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

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**A B S T R A C T**

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.

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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 (\textit{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 [\textit{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 (\textit{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...
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.

Crop simulation

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 nitrogen 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, r² = 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
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.

yield

influence of reducing the plant population to 50,000 plants ha

grown-season rainfall at the four locations in Africa where APSIM-Sorghum was

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              | Allisol 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 (%) | Org C (%) | Org C (%) | 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 |

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-

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)   |
| Chlorite                |                     |                     |                     |                     |
| Short duration          |                     |                     |                     |                     |
| Current                | 61.5 108 1660 4155 59.3 107 3022 6549 59.3 107 3799 7554 59.8 107 4803 8938 | +1 56.4 105 1080 4117 56.3 103 2893 6372 56.8 103 3700 7200 57.3 104 4769 8691 | +3 55.3 100 1716 4071 54.2 99 2967 6141 54.4 99 3642 7067 54.8 100 4683 8450 | +5 55.3 100 1759 4131 54.5 99 2913 6241 54.8 100 3662 7205 55.1 100 4425 8476 |
| Medium duration         |                     |                     |                     |                     |
| Current                | 71.6 119 1503 4444 67.6 115 2858 7158 66.9 114 4105 9196 67.1 114 5301 10,612 | +1 67.4 113 1573 4466 64.3 110 2900 7062 63.8 110 4107 8905 64.0 110 5225 10,259 | +3 65.5 109 1651 4466 61.2 110 2915 6823 61.0 110 3957 8549 61.2 106 5118 9871 | +5 63.5 106 1729 4554 61.3 110 2933 6919 61.0 110 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 3222 9646 71.5 118 5412 11,706 | +3 73.0 118 1348 4778 69.3 114 2677 7189 67.6 113 3894 9327 68.4 113 5316 11,850 | +5 72.5 117 1639 4876 69.2 114 2725 7179 67.7 112 3767 9097 69.0 114 4773 10,438 |
| Malindi                |                     |                     |                     |                     |
| 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 1841 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 2931 5508 44.4 94 3896 5783 |
| Medium duration         |                     |                     |                     |                     |
| Current                | 70.1 115 1537 4409 65.4 115 2248 6281 57.6 115 2574 6919 54.9 117 2845 7372 | +1 64.0 109 1644 4356 61.4 110 2317 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 3099 6742 | +5 52.3 99 1778 4133 51.6 98 2340 5478 47.4 98 2682 5968 47.0 100 2943 6322 |
| Long duration           |                     |                     |                     |                     |
| Current                | 82.8 127 1319 4614 63.1 123 1823 6334 66.8 123 2260 7398 64.5 128 2561 7883 | +1 75.9 120 1419 4552 62.2 119 1913 6205 61.1 119 2344 7122 54.5 119 2904 7582 | +3 59.2 109 1553 4420 59.7 109 2034 5880 52.9 111 2441 6655 52.6 112 2720 7105 | +5 56.6 105 1565 4286 52.5 104 2088 5585 50.0 106 2395 6214 51.8 107 2592 6595 |
| Katumani               |                     |                     |                     |                     |
| Short duration          |                     |                     |                     |                     |
| Current                | 92.5 145 1195 4066 89.5 143 2368 6700 79.4 142 2584 7369 79.3 143 2627 7719 | +1 80.1 130 1378 4211 76.7 131 2446 6564 68.6 130 2568 7008 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 55.1 98 1710 4011 52.7 99 2567 5634 51.0 100 2787 5999 48.5 100 2956 6248 |
| Duration         | Mean | SD  |
|------------------|------|-----|
| Medium duration  | 106.8| 159 |
| +1               | 94.5 | 144 |
| +2               | 74.9 | 121 |
| +3               | 61.9 | 107 |
| +4               | 59.0 | 83.3|

| Long duration    | 121.5| 175 |
| +1               | 108.4| 160 |
| +2               | 89.5 | 135 |
| +3               | 74.8 | 120 |

| Beitbridge       | 66.4 | 117 |
| +1               | 66.0 | 118 |
| +2               | 57.7 | 121 |
| +3               | 55.4 | 126 |

| Medium duration  | 58.8 | 134 |
| +1               | 58.9 | 133 |
| +2               | 54.0 | 133 |
| +3               | 50.5 | 141 |

| Long duration    | 65.4 | 150 |
| +1               | 65.7 | 150 |
| +2               | 59.9 | 153 |
| +3               | 46.6 | 152 |

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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 1000 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 of 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).

### 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).
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 4). 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:

| Temperature regime (°C) | Short duration | Medium duration | Long duration |
|-------------------------|----------------|-----------------|---------------|
|                         | 0 kg N ha⁻¹    | 40 kg N ha⁻¹    |               |
|                         | T (mm) E (mm)  | T (mm) E (mm)   | T (mm) E (mm) |
| Chitaula                |                |                 |               |
| 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                 | 52 227 104 229 | 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 |
| Beitbridge              |                |                 |               |
| 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                      | 47 141 55 140  | 49 146 58 146   | 51 154 59 151  |
| +5                      | 48 147 54 142  | 51 153 57 151   | 52 156 58 154  |
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.

| Location | Short duration | Medium duration | Long duration |
|----------|----------------|-----------------|---------------|
| Current  | +1 °C | +2 °C | +3 °C | +4 °C | +5 °C |
| 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 |
| 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 |
| 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 |

**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).
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 fertiliser 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 plants ha\(^{-1}\) | 80,000 plants 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    | 1853    | 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     | 887      | 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 Agrotechnology 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 the APSIM model used in this study, decreasing with increased levels of applied fertilizer. Whether such decreases are symptomatic of climate change or more likely to be a result of 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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