Fig. 1. The CL located in between the EH and WH has a relatively flat topography compared with the mountainous relief in the two highlands. Luvisols, Nitosols, Andosols, Cambisols and Vertisols are the dominant soil types in the CRV. Of the dominant crops maize and wheat, late maturing varieties are predominantly cultivated in the EH and WH whereas early maturing varieties prevail in the CL. Crop production in CRV is mostly rainfed and the actual productivity is low due to the low input use and the poor crop management (Getnet et al., 2015).

2.2. Data

The minimum data to estimate water-limited crop yields (Yw) include data on daily weather, soil characteristics that determine root zone water holding capacity and runoff, and information of cropping systems including sowing dates, phenology, and optimum plant population density (Van Ittersum et al., 2013). The climate, soil, crop phenology and yield data used for APSIM model calibration and evaluation are described in Table 1.

21-years climate record database containing daily rainfall, minimum and maximum temperature, and solar radiation from three locations, were used for long-term simulations to represent the three homogeneous farming zones in the CRV, i.e., Kulumsa for the EH, Melkassa for the CL and Butajira for the WH.

APSIM-soil was parameterized for a Luvisol, Andosol and Vertisol based on measurements conducted at Galessa, Melkassa and Meisso, respectively by the Ethiopian Institute of Agricultural Research (EIAR) and Kindu et al. (2008) (Annex 1). These three soils were selected because observed runoff data was available for calibration of the fallow water balance, and the soils represent 60% of all soils in the CRV. The soil properties included soil bulk density, saturated water content, soil water at field capacity and wilting point. Where soil water at wilting point and field capacity were not directly available in soil descriptions, the parameters were estimated from other soil properties like texture and bulk density using pedotransfer functions (Chikowo et al., 2008). Other soil parameters such as soil albedo, diffusivity constant, rates of unsaturated and saturated flows were adopted from similar soils already described in APSIM. Runoff data was obtained from previous studies on experimental runoff plots on bare Andosols (at Melkassa), and Vertisols (at Meisso) (Welderufael, 2006; Welderufael et al., 2009); and Luvisols (at Galessa, EIAR data).

Crop phenology and yield data (two maturity types for both maize and wheat) from Kulumsa and Melkassa research centers of EIAR (Table 1) were used to calibrate the APSIM-maize and APSIM-wheat models. Kulumsa is representative for the EH and WH, whereas Melkassa for the CL. The crop data originated from the rainfed National Variety Trials (NVTs), in which weeds were controlled by intensive and timely hand weeding, and diseases and pests were controlled with pesticides. The NVTs received locally recommended N and P fertilizer rates, i.e., 100 kg N and 44 kg P at the EH and WH; 41 kg N and 20 kg P at the CL for maize; and 50 kg N and 30 kg P at the EH and WH; 41 kg N and 20 kg P at the CL for wheat (Getnet et al., 2015). Maize was sown at a density of 5.3 plants m^{-2} for early maturing varieties at Melkassa and 6.6 plants m^{-2} for late maturing varieties at Kulumsa whereas both wheat varieties were sown at a density of 320 plants m^{-2} at Melkassa and Kulumsa.

Data on yield response to various nitrogen levels across locations and years were collected from secondary sources (Table 2). The data was used to validate the performance of the calibrated maize and wheat models in response to variations in nitrogen levels.

2.3. Description of the APSIM model

APSIM is a software tool that enables to simulate G x E x M interactions (McCown et al., 1996; Keating et al., 2003). The central

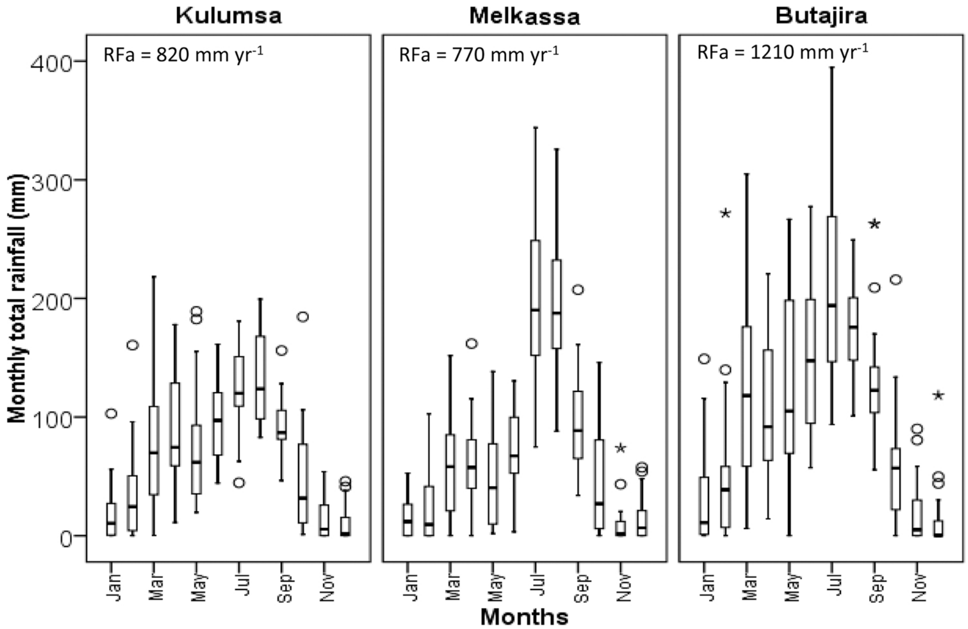


Fig. 1. Distribution and variability of monthly rainfall at Kulumsa, Melkassa and Butajira (1989–2009) representing the Eastern highlands, central lowlands and Western highlands of CRV, respectively; RFa = annual total rainfall.

Table 1
Description of the data used for calibration and evaluation of APSIM for runoff, phenology and yield.

Data	Type	Location	Year	Scale/detail	Source
Current climate	Rainfall, Tmin, Tmax, Solar radiation	Galessa[c], Meisso, Melkassa, Kulumsa, Butajira	21 yrs. (1989-2009)	Daily	National Meteorology Agency and EIAR
Soil	Luvisols Andosols Vertisols	Galessa, Melkassa, Meisso		4–6 soil layers	EIAR soil profile descriptions, reports
Runoff	Luvisols Andosol Vertisols	Galessa: Melkassa: Meisso:	2007 2004 2004	Daily runoff from 2 × 2 m runoff plots	Reports, database
Maize phenology and yield	Melkassa-1[a] BH660Q[b]	Melkassa, Kulumsa	2000, 2004, 2005 2002–2004, 2008	1.5 × 5 m; 3 replications	EIAR experimental data
Wheat phenology and yield	Hawi[a] Digelu[b]	Melkassa Kulumsa	2004, 2005, 2008 2005, 2007, 2008	3 × 3 m; 3 replications	EIAR experimental data

[a] Early maturing varieties;
[b] Late maturing varieties;
[c] is location for which daily rainfall, Tmin and Tmax are available for 2 years and solar radiation data was obtained from the NASA power database; Data from Galessa and Meisso locations are used only for runoff calibration; Tmin = minimum temperature; Tmax = maximum temperature. EIAR = Ethiopian Institute of Agricultural Research; Kulumsa represents the Eastern highlands, Meisso and Melkassa represents the Central lowlands, and Butajira and Galessa represent the Western highlands.

position in the model is taken by the soil where changes in the soil state variables are simulated continuously in response to weather, crop growth and management (McCown et al., 1995, 1996; Probert et al., 1998). APSIM provides a flexible structure to simulate effects of climate and soil management on crop growth and yield based on several integrated simulation modules (Keating et al., 2003). In this study, the emphasis is on the water balance, crop (maize and wheat), nutrient (N), and management (planting density, maturity type, sowing rules, residue removal) modules.

2.3.1. APSIM-SoilWat module

A reliable estimation of the soil water balance is required for an accurate estimation of crop growth and yield as well as hydrology. The APSIM SoilWat module is a cascading water balance model (Asseng et al., 1998) that specifies the water retention characteristics of the soil mainly in terms of saturated water content (SAT), drained upper limit (DUL), and lower limit (LL) (Probert et al., 1998).

Runoff, drainage, soil evaporation, transpiration, unsaturated flow and solute flux/flow are the main water flows calculated in the APSIM-SoilWat module (Verburg, 1995). In APSIM-SoilWat, runoff is estimated using the USDA-SCS curve number (CN) approach that includes effects of soil water content, crop height, and soil cover both from crop and crop residues (USDA-NRCS, 2004). A user-supplied CN for average antecedent rainfall condition (CN) is used to calculate the wet (high runoff potential) and the dry (low runoff potential) curves. The SoilWat module uses the family of curves between these extremes to calculate runoff depending on the daily soil moisture content. Furthermore, the CN is progressively reduced in response to the development of crop cover and crop height up to a certain threshold above which there is no effect.

2.3.2. APSIM-maize and wheat

The APSIM maize and wheat modules simulate crop growth and development with a daily time step using temperature, rainfall and radiation (from the input module), soil water supply (from the SoilWat module) and soil nitrogen (from the soil N module). The modules provide information on crop cover to the SoilWat module for calculation of

Table 2
Description of data sources used to evaluate yield response of rainfed maize and wheat at various nitrogen levels in APSIM.

Crop	Variety[a]	Location	Latitude	Longitude	Experimental year (s)	N rates/ treatments (kg N ha^{-1})	Source
Maize	Late maturing (BH660)	Bako	9° 0′26.00"N	37° 1′12.00"E	2000, 2001, 2002,2003, 2004	69, 92, 115	Tolossa et al. (2007)
		Achefer	11°21'55.59"N	36°56'59.74"E	2014	92, 115,138,161	Zeleke et al. (2018)
		Tepi	7°11'17.50"N	35°25'6.92"E	2016	0, 23, 46, 69, 92, 115, 138	Temteme et al. (2018)
	Early maturing (Melkassa-1)	Tibe	9°38'58.78"N	37°32'5.49"E	2000, 2001, 2002,2003, 2004	69, 92, 115	Tolossa et al. (2007)
		Melkassa	8°24'53.19"N	39°19'20.38"E	2014	0, 41, 169	Solomon (2018)
Wheat	Late maturing (Digelu)	Hawzen	13°57'16.00"N	39°27'2.00"E	2013	0, 46, 69, 92, 138	Bereket et al. (2014)
		Enewari	9°52'0.47"N	39°10'0.03"E	2014, 2015	0, 120, 240, 360	Fresew et al. (2018)
		Sinana	7° 0′13.23"N	40° 0′5.82"E	2008	0, 23, 46, 69	Woyema et al. (2012)
	Early maturing (Hawi)	Akaki	8°51'15.16"N	38°50'8.37"E	1993, 1994, 1995	0, 23, 46, 69, 92, 115	Erkossa et al. (2000)
		Chefe Donsa	8°58'5.87"N	39° 7′59.87"E	1993, 1994, 1995	0, 23, 46, 69, 92, 115	Erkossa et al. (2000)
		Adaba	6°57'28.87"N	39° 22'29.97"E	2010	30, 60, 90, 120	Haile et al. (2012)
		Fiche	9°46'54.62"N	38°45'25.55"E	2014	0, 32, 64, 96	Alemu et al. (2019)

[a] these varieties were initially calibrated for phenology and yield at single N level per variety and location before they were used for evaluation at various N levels.

evaporation rates and runoff.

2.4. Model calibration

APSIM-SoilWat, APSIM maize and APSIM wheat were calibrated before they were used for simulation of the different G x E x M options.

2.4.1. Calibration of the APSIM-SoilWat module

APSIM-Soil was parameterized for three soil types (Annex 1). Soil evaporation is assumed to take place in two stages: a constant rate (when soil is sufficiently wet) and a falling rate (the water content of the soil has decreased below a threshold). These rates are described through the use of two parameters: U and CONA. The U and CONA were set at 6 mm day^{-1} and 3.5 mm day^{-1}, respectively (Chikowo et al., 2008; Dalgliesh et al., 2016). Initial water was set at 50% of the maximum available water.

We calibrated the bare soil runoff curve number for each soil type by comparing simulated with observed daily runoff measurements from one year with several rainfall events. We used R^2, the Root Mean Square Error (RMSE) and model efficiency (ME) statistics to evaluate model performance.

$$RMSE = \left[\left(\frac{1}{n}\right)\sum_{i=1}^{n}(Oi - Si)^2\right]^{\frac{1}{2}} \quad (1)$$

$$ME = 1 - \frac{\sum_{i=1}^{n}(Oi - Si)^2}{\sum_{i=1}^{n}(Oi - \overline{O})^2} \quad (2)$$

Where Oi and Si are observed and simulated values of the i^{th} event respectively, and O is the mean of observed values. The model reproduces observed data best when ME is close to 1 and RMSE has a low value.

Due to scarcity of measured data on other water balance components, we assumed that a model calibrated for runoff, coupled with fair estimates of season length and yield would allow for reliable simulations of the other water balance components.

2.4.2. Calibration of APSIM-Crop modules

The crop phenology and yield data from experimental NVTs at Melkassa and Kulumsa were used for the calibration and evaluation of APSIM maize and APSIM wheat. We calibrated the model based on experimental data on phenology and yield for one early maturing and one late maturing variety of maize and wheat (Table 2, Table 4). First, we adjusted the thermal time from planting to flowering until the flowering days were reasonably estimated. Then, we adjusted the thermal time between flowering and maturity until the simulated maturity dates matched observed dates. Finally, to adjust yield, we fine-tuned the thermal time between start of grain filling and maturity and the grain growth rate during grain filling. In the absence of data, we did not account for differences in phenology due to photoperiod and vernalization. We used two to three-year phenological (phenology) and yield data of the two maize and the two wheat varieties for model validation (Table 4).

2.5. Simulation

APSIM was configured to simulate the effect of various combinations of G x E x M factors and levels, including crop and variety (G), location-specific weather and soils (E), and planting density, crop residue management and N application (M) (Table 3). A factorial simulation was setup for each of the three locations, i.e., EH, CL and WH; and two crops, i.e., maize and wheat. For each location-crop combination, the simulation comprised all possible combinations of two varieties (early and late maturity types), six N levels, two plant densities, three crop residue management levels, two soil types and two climate scenarios totaling

Table 3
Factorial combinations of maize and wheat input and management options: factors and the levels within each factor used for simulation.

Factors	Number of levels per crop	Levels
Nitrogen application (kg ha^{-1})	6	20[a], 75, 125, 175, 250, 350
Plant density (plants m^{-2})	2	5.3 and 6.6 for maize; 250 and 320 for wheat
Crop residue management	3	0%, 50%, 100% crop residue removed after harvest
Maturity type	2	Early maturing (Melkassa-1 for maize, Hawi for wheat), late maturing (BH660 for maize and Digelu for wheat)
Soils	2	Lv and Vr (EH); Ad and Lv (CL); Lv and Vr (WH)
Climate scenario	2	Current (1989–2009) and mid-century (2050)
Locations	3	EH (Kulumsa), CL (Melkassa), WH (Butajira)

[a] This rate represents farmers' current average N application based on Getnet et al. (2015); Lv = Luvisols, Vr = Vertisols, Ad = Andosols; EH = Eastern highlands, CL= Central lowlands, WH = Western highlands

36,288 simulation-years each on a daily basis (Table 3).

We set the initial conditions of the soils based on profile information from representative soils. Sowing window was set between May 15 to June 30 for early maturing maize, April 1 to June 30 for late maturing maize, June 1 to August 15 for early maturing wheat, and May 15 to July 30 for late maturing wheat. The soil organic matter and soil nitrogen contents were reset annually in the simulation at planting to avoid the confounding effect of long-term dynamics of organic carbon associated with residue cover management. The climate scenarios represent current (1989–2009) and future climate for similar period in mid-century (ca. 2050). We selected the worst-case scenario from the range of changes in minimum (+3.2 °C) and maximum temperature (+3.5 °C) for the CRV, obtained from three Global Circulation Models (GCMs), run under the Representative Concentration Pathways RCP 8.5 of 571 ppm of CO_2 (Kassie et al., 2015). Changes in minimum and maximum daily temperatures were implemented by adding the temperature change to the historical values (Webb and Stokes, 2012).

In our crop simulation using future climate, we elevated the CO_2 concentration for wheat to the RCP 8.5 level of 571 ppm. We maintained the current CO_2 concentration of 350 ppm for maize because maize is saturated at that concentration and no effect on maize yield was expected from fertilization of the elevated CO_2 concentration (Leakey et al., 2006). APSIM outputs for further analysis included dry grain yield and annual values for runoff, drainage, soil evaporation and crop transpiration for all G x E x M combinations. To investigate the trade-off between crop yield and irrecoverable water losses through evapotranspiration, we calculated the water use efficiency (WUE) as the kg of grain yield per mm of water used by evapotranspiration per year based on simulation from current climate. Gross margins associated with increasing N rates were calculated based on fertilizer costs and benefits from grain yield. We used the farmers' purchasing price of urea, which was converted to a price per kg of N, and the average selling price of maize and wheat in recent years. Optimal N application rates were identified for each variety x location x soil conditions based on maximum WUE and gross margin. Yield that corresponds to N application rate from the current farmers' practice (20 kg N ha^{-1}) is used to estimate actual yield (Ya) whereas both Ya and Yw are simulated for 21 years.

3. Results

3.1. Model evaluation

The best estimate of bare-soil runoff (highest R^2, lowest RMSE and ME closest to 1) was obtained at a runoff curve number for average antecedent moisture condition of 78 for Andosols (RMSE = 4.7 mm day^{-1}; ME = 0.85), 82 for Luvisols (RMSE = 1.8 mm day^{-1}; ME = 0.43), and 88 for Vertisols (RMSE = 3.59 mm day^{-1}; ME = 0.90) (Fig. 2).

Observed and simulated phenology and yield data used for model calibration and evaluation are presented in Table 4. Observed maturity days ranged from 108 to 116 days after sowing (DAS) for early maturing maize (Melkassa-1), and from 182 to 237 DAS for late maturing maize (BH660). The maturity days ranged from 88 to 93 DAS for early maturing wheat (Hawi), and from 129 to 148 DAS for late maturing wheat (Digelu) across years and varieties planted in the two locations Melkassa and Kulumsa. Given the high variability across years in observed flowering dates, maturity dates and yield of all varieties of maize and wheat, the model evaluation suggested a reasonably close estimation of the observed phenology and yield (Table 4). The RMSE of flowering dates was 8.6 and 3.2 days; maturity dates were 13 and 5 days, and grain yield was 0.8 and 0.4 t ha^{-1}, respectively, for maize and wheat.

Experimental N levels used for evaluation of yield response to N rates ranged from 0 kg ha^{-1} to 169 kg ha^{-1} for maize and to 360 kg ha^{-1} for wheat. Observed yield for maize ranged between 3.3 and 12.4 t ha^{-1}

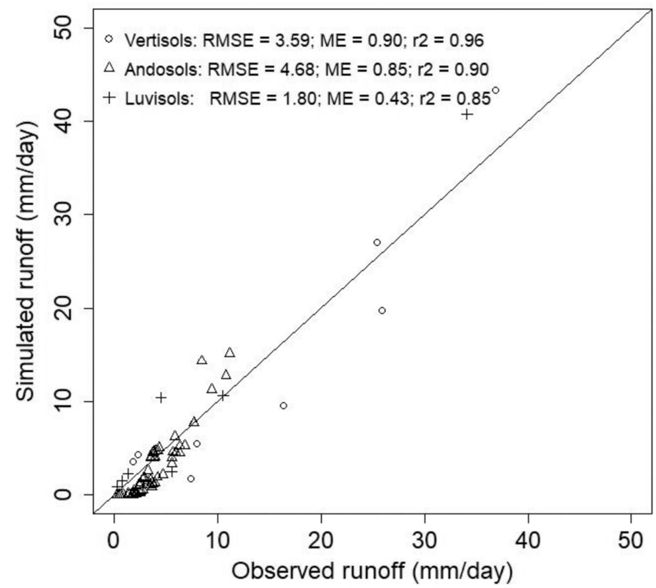


Fig. 2. APSIM model evaluation for runoff estimation of bare soils on three major soil types (representative for ca. 70% of the agricultural land) in the Central Rift Valley.

whereas simulated yield ranged between 2.2 and 12.6 t ha^{-1} across the N rates. Similarly, observed wheat yields ranged between 0.9 and 5.7 t ha^{-1} whereas simulated yields ranged between 0.8 and 5.5 t ha^{-1} across N rates. The evaluation statistics confirmed that APSIM calibrated for maize and wheat varieties in terms of phenology and yield (Table 4) can simulate yield variability resulting from variations in N application rate (Fig. 3).

The simulated season length for locations and years for which model validation for yield response to various nitrogen levels was conducted (Table 2) was estimated at 116–129 days and 152–179 days for early and late maturing maize varieties, respectively. Similarly, season length was 97–117 days and 115–128 days for early and late maturing wheat varieties, respectively. These are fair estimates based on the actual experience from the locations although measured season length data was lacking along with the N response data. The result is also similar to the season length reported by the Global Yield Gap Atlas (GYGA – www.yieldgap.org), i.e., 100–130 days and 130–180 days for early and late maturing maize, respectively, and 105–120 days and 120–149 days for early and late maturing wheat varieties, respectively (GYGA, 2021).

3.2. Yield gaps across farming zones

The simulated maize yield that corresponds to N application rate from the current farmers' practice (20 kg N ha^{-1}) is ca. 3 t ha^{-1} at the EH and WH, and ca. 2.5 t ha^{-1} at CL. Yield leveled off at water limited potential (Yw) of ca. 10 t ha^{-1} (250 kg N ha^{-1}) in the EH and Luvisols of WH, and at 12 t ha^{-1} (350 kg N ha^{-1}) in Vertisols of the WH. The Yw was about 8 t ha^{-1} (at 175 kg N ha^{-1}) on Luvisols, and at ca. 6 t ha^{-1} (125 kg N ha^{-1}) on Andosols of the CL. Consequently, maize yield gap (Yg) was about 7 t ha $^{-1}$ in both soils of the EH and Luvisols of the WH; 9 t ha^{-1} in the Vertisols of WH; 5.5 t ha^{-1} in Luvisols of CL and 3.5 in Andosols of the CL.

Wheat yield corresponding to farmers nitrogen application rate (20 kg ha^{-1}) is about 1.8 t ha^{-1} across the EH and WH, and 1.7 t ha^{-1} in CL. Yw is about 8 t ha^{-1} in EH, 6 t ha^{-1} in CL, and 7 t ha^{-1} in WH with little variation. Wheat Yg is estimated at 6.2 t ha^{-1} at EH, 4.3 t ha^{-1} at CL and 5.2 t ha^{-1} at WH. Both maize and wheat show spatial variable and high yield gaps.

Table 4
Observed and simulated phenology and yield of early and late maturing varieties of maize and wheat grown in the Central Rift Valley.

Crop	Model phase	Variety	Year	Planting date	Grain yield[a] (t ha^{-1})		Days from planting to flowering (days)		Days from planting to maturity (days)	
					Obs.	Sim.	Obs.	Sim.	Obs.	Sim.
Maize	Calibration	Melkassa-1	2004	19-Jun	5.32	5.34	57	57	114	113
		BH660	2002	15-Apr	7.39	7.36	99	99	186	188
	Evaluation	Melkassa-1	2000	20-Jun	4.67	5.03	54	57	108	116
			2005	23-Jun	5.65	5.34	53	54	116	111
		BH660	2003	30-May	8.80	7.16	95	112	195	204
			2004	29-May	6.80	6.80	116	110	182	206
			2008	16-Apr	6.72	7.11	113	119	237	225
Wheat	Calibration	Hawi	2008	14-Jul	3.08	3.09	50	51	88	88
		Digelu	2008	22-Jun	4.62	4.50	80	81	148	146
	Evaluation	Hawi	2004	25-Jun	2.90	2.92	49	51	89	86
			2007	13-Jul	2.08	2.68	50	51	93	87
		Digelu	2005	25-Jun	4.09	4.39	74	73	130	131
			2007	30-Jun	4.05	4.45	69	75	129	136

[a] Grain yield at 12.5% moisture content; Obs. = Observed, Sim. = Simulated; Melkassa-1 and Hawi are early maturing maize and wheat varieties, respectively, from experiments at Melkassa (1550 m.a.s.l). BH660 and Digelu are late maturing varieties of maize and wheat, respectively, from experiments at Kulumsa (2200 m.a.s.l).

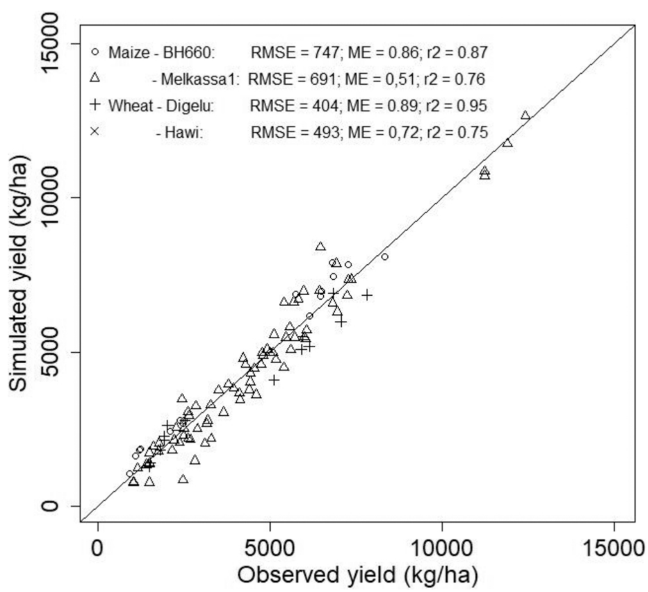


Fig. 3. APSIM model validation for yield response to various nitrogen levels.

3.3. Yield responses to N levels

There was a substantial variation in maize yield and response to N across HFZs (Fig. 4a). Maize yields were higher in EH and WH than in the CL. Average grain yield was 7.3 t ha^{-1} in EH, 5.7 t ha^{-1} in CL and 7.1 t ha^{-1} in WH (average across all management options, varieties and years). Maize yields also differed between varieties, i.e., 5.2 t ha^{-1} and 8.2 t ha^{-1} for early and later maturing varieties, respectively (across management, locations and years). Varietal selection gave a maize yield advantage of ca. 0.6–1.9 t ha^{-1} at 20 kg N ha^{-1} across HFZs. The yield advantage of the late maturing variety was higher at high N rates, i.e. 2–8 t ha^{-1} (across locations, soils, planting densities and crop residue levels). Yield response leveled off at lower N rates for the early maturing maize variety than for the late maturing variety. Yield of the early maturing maize ranged from 2.5 t ha^{-1} at 20 kg N ha^{-1} to a maximum of ca. 6 t ha^{-1} at 125 kg N ha^{-1} with similar response across HFZs, soils and plant densities (Fig. 4a). For the late maturing variety of maize, the yield response to N varied strongly across HFZs.

Differences in yield response between soils within the same HFZs were small, but on Vertisols of the EH maize yield declined with N rates beyond 250 kg ha^{-1} (Fig. 4a). By contrast, on the same soils in the wetter WH, a strong yield response was observed at higher N rates. The interaction effect between HFZ and soil on yield response can thus be explained by climatic differences. Grain yield was slightly higher at higher planting density across all HFZs, varieties and soils. The difference was higher for maize (ca. 0.5 t ha^{-1}) than for wheat (ca. 0.1 t ha^{-1}).

When 100% of the crop residues from the previous harvest were retained on Vertisols of the EH, the maize yield continued to increase up to ca. 14 t ha^{-1} at an N rate of 250 kg ha^{-1}, after which it leveled off (data not shown). There was a small increase in yield with an increase in residue retention on Luvisols of the EH, and Andosols and Luvisols of the CL (up to 0.5–2 t ha^{-1} at 250 kg N ha^{-1}). Residue retention had hardly any effect on yield on both soils of the high rainfall WH.

For wheat, the maximum yield and the response to N were highest in EH and lowest in CL (Fig. 4b). Contrary to maize the difference between the early and late wheat variety was only small, 4.6 vs. 5.0 t ha^{-1}. Nitrogen fertilization increased wheat yields from less than 2 t ha^{-1} at 20 kg N ha^{-1} to ca. 8 t ha^{-1} in the EH and WH, and ca. 6 t ha^{-1} in the lowlands at 250 kg N ha^{-1} (Fig. 4b). Yields leveled off at N rates of 250 kg ha^{-1} for both varieties across all HFZs and soils. The difference between varieties in yield response to N was generally small. Residue retention at harvest did not affect wheat yield.

3.4. Yield variability under current and future climate

Generally, yield variability across years was larger for maize than for wheat (Fig. 5). Yield variability was lower at low N input than at high N input for both crops and varieties across the major soils in all HFZs (Fig. 5a,b). The variability was often larger for the late maturing variety than for the early maturing variety, while it was extremely large for high N input, late maturing maize on Vertisols in the EH, and Andosols and Luvisols in the CL. In the latter situations, the cultivation of the late maturing maize at high N input was associated with a risk of low yields and sometimes crop failure and thus the risk of losing investments in fertilizer. For example, at high N rate on Vertisols of the EH at least a quarter of the years produced less than what could be produced at low N rate (see the lower quartiles and lower values of the whisker plot in Fig. 5a). Harvest failures of maize occurred more frequently on Vertisols in the EH than on other soils: three years with a complete failure and four years with very low yields out of the 21 simulation years were found on Vertisols, while over the same period no crop failures were simulated for Luvisols in the same HFZ. For wheat, though variability was relatively small, there were more extreme (low) outliers in the CL than in EH and WH. Similar to maize, wheat at high N input showed larger yield variability than wheat at low N input.

Climate change reduced yields of both maize and wheat at high N, but not or hardly at low N. On average (across HFZs, soils and varieties), maize and wheat grain yields decreased due to climate change by ca. 1.1 t ha^{-1}and 0.9 t ha^{-1}, respectively, at an N rate of 175 kg ha^{-1} compared with 0.2 t ha^{-1} and 0.03 t ha^{-1} at an N rate of 20 kg ha^{-1}.

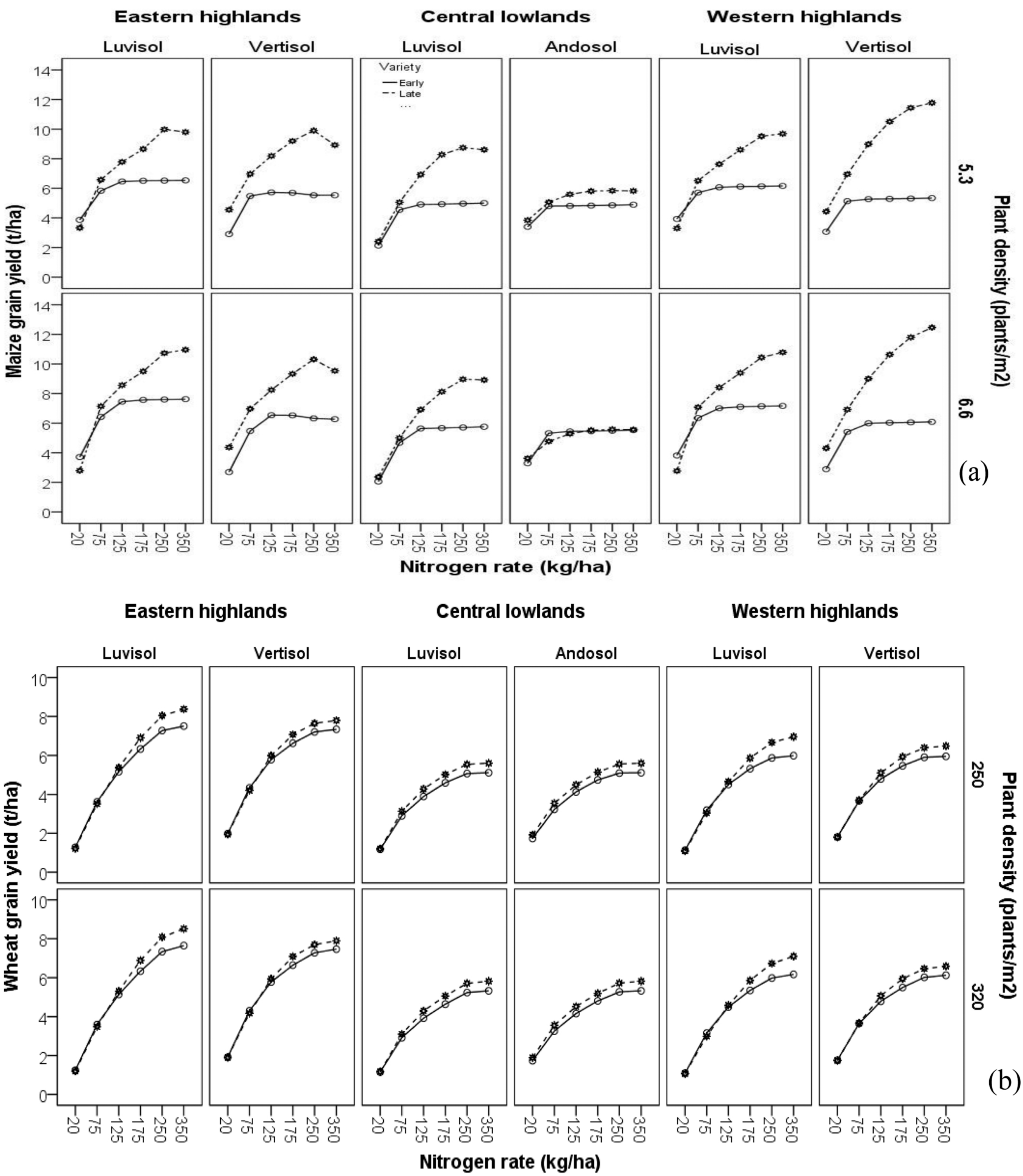


Fig. 4. Simulated response of early and late maturing varieties of (a) maize and (b) wheat grain yield to nitrogen fertilization in major soils of the Eastern highlands, Central lowlands and Western highlands for two plant densities at 100% crop residue removal for current climate (1989–2009).

Early maturing varieties of both crops seemed more robust to climate change with smaller yield reductions compared to late maturing varieties (Fig. 5ab). For maize, the impact of climate change was more pronounced in the already risky HFZ-soil combinations, i.e., on Vertisols in the EH and Andosols in the CL. Variability is mostly low under future climate because productivity is affected in most of the years as explained by lower median compared with yield under current climate in which only few dry years result in low yield with higher median. For wheat, the impact of climate change was consistent across HFZs and soils, with a larger variability for the late maturing variety and the higher N rate.

Generally, climate change reduces Yw resulting in lower yield gaps. This implies that the scope for closing yield gap using intensification options, and the N rates required to attain Yw will be reduced.

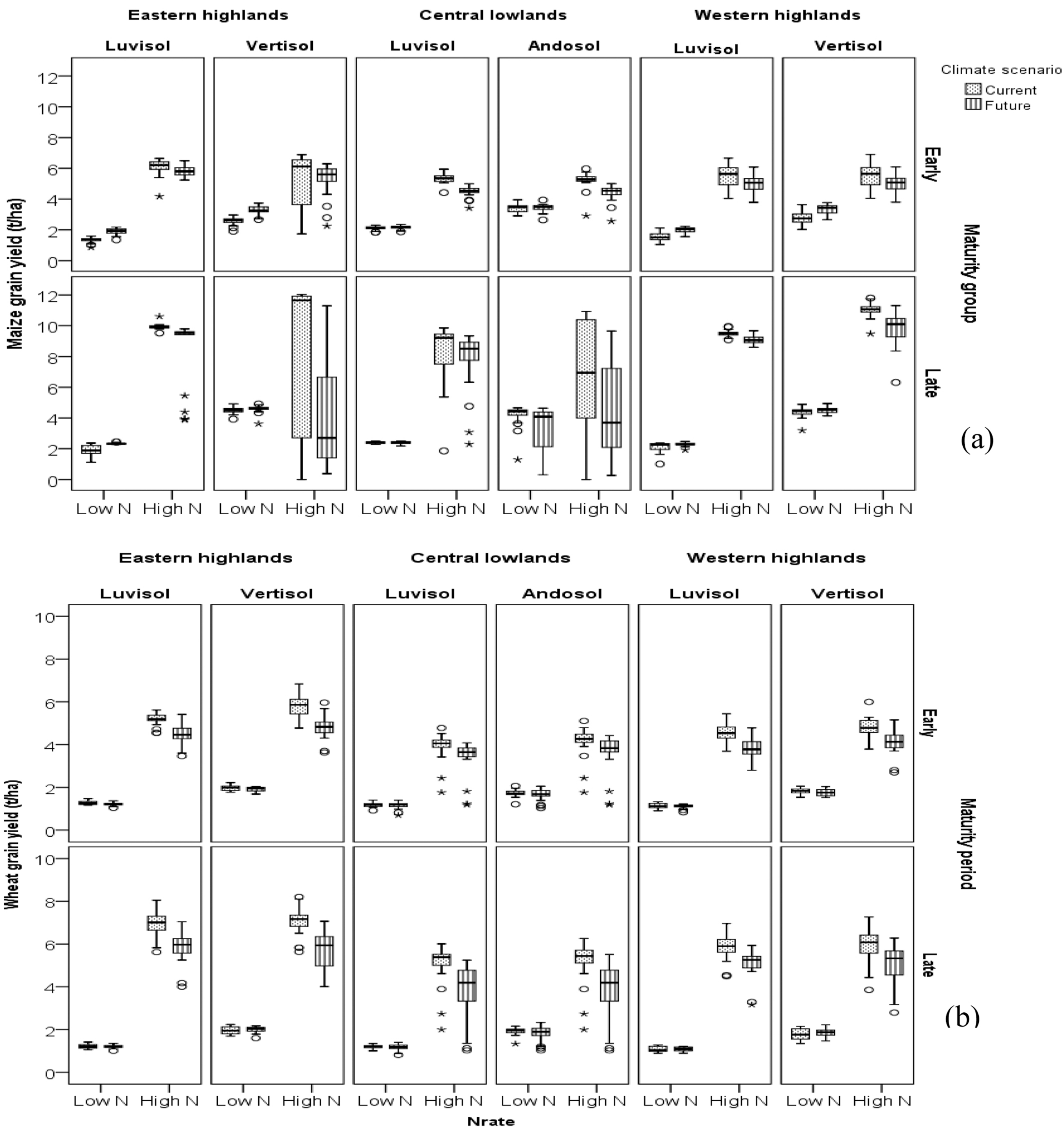


Fig. 5. Variability of (a) maize and (b) wheat grain yield across years under current (1989–2009); and future (2050 s) climate scenarios in major soils across HFZs of the CRV at 100% crop residue removal; plant density of 5.4 plants m^{-2} for maize and 250 plants m^{-2} for wheat; the low N rate is the average farmers' rate of 20 kg N ha^{-1}; the high N rate is 125 kg ha^{-1} for early and 175 kg ha^{-1} for late maturing varieties.

3.5. Water balance

3.5.1. General effects of G x E x M combinations

The relative importance of water balance components varied with HFZs, crop residue removal, and soils (Fig. 6). Vertisols, for example, generated more runoff than Luvisols in the same HFZ. The annual soil evaporation and crop transpiration were the largest terms in the water balance on maize land (Fig. 6a). The share of soil evaporation in the water balance was 33–51% on Luvisols, 49–52% on Andosols and 33–58% on Vertisols. The share of crop transpiration was 21–28% on Luvisols, ca. 23% on Andosols and 23–30% on Vertisols.

On wheat fields, drainage, soil evaporation and transpiration were the largest terms. Less runoff and more drainage were observed for wheat compared with maize (Fig. 6). Runoff from wheat fields contributed less than 10% to the annual water balance.

3.5.2. Plant density and crop residue management

As the effects of residue removal on the water balance were the same for both plant densities only results for the low plant density are shown (Fig. 6). Runoff and soil evaporation increased, whereas drainage

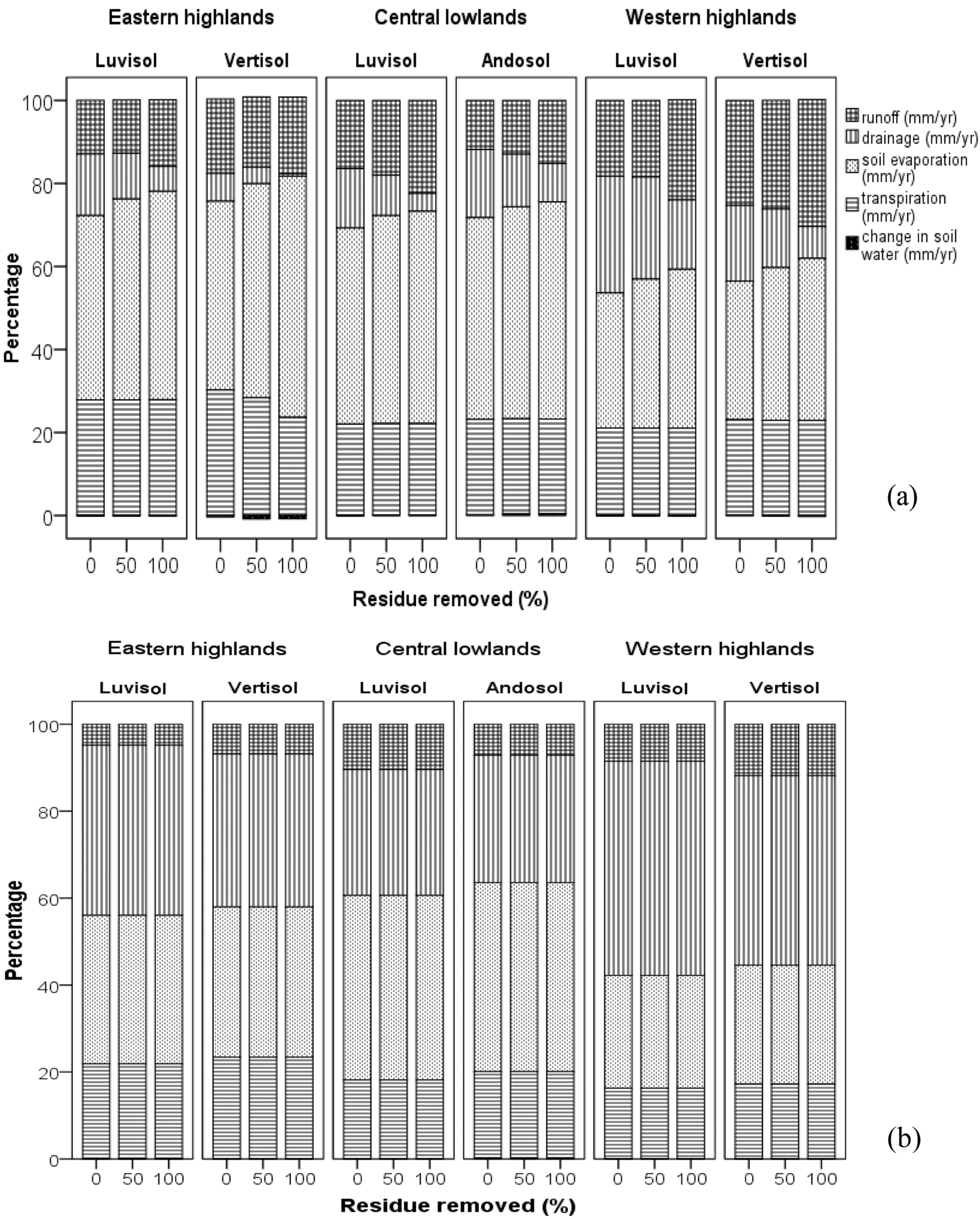
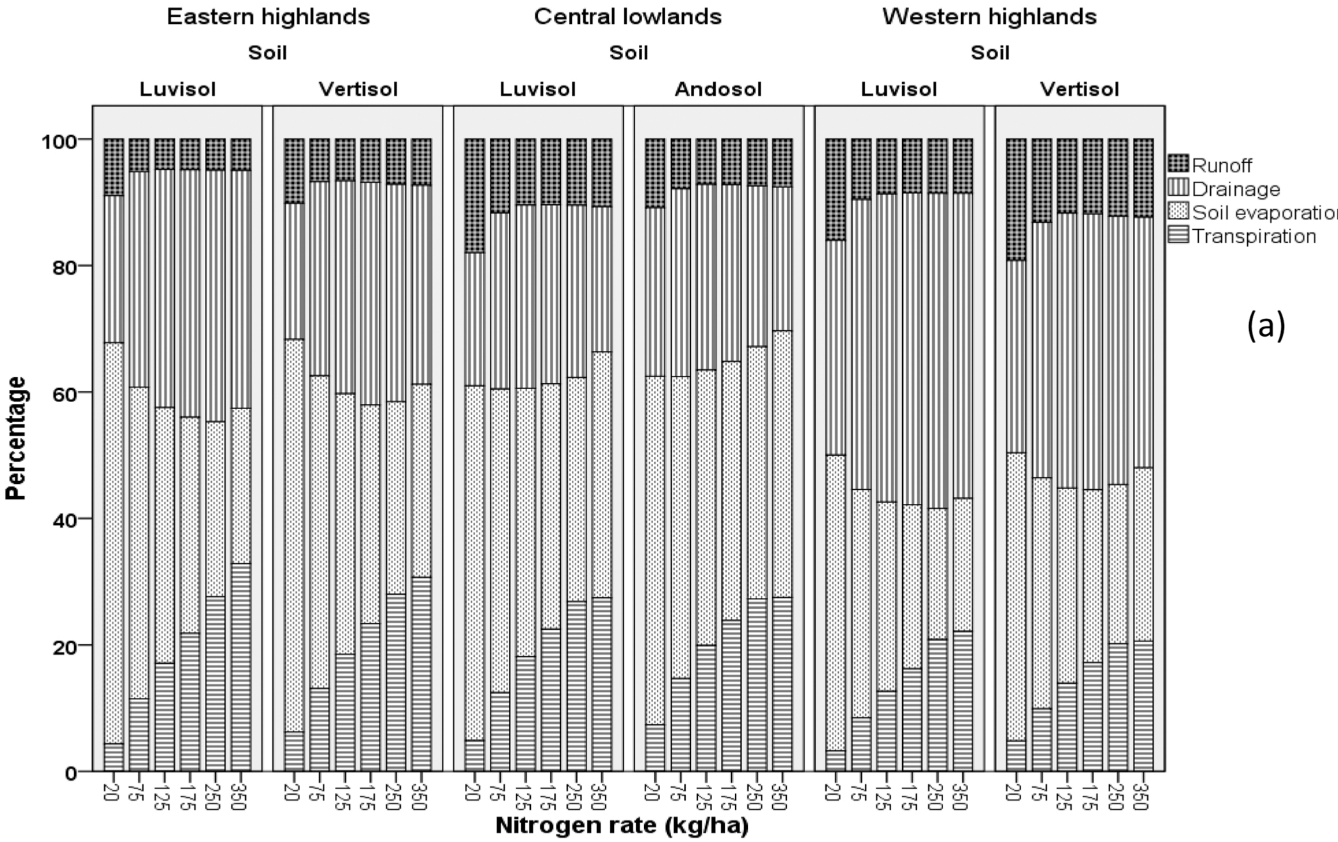


Fig. 6. Effect of residue removal on the components of the annual water balance on (a) maize, and (b) wheat fields across HFZs and major soils of the CRV. Data are from the early maturing variety for the Central lowlands at 125 kg N ha^{-1} and for the late maturing varieties for the Eastern and Western highlands, at 175 kg N ha^{-1}, and based on low plant densities.



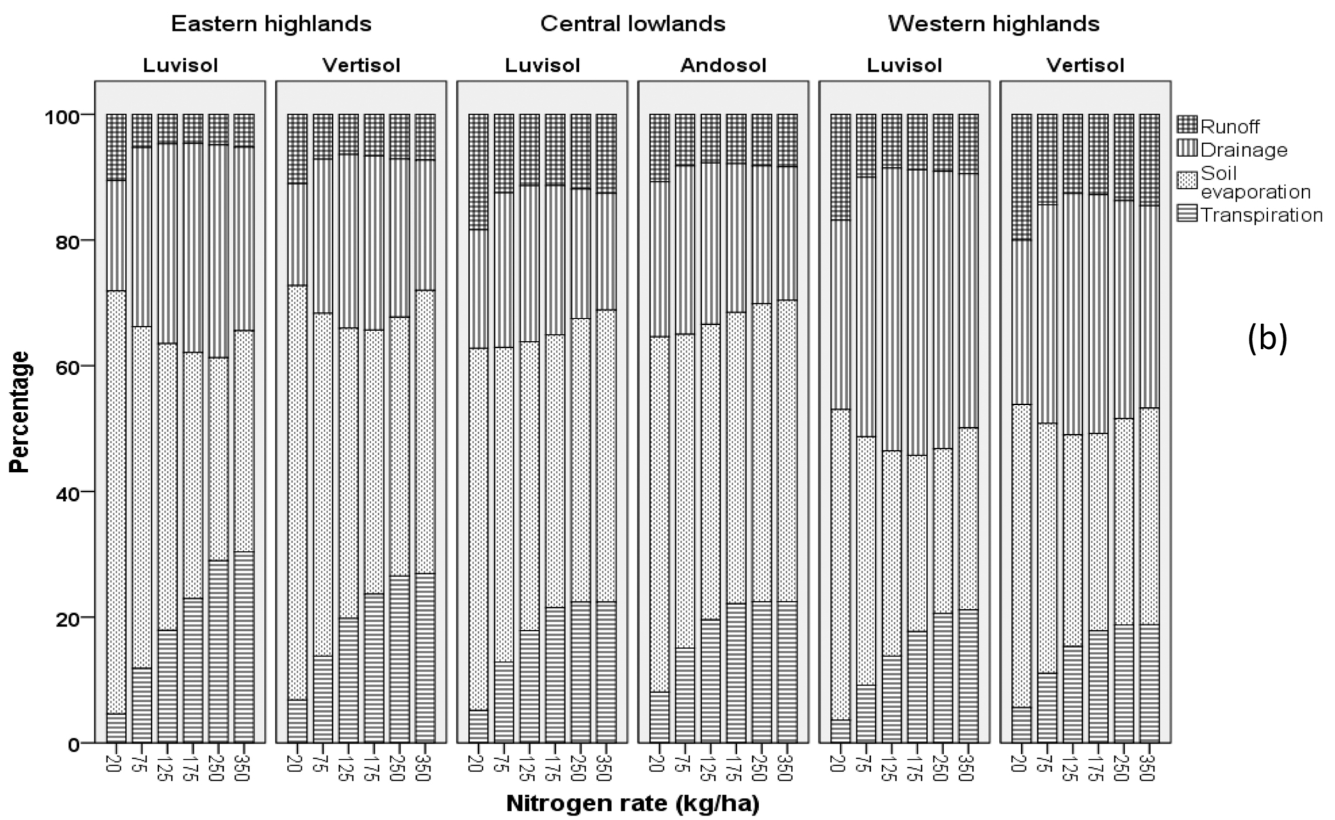


Fig. 7. Effect of nitrogen fertilization on the components of the annual water balance on (a) maize, and (b) wheat fields across HFZs and major soils of the CRV. Data are from the early maturing variety for the Central lowlands and from the late maturing varieties for the Eastern and Western highlands at 100% crop residue removal; plant density of 5.3 plants m^{-2} for maize and 250 plants m^{-2} for wheat.

Table 5
The impacts of climate change on the components of the water balance across HFZs, soils, varieties and N levels of maize and wheat.

HFZ	Soil	N rate	Maize: Change in runoff (mm yr⁻¹) Early	Maize: Change in runoff Late	Maize: Change in drainage (mm yr⁻¹) Early	Maize: Change in drainage Late	Maize: Change in soil evaporation (mm yr⁻¹) Early	Maize: Change in soil evaporation Late	Maize: Change in transpiration (mm yr⁻¹) Early	Maize: Change in transpiration Late	Wheat: Change in runoff (mm yr⁻¹) Early	Wheat: Change in runoff Late	Wheat: Change in drainage (mm yr⁻¹) Early	Wheat: Change in drainage Late	Wheat: Change in soil evaporation (mm yr⁻¹) Early	Wheat: Change in soil evaporation Late	Wheat: Change in transpiration (mm yr⁻¹) Early	Wheat: Change in transpiration Late
Eastern highlands	Luvisol	20	1	0	-23	-45	17	30	6	15	12	13	-37	-47	24	32	1	2
		75	2	-4	-28	-52	19	35	6	23	1	1	-43	-46	43	42	0	3
		125	2	-12	-22	-45	19	40	1	21	-1	-1	-48	-48	48	43	1	6
		175	5	-23	-11	-33	10	66	-12	1	-1	-2	-49	-48	48	41	3	9
		250	12	-12	-4	-22	4	18	-21	14	0	0	-48	-49	44	38	4	11
		350	12	-36	-4	-4	4	62	-21	-23	4	2	-79	-69	91	87	-15	-20
	Vertisol	20	-5	-2	-22	-49	19	33	7	19	5	7	-34	-43	24	31	4	5
		75	-5	-15	-18	-36	14	62	5	-6	2	3	-42	-51	37	42	3	6
		125	-4	-32	-11	-23	11	77	2	-26	-3	-2	-47	-49	44	41	5	10
		175	4	-34	-1	-5	1	75	-5	-40	-3	-2	-57	-62	56	61	4	3
		250	9	-18	-1	0	-7	31	-3	-16	-1	0	-68	-75	66	88	3	-12
		350	9	-9	-1	0	-8	1	-2	6	-1	0	-109	-88	130	119	-19	-31
Central lowlands	Luvisol	20	3	-6	-34	-54	23	45	6	18	3	3	-18	-19	12	13	2	3
		75	-8	-31	-22	-20	25	46	4	11	7	12	-27	-31	17	22	3	-3
		125	-4	-7	-11	0	24	16	-11	-9	8	16	-34	-37	29	38	-2	-16
		175	1	-10	-6	0	23	17	-19	-8	8	18	-38	-41	39	60	-8	-37
		250	1	-6	-7	0	23	11	-18	-9	12	20	-55	-50	81	93	-37	-63
		350	1	-3	-7	0	23	7	-18	-7	16	22	-37	-37	63	83	-42	-67
	Andosol	20	-3	-12	-33	-38	26	48	7	2	-1	0	-17	-18	11	12	6	5
		75	-7	-12	-15	-19	27	48	-6	-19	3	7	-24	-28	18	24	3	-4
		125	-3	-9	-3	-9	26	46	-20	-28	5	11	-31	-34	29	43	-3	-20
		175	-3	-8	-4	-4	26	45	-21	-33	5	12	-36	-34	45	66	-14	-44
		250	-3	-8	-4	-3	26	45	-20	-34	7	12	-29	-25	63	77	-40	-64
		350	-3	-8	-4	-3	26	45	-20	-34	6	12	-13	-12	48	67	-42	-67
Western highlands	Luvisol	20	2	5	-47	-71	38	51	7	15	9	10	-41	-46	29	32	3	5
		75	-2	1	-44	-79	39	57	7	22	7	5	-49	-55	37	41	6	9
		125	-1	-2	-33	-76	39	60	-4	22	3	-1	-46	-45	35	33	7	14
		175	2	-3	-20	-73	39	60	-18	18	7	4	-53	-47	42	25	4	18
		250	3	-2	-18	-57	38	58	-21	2	10	6	-78	-69	77	66	-9	-3
		350	3	5	-18	-22	38	36	-21	-19	17	11	-114	-94	121	96	-24	-12
	Vertisol	20	-12	-13	-35	-60	39	55	9	20	3	10	-36	-52	26	32	7	9
		75	-8	-7	-33	-73	40	59	4	22	13	15	-56	-68	34	39	9	14
		125	-7	-9	-16	-70	39	60	-15	19	15	11	-69	-61	48	34	7	17
		175	-7	-9	-11	-56	39	59	-21	7	11	11	-67	-68	51	49	6	7
		250	-6	-7	-10	-27	39	51	-21	-17	22	19	-108	-94	105	93	-18	-17
		350	-6	-7	-11	-21	39	51	-21	-22	32	26	-103	-90	99	85	-27	-22

Table 6
Fertilizer costs incurred and gross margins per hectare for early and late maturing varieties of maize and wheat at different N rates. Gross margin was calculated as the product of grain yield (from simulation using current climate) and price, minus the cost of N; bold numbers are the highest gross margins per zone (soil) and crop variety.

	N rate (kg ha^{-1})	Cost (USD) of N ha^{-1}	Gross margin (USD) ha^{-1} Maize Early	Maize Late	Wheat Early	Wheat Late
Eastern highlands (Luvisols)	20	28	256	379	417	397
	75	105	840	997	1158	1121
	125	174	***1125***	1456	1630	1701
	175	244	1095	1884	1966	2165
	250	348	945	***2090***	***2191***	***2460***
	350	488	808	2056	2133	2436
Central lowlands (Andosols)	20	28	698	861	577	643
	75	105	***1020***	1109	1023	1133
	125	174	943	1207	1266	1393
	175	244	876	***1214***	1411	1551
	250	348	777	1128	***1430***	***1591***
	350	488	644	986	1298	1467
Western highlands (Vertisols)	20	28	570	905	603	601
	75	105	***1020***	1389	1175	1186
	125	174	1000	1778	1499	1608
	175	244	934	2114	1664	1826
	250	348	834	***2244***	***1712***	***1884***
	350	488	700	2163	1590	1775

decreased with an increasing percentage of maize crop residue removal across HFZs and soils (Fig. 6a). Crop residue removal had no effect on the water balance of wheat (Fig. 6b).

3.5.3. Nitrogen fertilization

In both crops, nitrogen fertilization increased transpiration, which was associated with a decrease in drainage in maize (Fig. 7a), and a decrease in soil evaporation in wheat (Fig. 7b).

Increasing the N application rate from the current farmers' practice (20 kg N ha^{-1}) to 75 kg N ha^{-1} in maize increased the transpiration by 45–91% in the highlands and 25–84% in the lowlands. The increase in transpiration was associated with a decrease in drainage of 25–60% in EH and WH, and 40–80% in the CL (ranges across locations, soils, varieties and plant density levels). For wheat, the same increase in the N application rate (from 20 to 75 kg N ha^{-1}) increased transpiration by 100–160% in EH and WH, and 75–150% in the CL (Fig. 6b). Drainage increased by 30–50% in EH and WH, and 8–30% in the CL, while runoff decreased by 27–50% in EH and WH, and 22–33% in CL (Fig. 6b). Wheat at lowest N rate (20 kg N ha^{-1}) produced more runoff than at the higher N rates.

3.5.4. Climate change

Climate change decreased drainage (10–50%) and increased soil evaporation (6–20%) across all G x E x M combinations for both crops (Table 5). The magnitude of change varied across HFZs, crops and N levels. For example, the decrease in drainage was greater in the highlands (up to 80 mm yr^{-1} for maize and up to 115 mm yr^{-1} for wheat) than in the lowlands (Table 5). Transpiration slightly increased with climate change at low N rates (1–18%) but decreased at high N rates (0.5–15%).

3.6. Economic analysis

The largest increase in gross margins was obtained by increasing the N application rate from 20 to 75 kg N ha^{-1}. For both wheat varieties,

Table 7
The prospects of variety selection and N fertilization management options of rainfed maize and wheat in terms of narrowing prevailing yield gaps, increasing water use efficiency and profitability across locations and selected soils in the CRV.

		Maize									Wheat								
		Eastern highlands (Luvisol)			Central lowlands (Andosol)			Western highlands (Vertisol)			Eastern highlands (Luvisol)			Central lowlands (Andosol)			Western highlands (Vertisol)		
Variety	N-rate (kg ha^{-1})	Yield (t ha^{-1})	WUE	Profit	Yield (t ha^{-1})	WUE	Profit	Yield (t ha^{-1})	WUE	Profit	Yield (t ha^{-1})	WUE	Profit	Yield (t ha^{-1})	WUE	Profit	Yield (t ha^{-1})	WUE	Profit
Early	20	○ 1.3			◑ 3.4			◔ 2.8			○ 1.2			○ 1.7			◔ 1.8		
	75	◔ 3.3			◕ 5.3			◑ 5.3			◑ 3.3			◑ 2.9			◑ 3.2		
	125	◑ 6.1			◑ 5.2			◑ 5.5			◑ 4.5			◕ 3.6			◑ 4.1		
	175	◑ 6.3			◕ 5.2			◑ 5.5			◕ 5.3			◕ 3.8			◕ 4.6		
	250	◑ 6.0			◕ 5.3			◑ 5.5			◕ 6.0			◕ 3.9			◕ 4.8		
	350	◑ 6.1			◕ 5.3			◑ 5.6			◕ 6.1			◕ 3.9			◕ 4.8		
Late	20	◔ 1.9			◑ 4.2			◑ 4.4			○ 1.2			○ 1.8			◔ 1.9		
	75	◑ 5.1			◕ 5.7			◑ 7.0			◑ 3.2			◑ 3.0			◑ 3.5		
	125	◑ 7.6			◕ 6.5			◕ 9.1			◑ 4.9			◕ 3.5			◑ 4.5		
	175	◕ 9.9			● 6.8			● 11.0			◕ 5.9			◕ 3.8			◕ 5.0		
	250	● 11.4			● 6.9			● 12.1			◕ 6.7			◕ 3.8			◕ 5.2		
	350	● 11.9			● 6.9			● 12.4			● 6.9			◕ 3.8			◕ 5.3		

The catagories for the class in symbols is based on result in Table 4 of Getnet *et al*., 2015.
○ Yield levels less than the Ya i.e. calculated from farmers' average in the respective HFZ
◔ Yield levels greater than Ya (less than the Ya95) calculated from best performing farmers in the respective HFZ
◑ Yield levels greater than Ya95% (less than 80% of Yw) calculated from experimental yield for the respective HFZ
◕ Yield levels greater than 80% of Yw (less than Yw) calculated from experimental yield for the respective HFZ
● Yield levels greater than the Yw calculated from experimental yield for the respective HFZ
Bars to compare the water use efficiency (kg grain ha^{-1} mm^{-1}) at various N levels
N levels at which the benefit from additional yield exceeds the additional cost of N (where there is profit).

gross margins increased further with increasing N input up to 250 kg ha^{-1} across all locations and soils (Tables 6 and 7). For maize, the optimum N application rate was lower for the early maturing variety at 75–125 kg ha^{-1} than for the later maturing variety at 175–250 kg ha^{-1} range depending on the location (Tables 6 and 7).

3.7. Water use efficiency

The water use efficiency (WUE) varied with crops, varieties, locations, soils and management such as plant density and crop residue removal. Table 7 provides an overview of the WUE variation with N application and variety for selected soils in each HFZ. The maximum WUE of maize was 9–16 kg grain ha^{-1} mm^{-1} on Luvisols in the EH (higher value for the late variety), 9–10 kg grain ha^{-1} mm^{-1} on Andosols in the CL, and 8–15 kg grain ha^{-1} mm^{-1} on Vertisols in the WH. The maximum WUE was attained at N rates of 125, 75 and 75 kg ha^{-1} in EH (Luvisols), CL (Andosols) and WH (Vertisols), respectively, for the early maturing variety and at N rates of 250, 250 and 350 kg N ha^{-1} for the late maturing variety in those HFZs and soils.

For wheat, WUE hardly differed between the two varieties, i.e., 17–18 kg grain ha^{-1} mm^{-1} in the EH, 9–10 kg grain ha^{-1} mm^{-1} in the CL, and 11–12 kg grain ha^{-1} mm^{-1} in the WH, with the higher value for the late maturing variety. Maximum WUEs were attained at 250 kg N ha^{-1} across the three HFZs and both varieties.

4. Discussion

4.1. Yield and water balance

Simulated yields of maize and wheat varied with location, soil, variety, N input level and management. Yields were higher in EH and WH and lowest in CL as a result of the higher seasonal rainfall and earlier onset of rainfall in the highlands compared with CL. This trend matches the differences in actual and experimental yields across the three HFZs (Getnet et al., 2015). In addition to the climatic and soil factors related to location, variety selection and nitrogen input had the strongest impact on maize yield. Yields of the late maturing varieties were higher than that of the early maturing varieties particularly in the highlands of the CRV, because the growing period in the highlands is long enough to accommodate the maturity period of the late maturing varieties. To fully benefit from the longer growing periods in the highlands higher N rates are needed than in the CL. However, decisions related to N input should be made with care as the yield response varied across locations, soil types and varieties. For example, a high N rate (> 175 kg N ha^{-1}) resulted in severe yield reduction for the later maturing maize growing on Vertisols of the EH (Fig. 4a), associated with water stress shortly before the start of grain filling period (data not shown). In addition, high year-to-year variability and frequent crop failures in maize on Vertisols (Fig. 5a) illustrated the riskiness of high-input cultivation in these conditions. In contrast with maize, high-input wheat production was fairly insensitive to climate variability, particularly under current climate conditions (Fig. 5b). This is because runoff from wheat fields was lower (Fig. 6), resulting in higher water availability and less drought stress compared to maize.

Our simulation results indicated a small positive effect of residue retention on maize yield. Crop residue retention increases the soil infiltration capacity (Woyessa and Bennie, 2007), water availability and yield (Wilhelm et al., 2004), and rainwater use efficiency (Zeleke et al., 2004). However, farmers in the CRV prefer to use crop residues for feeding livestock during the dry period and therefore usually harvest the residues.

The effect of crop residue management on runoff was weaker in wheat than in maize, which could be related to the larger residue production of maize (10–12 t ha^{-1} compared to 3–4 t ha^{-1} for wheat) and the low runoff in wheat anyway. Another reason could be related to the higher decomposition rate of wheat straw compared with maize (Broder and Wagner, 1988), resulting in less residue cover protecting the soil surface.

Varietal differences were smaller for wheat than for maize, which could be due to several factors. First, the genetic characteristics of the varieties that are currently used in the CRV are not well known. We, therefore, did not specify some varietal parameters for wheat (vernalization sensitivity and photoperiod sensitivity) to avoid incorrect assumptions. Second, detailed analyses of the simulations showed that the late maturing wheat variety produced more vegetative biomass, which resulted in more water stress later on in the growing season than for the early maturing variety. In a sensitivity analysis assuming no water stress (full irrigation) larger differences in yields between both varieties were simulated (data not shown).

Intensification through high N rates was associated with an increase in transpiration in both crops, but the effect on other water balance components differed between maize and wheat. For example, wheat intensification decreased runoff, whereas maize intensification decreased drainage. Less runoff and more drainage observed for wheat compared with maize could be because of the better and more even soil cover in wheat. This can be explained by (i) wheat having a higher leaf area index (LAI) throughout the growing season compared with maize, and (ii) higher LAI is attained in relatively shorter period after planting in wheat whereas it takes more time for maize (Kang et al., 2002) providing wheat fields better soil cover across the season resulting in lower soil evaporation, less runoff and more infiltration.

With increased N rates, evaporation in wheat was much more reduced than in maize. This is because the wide row spacing of maize (0.75 m) leaves a larger part of the soil bare during a larger part of the growing season. This increases the risk of soil evaporation and runoff as total vegetation cover determines runoff to a large extent (Descheemaeker et al., 2006; Chen et al., 2010).

4.2. Prospects for yield gap closure and trade-off between intensification and water balance components

The CRV is characterized by large but differentiated yield gaps across HFZs (Getnet et al., 2015). Our work revealed promising possibilities to narrow the prevailing yield gaps by combining appropriate varieties and N inputs for location-specific conditions. To reduce the trade-off between water use through evapotranspiration and increased production, location-specific input and management combinations should aim at maximum WUE. Table 7 provides a visualization of the tradeoffs between maximizing yield and increasing water use efficiency and profit. WUE increased with the N application rate, but varied by location, crop and variety. For the late maturing maize variety, the yield from the N rate at which WUE and gross margin were maximum, i.e., 11.4 and 12.1 t ha^{-1} in the EH and WH, respectively (Table 7) exceeded the water limited yield potential (Yw) that was based on experimental data, i.e., 10.9 and 10.8 in the EH and WH, respectively (Getnet et al., 2015). For the early maturing maize variety, yield at maximum WUE (5.3 t ha^{-1} in CL) corresponded to about 80% of the Yw (5.2 t ha^{-1}) in the same farming zone. For both wheat varieties, it was possible to achieve more than 80% of Yw using the N rate corresponding to maximum WUE and gross margins with yield levels of 6.7 and 5.2 t ha^{-1} in EH and WH, respectively, for a late maturing variety and 3.8 t ha^{-1} in CL for an early maturing variety (Table 7). Maize WUE obtained in the CRV, i.e., 16.3 kg ha^{-1} mm^{-1} in EH and 15.2 kg ha^{-1} mm^{-1} in WH, was slightly less than an average productivity of 18 kg ha^{-1} mm^{-1} reported for sub Saharan Africa (SSA), however, the values are within the range reported taking into account spatial variability (10–30 kg ha^{-1} mm^{-1}) (Edreira et al., 2018). At field scale, the trade-off between higher yields and increased crop water use (evapotranspiration) is particularly strong in maize. For wheat the trade-off was weaker because the increase in crop transpiration was associated with a decrease in soil evaporation, i.e., overall evapotranspiration hardly changed.

Intensification can lead to land saving as the same amount of grain can be produced with less land than for lower intensification levels. However, because of the trade-off with water losses through evapotranspiration, intensification should be accompanied by strategies to save land for other land uses, which potentially improve regulatory ecosystem services. These could include conversion of marginal land to natural vegetation (Descheemaeker et al., 2009) or carefully managed grazing land. Soil and water conservation practices on cultivated land would benefit regulatory water flows as well (Nyssen et al., 2010; Adimassu et al., 2017).

4.3. Climate change effects

Our simulations suggest that the pessimistic scenario of climate change by 2050 reduces future crop yield by 15 – 25% for wheat and 2–30% for maize. The result is comparable to the yield reduction of 17% for wheat and 5% for maize across Africa projected for the same period (2050 s) by Porter et al. (2014). Muluneh (2020) reported 9% maize yield reduction for the Rift valley in Ethiopia. Higher temperature associated with climate change drives a faster accumulation of thermal time, resulting in shortening of the growing period (Trudgill et al., 2005). For maize and wheat, the maturity period was reduced by 19–21% and 12–16% (range between HFZs and variety), respectively. This implies that crops may not be able to utilize the available moisture of the full growing season. Under climate change, higher temperature enhances evaporation and transpiration (Table 5) and increases water stress (Bates et al., 2008; Moratiel et al., 2010). The effect of climate change on yield is stronger at higher N levels because the larger vegetative biomass increases water stress during in-season dry spells. Hence, climate change reduces Yw and will result in lower yield gaps. This implies that the scope for closing the yield gap using intensification options is reduced whereas the use of late maturing varieties may be limited in the future associated with the potential change in season length as well as the potential heat stress from the increased temperature. We acknowledge that we only investigated one, fairly extreme, scenario of climate change, and considered only temperature changes and CO_2 concentration changes. Beside the strong effect on evaporation and transpiration, climate change also led to reduced drainage (Table 5). At high N levels the reduction in drainage was smaller in maize than in wheat, because drainage under maize was already very low at high N levels under the current climate. For wheat though, the large amount of drainage water available at high N levels was strongly reduced by climate change.

4.4. Economics of N fertilization

Our estimations of N requirements to achieve 80% of Yw for maize compare well with the minimum N requirement reported in the Global Yield Gap Atlas for Butajira (252 kg ha^{-1}) and Melkassa (90 kg ha^{-1}) representative of the late and early maturing maize growing locations in the study area, respectively (Ten Berge et al., 2019; GYGA, 2021). It also matches the estimate for low and medium potential maize growing areas (100–120 kg ha^{-1}) in SSA (GYGA, 2021). Although yield increase was possible by increasing the N level up to 250 kg ha^{-1} in most cases, the marginal return and WUE diminished at N rates below the rates at which maximum yield was attained. Yet, it was possible to attain at least 80% of the water-limited potential yield while maximizing gross margins and WUE. The rate that maximized gross margin varied with soil types, crops and varieties, but was similar to the rate required to maximize WUE. Although high N rates allowed increasing gross margins, the associated investment costs are high for small holder farmers. Therefore, the access to fertilizer and availability of financial resources and credit facilities are important boundary conditions for increased N use by smallholders (IFDC, 2012).

We did not include other costs of N application (e.g., labor) or the possible additional benefit from the increase in biomass in this economic analysis. We also did not account for the larger risk associated with high N input, which was particularly evident for maize in Vertisols of the EH and Andosols of CL (Fig. 5).

5. Conclusions and recommendations

There is scope to increase crop yields through increasing N input far beyond farmers' current practice, even though yield variability can be large depending on location and soil type. Especially for maize in the highlands, variety selection is important to fully exploit the yield benefit from increased N input. Although less important compared with the use of fertilizers, increased planting density and residue retention could also increase yield if constraints related to animal feed and land use arrangements in the current farming systems would be alleviated. There is potential to attain at least 80% of the Yw in most HFZs and soils with N rates that result in high water use efficiencies and favorable cost-benefit ratios. These N rates are 250 kg ha^{-1} for late maturing and 75–125 kg ha^{-1} for early maturing maize varieties, and up to 250 kg ha^{-1} for both varieties of wheat. Experimentation is needed to confirm and fine tune the simulated outcomes of these N rates that are well above the presently "recommended" rates.

Projected temperature increases under climate change by 2050 are likely to decrease yields in the CRV. Furthermore, the variability in yield increased with climate change, making farmers' decisions to select proper variety, management and input levels riskier. The trade-off between yield and water use through evapotranspiration will be aggravated under climate change due to increased evapotranspiration on the one hand and decreased yield on the other hand. Hence, climate change will increase the demand for agricultural land and water to produce the same amounts of cereals.

This field scale analysis provided insight in the potential to narrow the yield gap using different combinations of input use and management options. Despite the potential, trade-offs between achieving high crop yields and increased water use at field scale are unavoidable. The approach shows scope for site, crop and variety specific nitrogen recommendation. Regional studies are required to better understand the wider implications of the trade-offs for the water balance and production goals in the Central Rift Valley.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Annex 1. Soil hydrologic properties of three soil types used in the SoilWat module.

Soil type	Depth (cm)	BD (g cm^{-3})	LL (mm mm^{-1})	DUL (mm mm^{-1})	SAT (mm mm^{-1})
Andosols	0–20	1.190	0.195	0.355	0.497
	20–50	1.200	0.203	0.360	0.497
	50–75	1.140	0.180	0.376	0.535
	75–100	1.140	0.180	0.376	0.535
	100–125	1.160	0.202	0.392	0.535
	125–150	1.160	0.202	0.392	0.535
Luvisols	0–15	1.180	0.199	0.388	0.505
	15–30	1.220	0.199	0.405	0.490
	30–60	1.220	0.256	0.405	0.490
	60–90	1.225	0.256	0.434	0.488
	90–120	1.225	0.260	0.434	0.488
	120–150	1.310	0.260	0.434	0.488
Vertisols	0–25	1.100	0.240	0.337	0.500
	25–50	1.170	0.273	0.359	0.480
	50–90	1.400	0.336	0.442	0.470
	90–132	1.480	0.302	0.436	0.440
	132–200	1.300	0.253	0.381	0.500

BD = bulk density; LL=the soil water lower limit (at 15 bar pressure); DUL= soil water at drain upper limit of the soil; SAT= water content when the soil is saturated

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