Simulation analysis of factors affecting sorghum yield at selected sites in eastern and southern Africa, with emphasis on increasing temperatures

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ABSTRACT

Global warming is widely predicted to decrease crop yields in tropical, sub-tropical and Mediterranean climatic regions as a result of a speeding up of phenological development and shortening of the time to maturity. We used a well-tested simulation model, APSIM-Sorghum, to evaluate the impact of temperatures +1 °C, +2 °C, +3 °C, +4 °C and +5 °C above current temperatures measured over the past ~50 years at four sites in eastern and southern Africa, namely, Katumani and Makindu in Kenya, Chitala in Malawi and Beitbridge in Zimbabwe, on the yield, aboveground biomass, transpiration and soil evaporation of short-, medium- and long-duration sorghum [Sorghum bicolor (L.) Moench] cultivars given, 0, 20, 40, and 80 kg nitrogen (N) ha^{-1}. When fertilized with 80 kg N ha^{-1}, warming temperatures decreased average yields at Chitala and Beitbridge and yields were unchanged at Makindu and Katumani, but with no added fertilizer average yields increased with increase in temperature at all sites except the hottest and driest site, Beitbridge, where the simulated yields decreased with increasing temperature. Simulation of the changes in soil organic carbon showed that the higher temperatures increased the rate of loss of soil organic carbon and increased nitrogen uptake at all except the driest and hottest site. A micro-dose (20 kg N ha^{-1}) of added nitrogen increased the simulated yields by an average of 19% at Beitbridge, 36% at Makindu, 59% at Katumani and 72% at Chitala, considerably greater than any increase from increased temperatures. The use of longer-duration cultivars and lower or higher populations could not consistently be used to overcome any reductions in yield from warming temperatures. We conclude that low-input, small-holder farmers will not immediately have reduced sorghum yields as a consequence of global warming, but micro-dosing with nitrogen fertilizer will significantly increase yields even in the hottest and driest locations.

1. Introduction

In Sub-Saharan Africa, 200 million people, or one in every three, are malnourished, while cereal yields are at best growing more slowly than population. Over the past five decades, maize (*Zea mays* L.) yields have increased from about 1000 to 1500 kg ha^{-1} in eastern Africa and from 1200 to 3500 kg ha^{-1} in southern Africa, while sorghum [Sorghum bicolor (L.) Moench] yields have increased from 750 kg ha^{-1} in both eastern and southern Africa to 1100 kg/ha in eastern Africa and 1500 kg ha^{-1} in southern Africa, much less than the increases in the developed world (FAOSTAT-Agriculture, 2010). Peanut (*Arachis hypogaea* L.) yields have increased from

800 to 1800 kg ha^{-1} in southern Africa, but only from 550 to 650 kg ha^{-1} in eastern Africa (FAOSTAT-Agriculture, 2010). The dual system of commercial and small-holder farmers in Africa, particularly southern Africa, hides the reality that on-farm yields of these staple crops on small-holder farms has remained steady or declined over the same period (World Bank, 2007). The population, rapidly increasing at 2.5% per annum despite a high death rate from HIV/AIDS (http://esa.un.org/wpp/Excel-Data/population.htm (accessed May 2012)), means that small-holder farmers in sub-Saharan Africa need to substantially increase food production in the face of climate change.

Studies of recent trends in climate for eastern and southern Africa show that the region has been warming at a rate of 0.5–2.0 °C per century for the past four decades (Hulme et al., 2001; New et al., 2006; ICPAC, 2007) with high temperature extremes becoming more frequent (New et al., 2006). Changes in rainfall have greater uncertainty, but a detailed analysis of 104 stations across Mozambique, Zambia, Malawi and Zimbabwe showed a

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trend for a delay in consistent rain for planting, a decrease in the number of rain days, an increase in the length of dry spells, and earlier maturity (Tadross et al., 2007). Median temperatures are predicted to rise in eastern and central Africa by about 1 °C by 2030 (ICPAC, 2007; Lobell et al., 2008) and by 3–4 °C by the end of the 21st century, while some models predict increases up to 5 °C in southern and eastern Africa (Christensen et al., 2007). Predictions of future rainfall are less certain. It is generally agreed that rainfall will increase in eastern Africa, particularly in the Great Lakes region, by about 5% by 2030 (ICPAC, 2007; Lobell et al., 2008) and 7% by the end of the century (Christensen et al., 2007) and likely to decrease by 4% in southern Africa by the end of the century (Christensen et al., 2007). Of particular concern is the predicted shortening of the crop growing season in southern Africa, particularly the increase in dry spells in the early part of the growing season that delays planting (Tadross et al., 2007).

Analyses of the effects of increasing temperatures on grain yield predict that yields are likely to increase at higher latitudes, but to decrease in the semi-arid and sub-tropical agricultural regions (Jones and Thornton, 2003; Visser and Both, 2005; Cooper et al., 2009; Turner and Meyer, 2011; Turner et al., 2011) as a result of higher temperatures speeding phenological development, and decreasing leaf area, radiation interception and biomass production. However, these predictions are based on data for high-input agricultural crops and the question is whether similar decreases in yield occur with the low-input crops of small-holder farmers. In this paper we use a well-tested simulation model to determine the influence of changes in temperature on yield and factors influencing the yield of sorghum, the staple crop of small-holder farmers in many areas of sub-Saharan Africa, with a range of input levels and management options. We do not include the influence of higher carbon dioxide (CO_2) concentrations as Cooper et al. (2009) have shown that the so-called CO_2 fertilizing effect is small compared to the impact of higher temperatures or water shortage in peanut, and sorghum is a C_4 species in which a doubling of CO_2 has a much smaller effect on yield than in C_3 species such as peanut (Cure and Acock, 1986; Seneweera and Norton, 2011). Using the reported CO_2 responses of sorghum (Ottman et al., 2001; Prasad et al., 2006) with the Michaelis–Menten rectangular hyperbola method, Hatfield et al. (2008) estimated that the expected CO_2 increase over the next 30 years is anticipated to have a negligible effect (1%) on sorghum yields. Further, we did not directly include the effects of changes in rainfall as rainfall in eastern Africa is predicted to increase or to remain unchanged, except for a delay in the rains at the start of the growing season in southern Africa (Christensen et al., 2007; Tadross et al., 2007). However, we utilized the variation among seasons to elucidate the effect of rainfall on yields in a changing climate.

2. Materials and methods

2.1. Crop simulation

We used a simulation model, APSIM-Sorghum (Keating et al., 2003) version 7.1, to determine the effects of increasing temperature on the yield and development of sorghum [S. bicolor (L.) Moench]. APSIM-Sorghum simulates the growth of a sorghum crop in a daily time-step on an area basis. Sorghum growth in the model responds to climate (temperature, rainfall and radiation), soil water supply and soil nitrogen, and returns information on the soil water and nitrogen uptake on a daily basis to reset these systems. Information on crop cover is also provided to the soil water component for the calculation of evaporation rates and runoff. APSIM-Sorghum predicts leaf area development, nitrogen percentage and plant biomass, root depth and biomass, grain yield and nitro-

gen content on a daily basis (www.apsim.info/apsim/releases/Apsim70/Documentation/4%20Module%20Reference/Sorghum.htm). It accurately simulates actual crop phenology, yields and yield attributes across a range of soil types, seasons and crop rotations (Ncube et al., 2009; Hansen et al., 2009; Hammer et al., 2010). The model is sufficiently robust to simulate the performance of sorghum under a range of different bio-physical conditions. In the case of Africa, MacCarthy et al. (2009, 2010) have tested the performance of the model under different management conditions in semi-arid Ghana where conditions are similar to the sites in this paper. Their studies have indicated that the simulated grain yield of sorghum to both nitrogen and phosphorus application matched well with the observed grain yield with an overall internal coefficient of efficiency of 0.64. Over a range of yields from 500 to 4000 kg ha^{-1} at two sites in East Africa, two population levels and two levels of nitrogen fertilizer, the simulated grain yield (SY) was linearly related to the observed grain yield (OY) (SY = 0.95 + 333, r^2 = 0.55). Considering the widespread use of the model and its well demonstrated efficiency in simulating water and fertility stresses on sorghum productivity, no attempt was made to calibrate the model for this study. Given that the model is driven by daily weather data, it can be used to evaluate the impacts of temperature and rainfall. Temperature is a key driver of phenological development. Each day the phenology routines calculate thermal time in degree days from 3-hourly air temperatures interpolated from the daily maximum and minimum temperatures. A cardinal mean temperature of 32 °C is assumed in APSIM-Sorghum, such that time to flowering is reduced linearly from 10 °C to 32 °C and then increases with mean temperatures from 32 °C to 42 °C at which temperature development stops (Hammer et al., 1993; Carberry et al., 1993). Water availability is determined by the soil characteristics, root growth, initial soil water content, rainfall and evapotranspiration. If the daily demand for water exceeds supply, a water stress factor determined by the supply:demand ratio comes into play and reduces photosynthesis, phenological development and leaf expansion. In each simulation run, it was assumed that weeds, diseases and waterlogging did not affect yields, and as there is no clear regional trend in changes in the diurnal temperature range (New et al., 2006), temperature increases were equally reflected in changes in both the maximum and minimum air temperatures. The key parameters used in the simulation runs are given in Table 1.

2.2. Locations

Sites in Kenya, Malawi and Zimbabwe were chosen that had reliable long-run (45–52 years) weather information and measured soil data. The two sites in Kenya were at Katumani with an annual rainfall of 700 mm and Makindu with an annual rainfall of 620 mm. They were chosen because they had similar annual and growing-season rainfall, but Katumani is cooler than Makindu (Table 2). Chitala in Malawi and Beitbridge in Zimbabwe are both hotter than the two Kenyan sites; Chitala is the wettest site with annual rainfall of 890 mm while Beitbridge is the driest site with 348 mm annual rainfall. Table 2 gives the long-term (~50 years) mean maximum and minimum temperatures and mean rainfall for the growing season at each location.

2.3. Simulating the effect of temperature, fertilization, and plant population

APSIM-Sorghum was run for each location using the measured climate conditions for the ~50-year period (referred to as current climate), then re-run with a 1 °C, 2 °C, 3 °C, 4 °C and 5 °C increase in temperature on each day during the growth of the sorghum crop, and with no additional nitrogen, 20, 40 and 80 kg ha^{-1} of

Table 1

Key soil, crop and management parameters used in the simulation analysis with APSIM-Sorghum. The organic carbon (Org C) fractions given are the total ($_T$), biomass fraction ($_B$) and inert fraction ($_I$); the difference between the total and the sum of the fractions in the biomass and the inert is the humic fraction.

Parameter	Value					
Soil profile	Alfisol profile with a total depth of 1.5 m divided into six layers (0–0.15, 0.15–0.30, 0.3–0.6, 0.6–0.9, 0.9–1.2, and 1.2–1.5 m)					
Plant available water	Maximum plant available water capacity of 163.5 mm with root depth constrained to 1 m					
Soil nitrogen (N) and organic carbon	Depth (m)	Org C_T (%)	Org C_B (%)	Org C_I (%)	Initial nitrate N (kg ha^{-1})	Initial ammonia N (kg ha^{-1})
	0–0.15	0.460	0.040	0.390	2.000	1.000
	0.15–0.30	0.380	0.020	0.470	1.000	1.000
	0.30–0.60	0.280	0.015	0.520	1.000	1.000
	0.60–0.90	0.230	0.010	0.620	1.000	0.500
	0.90–1.20	0.210	0.010	0.740	1.000	0.500
	1.20–1.50	0.150	0.010	0.830	1.000	0.500
Varieties	Short-, medium- and long-duration cultivars with default parameters					
Management	One "disc" type tillage to 0.15 cm depth applied on October 1 and one "planter" type tillage on October 14 every year					
	Planting criteria: planting with 25 mm rainfall over 2 days between October 15 and November 30					
	Plant population: 66,000 plants ha^{-1} in all simulations except those with variable populations					
	Row spacing and planting depth: 0.6 m and 33 mm					
	Fertilizer: as per the treatment					
	Soil water, nitrogen and surface organic matter: accumulated effects with no resets					
	Biomass at harvest: removed using "burn" option					

Table 2

Mean maximum and mean minimum growing-season temperatures and mean growing-season rainfall at the four locations in Africa where APSIM-Sorghum was used to evaluate the impact of temperature on the growth and yield of sorghum.

Location	Mean growing season climate			Period of record
	Max. temp.	Min. temp.	Mean rainfall (mm)	
Makindu, Kenya	28.6	17.1	379	1959–2004
Katumani, Kenya	25.4	13.9	352	1957–2009
Chitala, Malawi	32.1	16.7	745	1947–1999
Beitbridge, Zimbabwe	33.2	21.4	248	1951–2001

nitrogen fertilizer each year at sowing. The simulations were for a short-season sorghum cultivar similar to the one grown at the locations, and additionally for a medium-season and a long-season cultivar. The normal plant population used in the region is 66,000 plants ha^{-1}; simulations were also run to determine the influence of reducing the plant population to 50,000 plants ha^{-1} and increasing it to 80,000 plants ha^{-1}. The major runs were initiated with nitrogen levels and soil organic carbon levels for each site as given in Table 1 and were not re-initialized each year.

2.4. Simulated outputs

APSIM-Sorghum outputs the days to 50% flowering, days to maturity, biomass, seed yield, soil water, organic carbon and nitrogen content, soil water and nitrogen uptake, soil evaporation and plant transpiration. Daily values and yearly means of these parameters can also be output as required. Mean values of the days to 50% flowering, days to maturity, total biomass and seed yield for the run of years simulated were calculated, and probability of exceedence values for yield were plotted.

3. Results

3.1. Predicted effects of increasing temperatures on phenology and yield

At Chitala and Makindu with current climate conditions and no added nitrogen, the early cultivars flowered in about 60 days after sowing (DAS), while the medium-duration cultivars and the long-duration cultivars took an additional 10 and 20 days, respectively (Table 3). At Katumani the early cultivar took over 90 days to flow-

er and the medium-duration cultivar and long-duration cultivar took an additional 15 and 30 days, respectively, whereas at Beitbridge the early cultivar took 66 days to flower, the medium-duration cultivar took 59 days to flower and the long-duration cultivar flowered in 65 days, the same as the short-duration cultivar (Table 3). With climate change, the time to 50% flowering decreased with every 1 °C rise in temperature at all four sites and in all three cultivars with different phenologies (Table 3, only +1 °C, +3 °C and +5 °C presented). The time to maturity was also shortened by the warmer temperatures at all sites except Beitbridge where the medium-duration sorghum took longer to mature. At Katumani, a 5 °C increase in temperature with no added nitrogen reduced the growth period to maturity by ∼50 days (Table 3). Despite the decrease in the time to maturity at Makindu, Chitala and Katumani, the yields of the early-, medium- and late-duration sorghum cultivars all increased as the temperature increased given no additional fertilizer, whereas at Beitbridge which has low rainfall, an increase in temperature of 3 °C and 5 °C decreased the predicted yield by nearly 20% and 34%, respectively (Table 3). The yields simulated for Katumani, Chitala and Makindu with the current climate are in line with measured and expected yields for the sites and region (Jaetzold et al., 2006).

3.2. Predicted effects of nitrogen fertilization and increasing temperatures on yield

At all locations, the application of fertilizer at any level had little effect on the time to maturity, but had a large impact on the biomass and average yield, particularly at the three wetter sites (Table 3). At Chitala and Katumani, addition of 20 kg N ha^{-1} resulted in an 84% increase in yields (mean of all duration cultivars) in the current climate, but as the climate warmed the simulated yields increased in Katumani, while they decreased in the short-duration cultivar at Chitala. At Makindu and Beitbridge, where the yield increases from the additional fertilizer were more modest (44% and 14% across all cultivars, respectively), warmer temperatures had either no effect on yield (Makindu) or yields were reduced (Beitbridge) (Table 3). Increasing the amount of fertilizer to 40 kg N ha^{-1} (a commercial level of fertilizer) and 80 kg N ha^{-1} increased yields further at current temperatures, but at Chitala and Beitbridge the warmer temperatures reduced the simulated yields by ∼10% and ∼40% at +5 °C, while yields were stable at Mak-

Table 3

Simulated time to 50% flowering and maturity in days after sowing (DAS), seed yield and total aboveground biomass for short-, medium- and long-season cultivars of sorghum at current temperatures, with 1, 3 and 5 °C increases in temperature and 0, 20, 40 and 80 kg ha^{-1} of nitrogen fertilizer at four locations in Africa. Data are averages for ~50 years of simulation.

Temperature regime (°C)	0 kg ha^{-1} Nitrogen				20 kg ha^{-1} Nitrogen				40 kg ha^{-1} Nitrogen				80 kg ha^{-1} Nitrogen			
	50% Flower (DAS)	Maturity (DAS)	Yield (kg ha^{-1})	Biomass (kg ha^{-1})	50% Flower (DAS)	Maturity (DAS)	Yield (kg ha^{-1})	Biomass (kg ha^{-1})	50% Flower (DAS)	Maturity (DAS)	Yield (kg ha^{-1})	Biomass (kg ha^{-1})	50% Flower (DAS)	Maturity (DAS)	Yield (kg ha^{-1})	Biomass (kg ha^{-1})
Chitala																
Short duration																
Current	61.5	108	1660	4155	59.3	107	3022	6549	59.3	107	3799	7554	59.8	107	4803	8938
+1	58.4	105	1680	4117	56.3	103	2893	6372	56.8	103	3706	7290	57.3	104	4769	8691
+3	55.3	100	1716	4071	54.2	99	2907	6141	54.4	99	3642	7067	54.8	100	4683	8450
+5	55.3	100	1759	4131	54.5	99	2913	6214	54.8	100	3602	7205	55.1	100	4425	8476
Medium duration																
Current	71.6	119	1503	4434	67.6	115	2858	7158	66.9	114	4165	9196	67.1	114	5301	10,612
+1	67.4	113	1573	4446	64.3	110	2900	7062	63.8	110	4107	8905	64.0	110	5225	10,259
+3	63.5	109	1651	4466	61.2	106	2915	6923	61.0	106	3997	8549	61.2	106	5118	9871
+5	63.3	108	1729	4554	61.3	106	2933	6919	61.0	106	3912	8471	61.6	106	4821	9672
Long duration																
Current	83.7	131	1347	4713	77.9	125	2432	7193	74.7	122	3905	9862	75.0	122	5541	12,279
+1	78.4	124	1433	4736	73.5	120	2528	7165	71.1	117	3922	9646	71.5	118	5412	11,796
+3	73.0	118	1548	4778	69.3	114	2677	7159	67.6	113	3894	9327	68.4	113	5166	11,050
+5	72.5	117	1639	4876	69.2	114	2725	7179	67.7	112	3767	9097	69.0	114	4773	10,438
Makindu																
Short duration																
Current	59.2	105	1736	4132	57.4	105	2565	5821	54.4	106	2942	6368	52.6	107	3051	6714
+1	54.5	100	1792	4055	52.8	100	2579	5620	53.7	101	3004	6168	47.9	102	3175	6558
+3	48.4	93	1843	3878	46.8	93	2579	5252	48.3	94	3041	5796	48.6	96	3268	6193
+5	46.3	91	1856	3777	44.8	92	2524	4990	46.9	93	2937	5508	48.4	94	3086	5783
Medium duration																
Current	70.1	115	1537	4409	65.4	115	2248	6261	57.6	115	2574	6919	54.9	117	2845	7372
+1	64.0	109	1644	4356	61.4	110	2337	6109	51.4	108	2656	6700	53.2	110	2919	7124
+3	56.5	101	1753	4225	51.2	100	2391	5773	52.6	102	2811	6404	49.6	102	3069	6742
+5	52.3	99	1778	4133	51.6	98	2340	5478	47.4	98	2682	5986	47.0	100	2943	6322
Long duration																
Current	82.8	127	1319	4614	63.1	123	1823	6334	66.8	127	2265	7398	64.5	128	2561	7883
+1	75.9	120	1419	4552	62.2	117	1913	6205	61.1	119	2334	7122	54.5	119	2604	7582
+3	59.2	109	1553	4420	59.7	109	2034	5880	52.9	111	2443	6655	52.6	112	2720	7105
+5	56.6	105	1565	4286	52.5	104	2008	5585	50.0	106	2335	6214	51.8	107	2592	6595
Katumani																
Short duration																
Current	92.5	145	1195	4086	89.5	143	2368	6700	79.4	142	2584	7369	79.3	145	2627	7719
+1	80.1	130	1378	4211	76.7	131	2446	6564	68.6	130	2568	7098	65.4	131	2587	7341
+3	63.1	109	1588	4166	65.4	113	2554	6156	53.9	110	2630	6405	53.7	112	2757	6655
+5	53.1	98	1710	4011	52.7	99	2507	5634	51.0	100	2787	5999	48.5	100	2956	6248

Medium duration																
Current	106.8	159	1029	4363	105.8	159	1930	6969	94.3	159	2287	8162	83.3	158	2470	8544
+1	94.5	144	1133	4402	90.8	143	2021	6852	78.3	142	2148	7658	76.9	144	2467	8149
+3	74.9	121	1406	4447	77.1	125	2217	6550	64.2	122	2368	7118	59.7	123	2534	7388
+5	61.9	107	1581	4339	63.7	111	2329	6197	54.4	109	2417	6503	57.0	110	2839	6973
Long duration																
Current	121.5	175	933	4729	119.8	173	1546	6964	113.8	176	2096	8800	95.5	182	2292	9234
+1	108.4	158	1014	4765	110.2	160	1639	6915	90.5	156	1895	8161	83.9	156	2214	8803
+3	89.5	135	1197	4706	87.4	136	1885	6734	69.0	131	1962	7412	69.0	134	2219	7861
+5	74.8	120	1423	4625	67.7	121	1918	6260	58.6	117	2210	6989	59.0	121	2438	7284
Beitbridge																
Short duration																
Current	66.4	117	795	2479	49.2	124	899	2985	42.2	122	966	3044	45.2	122	980	3067
+1	66.0	118	767	2392	50.2	121	838	2842	37.5	120	904	2901	37.6	120	924	2922
+3	57.7	121	641	2205	43.6	121	740	2634	45.7	121	788	2663	45.6	120	796	2667
+5	55.4	126	510	2014	33.7	120	549	2319	34.6	121	563	2360	39.1	123	580	2416
Medium duration																
Current	58.8	134	671	2598	44.8	137	782	3158	43.6	138	874	3332	42.7	138	895	3351
+1	58.9	133	655	2494	47.0	136	767	3040	43.4	136	846	3189	42.0	136	864	3187
+3	54.0	133	573	2290	40.1	135	690	2781	39.9	134	721	2882	39.8	135	745	2918
+5	50.5	141	457	2130	43.9	137	533	2510	42.6	139	570	2596	42.5	139	575	2607
Long duration																
Current	65.4	150	593	2665	38.6	152	679	3241	38.3	153	749	3409	38.4	154	791	3496
+1	63.7	150	564	2536	40.4	150	673	3137	43.5	152	728	3263	43.9	153	779	3360
+3	59.9	153	481	2375	41.2	149	592	2868	40.7	151	651	2997	41.1	152	673	3033
+5	46.6	152	389	2199	38.2	154	453	2586	36.9	155	476	2694	36.7	155	473	2669

indu and continued to increase at Katumani as temperatures increased (Table 3).

The data in Table 3 are the averages for 45–52 years and do not reveal differences among years. Therefore we plotted the annual yields of sorghum as probability distributions to understand the variation in yields and the influence of rising temperatures on these yields. We first evaluated the influence of rising temperatures on the simulated yields of sorghum with no fertilizer, as currently used by small-holder farmers, and with 40 kg N ha^{-1}, that is with a commercial use of fertilizer. At Chitala, yields of the current short-duration cultivar varied over the 52 years from 500 kg ha^{-1} to 3800 kg ha^{-1} with no additional fertilizer, and increasing temperatures as high as 5 °C had little effect on yields in 50% of years (Fig. 1). In the better years when yields were above 1500 kg ha^{-1}, rising temperatures increased yields by a maximum of 400 kg ha^{-1}. The application of a commercial-farm level of 40 kg N ha^{-1} markedly increased the simulated sorghum yields to 2800–4500 kg ha^{-1} over the same years with the current climate, but in all years except the wettest 10% of years, warmer temperatures decreased the yields by up to 400 kg ha^{-1} (Fig. 1).

We then simulated the influence of a 3 °C rise in temperature on yields with a modest (20 kg ha^{-1}) increase in fertilizer nitrogen compared with the effect with the zero level of additional fertilizer used by small-holder farmers. At Makindu, with no additional fertilizer, a 3 °C rise in temperature increased sorghum yields of the current short-duration cultivar in almost all years except the exceptionally wet and productive years when yields were above 3300 kg ha^{-1} (Fig. 2). However, with a micro-dose of 20 kg N ha^{-1}, a 3 °C rise in temperature increased yields in 40% of years when the yields were below the median, but decreased yields in about 40% of years when the yields were above the median yield; again the exceptionally wet years when yields were above 3600 kg ha^{-1}, yields were similar to those at current temperatures (Fig. 2). However, the small increase in fertilizer increased sorghum yields significantly in all but the poorest 10% of years when yields at 0 kg N ha^{-1} were about 1000 kg ha^{-1} (Fig. 2). The increase in fertilizer use, however, did increase crop failures (yields less than 200 kg ha^{-1} resulted in 0 kg ha^{-1} harvested) in 2.5% of seasons at both current temperatures and with a 3 °C rise in temperature (Fig. 2).

Fig. 2. The influence of a 3 °C rise (open symbols) in temperature above the current temperatures (closed symbols) on the simulated yields of a short-duration cultivar of sorghum over 45 years at Makindu given 0 (squares) or 20 (circles) kg N ha^{-1}. Both the maximum and minimum temperatures were increased by 3 °C above the current values on each day from sowing to maturity.

3.3. Predicted effects of phenology, fertilization and increasing temperatures on yield

The speeding up of development induced by the higher temperatures observed at all sites except Beitbridge and the decrease in mean yield at higher temperatures in the fertilized sorghum (Table 3), can be counterbalanced by using late-duration cultivars (Table 3). When we compared the distribution of yields over the 52 years at Chitala with a 3 °C rise in temperature with no additional nitrogen, the medium- and long-duration cultivars had similar yields to the short-duration cultivar in the 50% of years when yields were below the median and lower yields in the 50% of years when yields were above the median (Fig. 3). The modest increase in nitrogen application of 20 kg N ha^{-1} increased yields at Chitala and using a medium-duration cultivar rather than a short-duration cultivar reduced yields in 50% of years, but increased yields in the wetter years when yields were above 3500 kg ha^{-1} (Fig. 3). With the application of the high level of fertilizer of 80 kg N ha^{-1}, the use of later-flowering cultivars increased yields in 85% of years and was only detrimental to yield when yields were below 4500 kg ha^{-1} (Fig. 3).
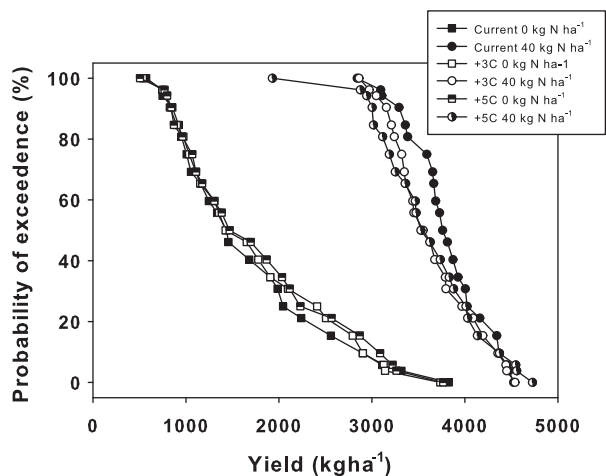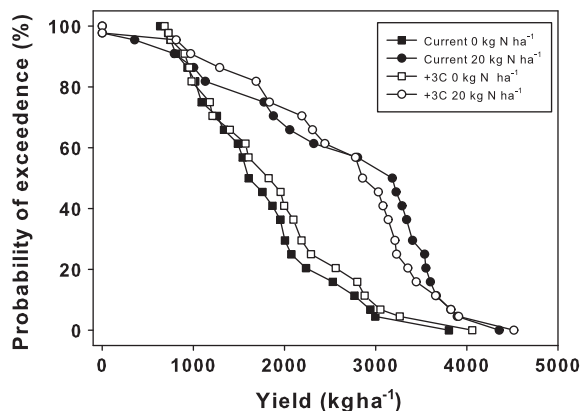

Fig. 1. The influence of a 3 °C (open symbols) and 5 °C (half-open symbols) rise in temperature above the current temperatures (closed symbols) on the simulated yields of a short-duration cultivar of sorghum over 52 years at Chitala given 0 (squares) or 40 (circles) kg N ha^{-1}. Both the maximum and minimum temperatures were increased by 3 °C and 5 °C above the current values on each day from sowing to maturity.
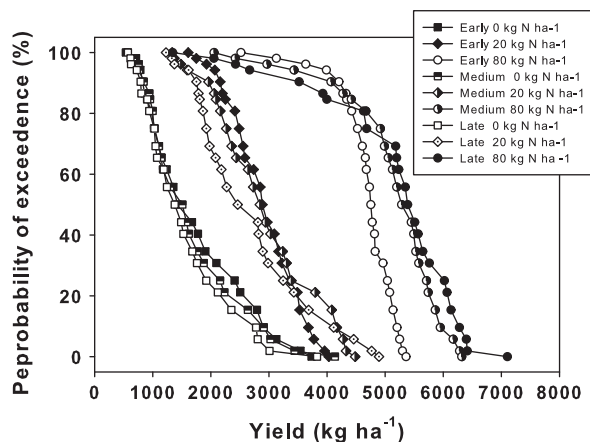

Fig. 3. The influence of a short-duration cultivar (early), a medium-duration cultivar (medium) and a long-duration cultivar (late) on the simulated yields of sorghum over 52 years at Chitala given 0 (squares), 20 (diamonds) and 80 (circles) kg N ha^{-1} and with a 3 °C rise in temperature above the current temperatures. Both the maximum and minimum temperatures were increased by 3 °C above the current values on each day from sowing to maturity.

3.4. Changes in soil evaporation and crop transpiration with increasing temperatures

We used APSIM-Sorghum to explore the water use by the crop in the various treatments. With current practice and a short-duration cultivar, soil evaporation varied from 73% to 80% of total evapotranspiration at the four sites (Table 4). With a temperature rise of 3 °C, the proportion of water lost by transpiration increased and the amount of water lost by soil evaporation decreased at the three sites where yields increased, but was unchanged at Beitbridge where yields decreased (Table 4). The addition of 40 kg N ha^{-1} increased the transpiration by the crop at all sites with little change in soil evaporation, so that the proportion of total evapotranspiration lost as soil evaporation decreased from 73–80% to 58–71% at current temperatures (Table 4). The addition of fertilizer clearly increased the proportion of the total evapotranspiration that was used in transpiration rather than being lost by soil evaporation.

Using longer season cultivars also increased the transpiration by the sorghum crop at all four sites and at the wetter sites increased the soil evaporation (Table 4). One of the consequences of the higher temperatures shortening the growing season was that it reduced the access to late rains and reduced the overall evapotranspiration of the sorghum at the wetter sites of Katumani and Makindu, but not at Beitbridge and Chitala. For example, at Katumani where the growth of the crop was shortened by about 1 month by a 3 °C rise in temperature, on average 86 mm of rain fell in that month. The question is whether longer-duration cultivars can make better use of the total seasonal rainfall in the warmer temperatures associated with climate change. The simulation suggests that the longer-duration cultivars were not able to take full advantage of the water left in the profile and any subsequent rain. For example, at Katumani the total evapotranspiration for sorghum grown with no additional fertilizer decreased from 283 mm to 241 mm with a 3 °C rise in temperature. Despite an additional 86 mm of rain in the 30 days after the short-duration crop matured, the evapotranspiration of the medium-duration cultivar was 258 mm, higher than the short-duration cultivar at the same temperature rise, but not as high as the 283 mm of the short-duration cultivar at the current temperature (Table 4). However, at Chitala where the crop (0 kg N ha^{-1}) with a 3 °C rise in temperature matured 8 days earlier and Makindu where it matured 12 days earlier, total evapotranspiration was not decreased or decreased only 9 mm, and using a medium-duration cultivar increased total evapotranspiration, but not yield (Table 3). This suggests that use of longer-duration cultivars cannot compensate for rising temperatures and shorter maturity as the temperatures rise, presumably because at the higher temperatures the transpiration efficiency of the crops is lower.

3.5. Predicted changes in soil organic carbon and nitrogen uptake by the crop with increasing temperatures

One possible reason for the increase with temperature in the simulated sorghum yields with current farming practice was the liberation of nitrogen from the soil microbial biomass. The mean soil organic carbon levels in the top 0.15 m of the soil at Katumani are 0.46% (Okwach and Simiyu, 1999). The organic carbon percentage decreased with depth as a result of a decrease in the biologically-active fraction in the microbial biomass and the humic fraction, while the inert fraction of the organic carbon increased with depth (Table 1). Using the 0.46% organic carbon observed at Katumani as a starting value for all locations, the decrease in soil organic carbon at the four locations was simulated by APSIM. Over the 52 years at Katumani, the soil organic carbon decreased at a rate of 0.028% decade^{-1} when temperatures were 5 °C higher than the current temperature, compared to 0.021% decade^{-1} at current temperatures. This can be seen in Fig. 4 where the decrease in organic carbon with current, +1 °C, +3 °C, and +5 °C temperatures is plotted for the four locations. The rate of decrease in organic carbon was greatest at the wettest site, Chitala, and least at the driest site, Beitbridge, while the impact of the increase in temperature was largest at Katumani, the coolest site, and negligible at the driest and hottest site, Beitbridge. We also simulated the changes in

Table 4
Simulated plant transpiration (T) and soil evaporation (E) for short-, medium-, and long-season cultivars of sorghum at current temperatures, with 1, 3 and 5 °C increases in temperature and 0 and 40 kg ha^{-1} of nitrogen fertilizer at four locations in Africa. Data are averages for ~50 years of simulation.

| Temperature regime (°C)	Short duration				Medium duration				Long duration			
	0 kg N ha^{-1}		40 kg N ha^{-1}		0 kg N ha^{-1}		40 kg N ha^{-1}		0 kg N ha^{-1}		40 kg N ha^{-1}	
	T (mm)	E (mm)	T (mm)	E (mm)	T (mm)	E (mm)	T (mm)	E (mm)	T (mm)	E (mm)	T (mm)	E (mm)
Chitala												
Current	84	235	159	223	92	240	198	219	101	248	216	218
+1	87	228	159	217	96	231	200	212	106	239	221	211
+3	94	225	170	215	106	226	212	210	117	232	235	209
+5	106	235	194	228	120	235	234	222	133	241	255	222
Makindu												
Current	57	158	100	167	64	167	100	167	70	177	109	174
+1	57	152	100	159	65	160	100	159	71	171	108	165
+3	59	147	103	154	66	152	103	154	73	161	108	158
+5	64	146	105	150	71	151	105	150	76	159	110	154
Katumani												
Current	56	227	104	229	61	248	116	248	68	268	126	263
+1	59	206	103	212	64	222	111	223	71	240	120	235
+3	61	180	99	182	68	190	110	195	74	207	116	202
+5	61	168	98	170	69	175	108	177	77	188	117	183
Betbridge												
Current	46	140	56	140	48	148	59	147	50	152	60	150
+1	47	140	55	139	49	147	59	147	51	153	60	150
+3	47	143	55	140	49	146	58	146	51	154	59	151
+5	48	147	54	142	51	153	57	151	52	156	58	154
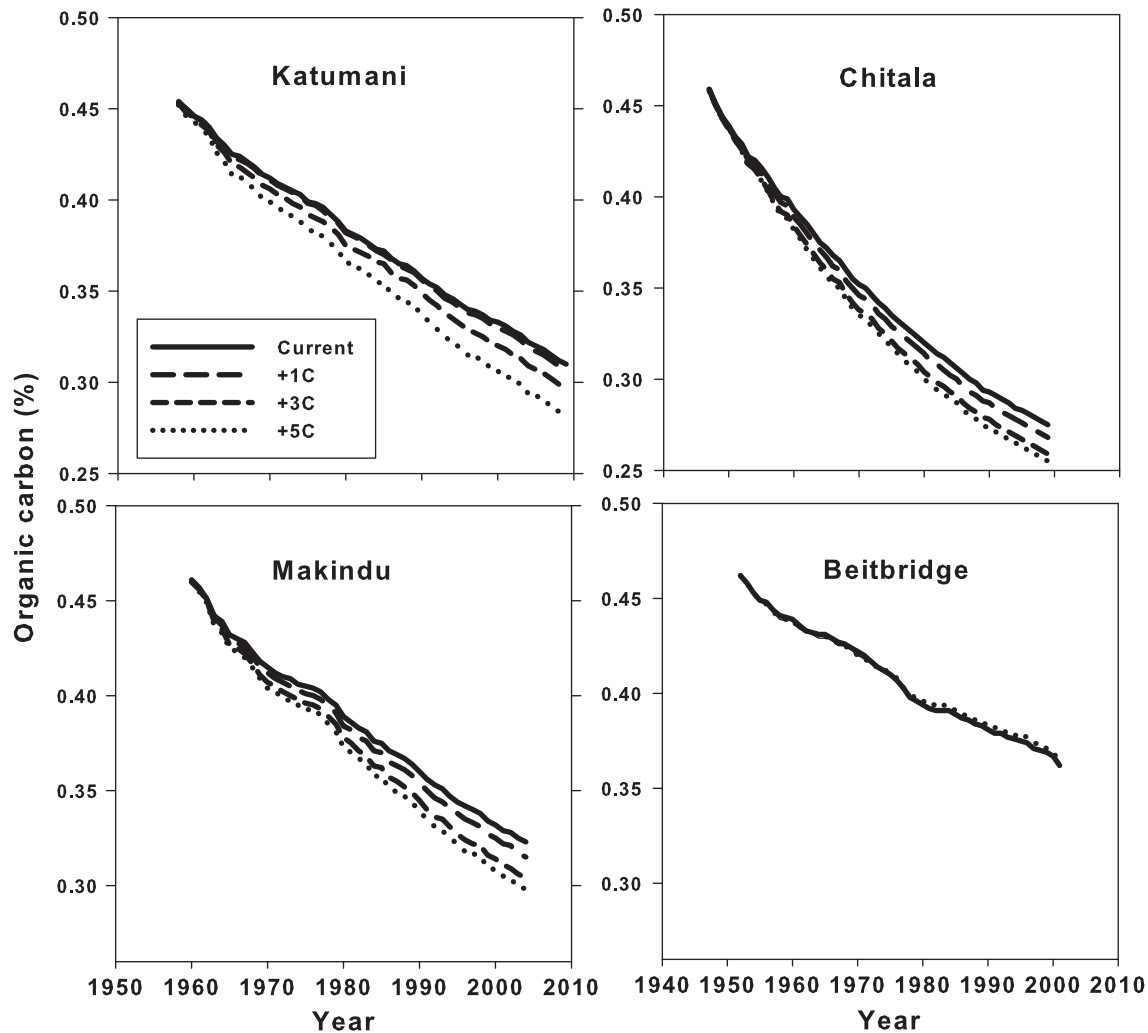
Fig. 4. Simulated change with time in soil organic carbon (%) in the upper 0.15 m of soil growing a short-duration sorghum crop at current (solid line), +1 °C (long dash line), +3 °C (short dash line) and +5 °C (dotted line) temperatures at four locations in Africa. At each location the starting level of soil organic carbon was set at 0.46% (Table 1).

soil organic carbon at different starting percentages. While the rate of decrease was slower with lower initial starting values, the results were similar to those in Fig. 4 in that the decrease was greater at the higher temperatures at all locations except at Beitbridge (data not shown). The breakdown of organic matter resulted in greater average annual nitrogen uptake by the sorghum with the rise in temperature at Katumani, Makindu and Chitala, but a decrease in uptake at Beitbridge in all three cultivars differing in time to flowering and maturity (Table 5). The warmer temperatures resulted in a decrease in the level of organic carbon in the soil (Fig. 4) that in the long term will reduce the mineralization of nitrogen and its uptake. The average figures in Table 5 hide a general decrease in nitrogen uptake with time from 40, 32, and 28 kg ha^{-1} year^{-1} in the first decade at Chitala, Makindu and Katumani to 14, 9 and 16 kg ha^{-1} year^{-1} in the fifth decade, respectively (data not shown). No consistent trend in nitrogen uptake in different decades was observed at Beitbridge. APSIM also enables the proportion of carbon in the different organic fractions to be simulated. We therefore did a sensitivity analysis of the effect of decreasing the proportion of organic carbon in the microbial biomass fraction. In the simulations, the initial proportion of organic carbon in the microbial biomass fraction was 0.040% and the inert fraction was 0.39% (Table 1); increasing the inert fraction at the expense of the biologically-active fraction slowed the breakdown of the organic matter and reduced the release of nitrogen (data not shown).

It also reduced the yield of sorghum, but the trends were similar and the boost to yield by the increase in temperature was also similar to that in Fig. 2 (data not shown).

Table 5
Mean simulated nitrogen uptake (kg ha^{-1} year^{-1}) by short-, medium-, and long-duration cultivars of sorghum at current temperatures and with 1 °C, 2 °C, 3 °C, 4 °C and 5 °C increases in temperature at four locations in Africa. Data are averages for ~50 years of simulation.

	Current	+1 °C	+2 °C	+3 °C	+4 °C	+5 °C
Short duration						
Chitala	23.55	24.24	24.87	25.39	25.80	26.13
Makindu	24.25	25.22	25.98	26.59	27.04	27.35
Katumani	20.88	21.33	21.93	22.72	23.56	24.36
Beitbridge	14.19	13.90	13.43	12.77	11.90	11.37
Medium duration						
Chitala	23.08	23.75	24.34	24.86	25.27	25.64
Makindu	23.41	24.15	24.98	25.70	26.34	26.50
Katumani	20.96	21.12	21.54	22.23	22.86	23.62
Beitbridge	12.20	12.03	11.77	11.50	10.81	10.01
Long duration						
Chitala	22.78	23.40	23.97	24.46	24.93	25.30
Makindu	22.53	23.14	23.82	24.33	24.85	25.14
Katumani	20.96	21.32	21.31	21.65	22.21	22.68
Beitbridge	11.00	10.93	10.78	10.38	10.06	9.70

3.6. Predicted effects of plant population, fertilization and increasing temperatures on yield

An alternative management tool to maintain yields with climate change is to alter the population density. An increase in the population density may reduce the loss of water by soil evaporation and increase water use efficiency during the season. On the other hand, if yields are reduced as a result of water shortage, particularly during seed filling, decreasing the planting density should benefit yield. At Chitala, Katumani and Makindu, with no additional nitrogen, increasing the plant population from the standard plant population of 66,000–80,000 plants ha^{-1} decreased yields or had no effect on yields at current temperatures and when temperatures were increased by 3 °C, but at Beitbridge yields were increased (Table 6). Decreasing the plant population with current farm practice increased yields at Makindu and Beitbridge, but this increase diminished as temperatures increased. When 20 kg ha^{-1} of nitrogen was applied, increasing the plant population from 66,000 to 80,000 plants ha^{-1} resulted in a decrease in yield at Chitala and Makindu, no change in yield at Katumani and an increase in yield at Beitbridge, while decreasing the population from 66,000 to 50,000 plants ha^{-1} decreased the yield at Chitala and Makindu at current temperatures and with a 3 °C rise in temperature, but increased yields at Beitbridge (Table 6).

4. Discussion

There is widespread agreement that in the tropics, sub-tropics and Mediterranean climatic zones, yields will decrease with the warming associated with climate change, which contrasts with the increased yields with global warming at higher latitudes (Cooper et al., 2009; Yadav et al., 2011; Turner and Meyer, 2011). At high nitrogen application levels similar to those used in commercial practice, the present simulation study showed that the mean yields of sorghum decreased with global warming at the two warmer sites, Chitala and Beitbridge, but did not change or increased at the two cooler sites in Kenya. However, the unexpected result from

the study was that using cultivars of similar maturity and a fertilizer level similar to the unfertilized levels of small-holder farmers in sub-Saharan Africa, the effect of global warming was to increase the mean yields at all locations (Table 3) and in all except the low-yielding (driest) years (Figs. 1 and 2). Our analysis suggests that this increase in yield results from an increase in the mineralization of soil organic matter at higher temperatures, and from the increase in water use by transpiration and a decrease in the proportion of water lost by soil evaporation. The higher temperatures increased the rate of mineralization of organic matter, as shown by the increased rate of the decline in soil organic carbon (Fig. 4), and increased the uptake by the sorghum crop of nitrogen from the soil (Table 5). However, this yield boost from the warmer temperatures is likely to be limited as the increased loss of soil organic carbon will reduce the amount of nitrogen mineralization and reduce the nitrogen available to the crop. This was clear as the analysis showed less soil nitrogen uptake in the fifth decade compared with the first decade after an increase in temperature.

What our analysis also demonstrates is that the application of a micro-dose of nitrogen (20 kg ha^{-1}) markedly increased the mean yields of the short-duration sorghum by 40% to 70% at the wetter sites and by 15% at the very dry site when the temperatures increased by 3 °C (Fig. 2). The additional nitrogen reduced the proportion of water loss by soil evaporation and increased water use by the crop in transpiration and substantially increased the harvest index of the crop. Thus, while yields may decrease with global warming when the sorghum is fertilized, the increased yields from the use of fertilizer more than makes up for the changes in yield associated with global warming in the unfertilized sorghum.

We used the simulation to explore other ways of maintaining yields with global warming. Using longer-season cultivars reduced yields at all four locations, unless high levels of nitrogen were applied when longer-duration cultivars increased yields at Chitala (Table 3). We conclude that for small-holder farmers the current short-season cultivars will still be required with global warming, even though this may limit yields in very good rainfall seasons (Fig. 3). With current small-holder management practices, decreasing the plant population from the current 66,000 plants ha^{-1} to

Table 6
Simulated average yields (kg ha^{-1}) of a short-duration cultivar of sorghum at three plant populations (50,000, 66,000 and 80,000 plants ha^{-1}) at current temperatures, with 1, 3 and 5 °C increases in temperature and 0, 20 and 80 kg ha^{-1} of nitrogen fertilizer at four sites in Africa. Data are averages for ~50 years of simulation.

Temperature regime (°C)	50,000 plants ha^{-1}			66,000 plant ha^{-1}			80,000 plant ha^{-1}		
	0 kg N	20 kg N	80 kg N	0 kg N	20 kg N	80 kg N	0 kg N	20 kg N	80 kg N
Chitala									
Current	1577	2582	3733	1660	3022	4803	1557	2763	4714
+1	1571	2532	3669	1680	2893	4769	1384	2717	4647
+3	1578	2503	3488	1716	2907	4683	1576	2692	4558
+5	1598	2473	3243	1759	2913	4425	1666	2686	4306
Makindu									
Current	1833	2063	2143	1736	2565	3051	1673	2516	3178
+1	1849	2124	2200	1792	2579	3175	1714	2541	3308
+3	1871	2188	2300	1843	2579	3268	1747	2533	3351
+5	1859	2101	2190	1856	2524	3086	1767	2478	3167
Katumani									
Current	1343	2385	2577	1195	2368	2627	1222	2406	2841
+1	1499	2443	2628	1378	2446	2587	1384	2434	2828
+3	1646	2472	2656	1588	2554	2757	1576	2526	3001
+5	1686	2462	2816	1710	2507	2956	1666	2514	3113
Beitbridge									
Current	826	921	1027	795	899	980	821	967	1039
+1	796	879	955	767	838	924	798	897	1001
+3	672	784	809	641	740	796	672	808	836
+5	515	606	620	510	549	580	538	609	623

50,000 plants ha^{-1} will increase yields on average at all except the wettest site (Chitala), while increasing the plant population to 80,000 plants ha^{-1} had little effect on average yields at current temperatures (Table 6). With addition of a small amount of fertilizer (20 kg N ha^{-1}), decreasing the plant population decreased yields even more at the wettest site, but increased yields at Beitbridge, the driest site (Table 6). With global warming, decreasing the plant population or increasing the plant population did not change the response, whether positive or negative, at all levels of fertilization (Table 6). We conclude that with the short-duration cultivar, the plant population of 66,000 plants ha^{-1} suits the present conditions at all sites except Beitbridge and changing the plant population with global warming will not have great benefits to the increases in yield at current levels of fertilizer use or in overcoming the decreases in yield at higher levels of fertilization.

Cooper et al. (2009) reported on a simulation study of sorghum in India in which the yields, estimated with the Decision Support System for Agro-technology Transfer (DSSAT) model which is similar to the APSIM model used in this study, decreased with increasing temperature. Indeed, similar decreases in yield were observed in short-duration pigeon pea [*Cajanus cajan* (L.) Millsp.], maize, pearl millet [*Pennisetum glaucum* (L.) R. Br.] and peanut (Cooper et al., 2009). The simulations in Cooper et al. (2009) were all run with nutrients non-limiting (equivalent to at least 40 kg N ha^{-1} in our study), confirming the observed lower yields with global warming simulated by the present study. However, our simulation clearly predicts an increase in mean yields with rising temperatures at low levels of nitrogen fertilizer, so that small-holder farmers are unlikely to be more vulnerable to climate change in the short term. However, if they are to overcome malnutrition, yields will need to increase and this study shows that small doses of nitrogen can markedly increase yields, but with a slightly increased risk of crop failure. Moreover, with increased levels of applied nitrogen, rising temperatures will reduce yields particularly in drier years, but mean yields with additional nitrogen will still be substantially higher than with traditional fertilizer levels.

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