Application of the GYGA approach to Kenya

GYGA coordination team and Dr. O. Adimo

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1. Description of cropping systems, climate, and soils in Kenya

*(by Dr. O. Adimo)*

Agriculture remains the mainstay of the Kenyan’s economy, providing 26% of the GDP, whereas 80% of the rural population derives their livelihood from agriculture and other related activities. It is also the nations’ top earner of foreign exchange, contributing some 60% of export earnings. Farmers in Kenya are involved in both small and large-scale farming of crops and/or livestock.

Kenya’s total area is about 587,000 km², of which 576,076 km² consists of land and 11,230 km² is covered by water. Of the total land area, 16% has a high to medium agricultural potential. The rest is arid and semi-arid land (ASAL) and, therefore, of low agricultural potential. Kenya has six agro-ecological zones as given in Table 1.

Table 1. Agro-ecological zones of Kenya

<table>
<thead>
<tr>
<th>Zone</th>
<th>Appr. Area (km²)</th>
<th>% Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>I. Agro-Alpine</td>
<td>800</td>
<td>0.1</td>
</tr>
<tr>
<td>II. High Potential</td>
<td>53,000</td>
<td>9.3</td>
</tr>
<tr>
<td>III. Medium Potential</td>
<td>53,000</td>
<td>9.3</td>
</tr>
<tr>
<td>IV. Semi-Arid</td>
<td>48,200</td>
<td>8.5</td>
</tr>
<tr>
<td>V. Arid</td>
<td>300,000</td>
<td>52.9</td>
</tr>
<tr>
<td>VI. Very Arid</td>
<td>112,000</td>
<td>19.8</td>
</tr>
<tr>
<td>Rest (waters etc)</td>
<td>15,600</td>
<td>2.6</td>
</tr>
</tbody>
</table>


Out of the ASAL’s 48 million ha, 24 million ha is only useful for nomadic pastoralism; the rest can support some commercial ranching and irrigated agriculture but with added technological input. Over 7 million people live in and derive their livelihoods from ASAL areas; the rest of the population lives in the 16% high to medium agricultural potential land areas. In a country where 80% of the population depends on agriculture, the high and medium potential areas have been split up into to small-scale farms of up to 0.5 – 10 ha. For example, 81% of the small-scale farmers occupy holdings of less than 2 ha. Considering that the population growth rate is 3.2%, the pressure on the land is continuously reducing the capacity to sustain food production and cash crop-farming. Despite these problems, Kenya is a leading producer of tea and coffee, as well as the third-leading exporter of fresh produce, such as flowers, vegetables and fruits. Small farms mostly grow maize and besides, produce potatoes, bananas, beans and peas. Table 2 gives the areas, production and yields for the major food crops in Kenya.
Table 2. Average (2010-2011) production, harvested area and yield of major food crops in Kenya

<table>
<thead>
<tr>
<th>Crop</th>
<th>Harvested Area (ha)</th>
<th>Total Production(t)</th>
<th>Yield (t ha⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maize</td>
<td>2159322.0</td>
<td>4089043.2</td>
<td>1.9</td>
</tr>
<tr>
<td>wheat</td>
<td>148,703.0</td>
<td>444373.6</td>
<td>3.0</td>
</tr>
<tr>
<td>Barley</td>
<td>21,827.0</td>
<td>72930.6</td>
<td>3.3</td>
</tr>
<tr>
<td>Beans</td>
<td>1,055,632.0</td>
<td>613902.0</td>
<td>0.6</td>
</tr>
<tr>
<td>Rice</td>
<td>25,197.0</td>
<td>92696.0</td>
<td>3.7</td>
</tr>
<tr>
<td>Sorghum</td>
<td>223,799.0</td>
<td>166626.9</td>
<td>0.7</td>
</tr>
<tr>
<td>Millet</td>
<td>118,289.0</td>
<td>74915.8</td>
<td>0.6</td>
</tr>
<tr>
<td>Cowpeas</td>
<td>214,492.0</td>
<td>113802.8</td>
<td>0.5</td>
</tr>
<tr>
<td>Green grams</td>
<td>188,416.0</td>
<td>91824.3</td>
<td>0.5</td>
</tr>
<tr>
<td>Pigeon peas</td>
<td>143,212.0</td>
<td>89390.1</td>
<td>0.6</td>
</tr>
<tr>
<td>Irish potatoes</td>
<td>135924.4</td>
<td>1846576.0</td>
<td>13.6</td>
</tr>
<tr>
<td>Tomatoes</td>
<td>18115.9</td>
<td>395297.8</td>
<td>21.8</td>
</tr>
<tr>
<td>Cabbages</td>
<td>19491.0</td>
<td>891771.0</td>
<td>45.8</td>
</tr>
</tbody>
</table>

Source: Agriculture Economic review 2012

Kenya has a very wide range of soil types, which is caused by its large variation in geology (parent material), relief and climate. Soil types vary from sandy to clayey, shallow to very deep, and from low to high fertility. However, many soil types have serious limitations such as salinity, sodicity, acidity, fertility and drainage problems. The major soil types used in agriculture are ferralsols, vertisols, acrisols, lixisols, luvisols and nitisols.

Food crops and other annual crops are grown according to the rainfall pattern, which is bimodal in nature. The long rains occur from March up to and including May and the short rains from October up to and including December. Following these rainfall patterns, annual single-crop systems and double-crop systems do occur.

2. Data sources and their use

Data that are used for the yield gap analyses for Kenya, are given in the following. More information about the applied GYGA approaches can be found at:
http://www.yieldgap.org/web/guest/methods-overview

2.1. Harvested area and actual yields

District-level data on annual actual yields were retrieved from the Kenya National Bureau of Statistics. We used all available actual yield data between 2000 and 2011 to calculate average actual yields per buffer zone (see the file with actual yields for more details). This has been done as follows: (a) determine the district(s) that best overlap with the reference weather station buffer; (b) calculate the average yield per buffer zone (via weighted averaging) based on the actual yields reported for the districts reported. Harvested areas were retrieved from the HarvestChoice SPAM crop distribution maps (You et al., 2006, 2009).
2.2. Soil data

Soil data have been derived from the “AfSIS-GYGA functional soil information of Sub-Saharan Africa” database (RZ-PAWHC SSA v. 1.0, Leenars et al. 2015, see link). We have used effective root zone depth (ERZD, in cm), available water holding capacity of fine hearth (between field capacity – pF=2.3 – and permanent wilting point, in %v/v) and gravel content to created 28 soil classes which consist of 7 classes of available water holding capacity aggregated over ERZD (i.e., 4, 5, 6, 7, 8, 9 and 10 %v/v, adjusted by gravel content) and 4 rootable soil depth classes (i.e., 40, 75, 115 and 150 cm). These soil classes are described in Table 3, along with the soil texture that corresponds to the same plant available water holding capacity in the root zone in Hybrid Maize (as based on tropical pedo-transfer functions).

We selected soil classes until achieving 50% area coverage of crop harvested area within reference weather station (RWS) buffer zones, with at least 3 dominant soil classes and at most 5 dominant soil classes. Then, water-limited yield potential was simulated for all selected soil classes and we discarded soil classes in which simulated water-limited yield potential is extremely low and highly variable, hence, unlikely to be used for long-term annual crop production. The mean water limited yield potential per buffer zone was then calculated by weighing (based on the area fractions per soil class) the simulated water limited yields for each of the selected soil classes.

Crop growth simulation have been done assuming the following soil and landscape characteristics: (a) no surface storage of water, (b) sufficient permeability of the soil to prevent soil saturation, (c) no ground water influence, (d) loss fraction of precipitation by surface runoff based on literature research as compiled in Appendix A (values based on the assumptions of optimal management and application of mulching) and depending on drainage class and slope angle; the drainage class per soil unit is derived from ISRIC-WISE (Batjes, 2012) data base and the slope angle is the mean angle per buffer zone (from HWSD slope map, see link) after clipping the zone by the crop harvested area mask, and (e) rooting depth is only limited by the soil in case that is indicated by ISRIC-WISE and/or the country agronomist.

Table 3. Description of the 28 soil classes.

<table>
<thead>
<tr>
<th>Soil class</th>
<th>Available water capacity of fine earth (v%) aggregated over ERZD, with FC = pF 2.3 with correction for gravel content</th>
<th>Effective root zone depth (cm)</th>
<th>Corresponding texture class in Hybrid Maize (as based on tropical PTF results)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>≤4</td>
<td>40</td>
<td>Loamy sand</td>
</tr>
<tr>
<td>2</td>
<td>5</td>
<td>40</td>
<td>Sandy clay loam</td>
</tr>
<tr>
<td>3</td>
<td>6</td>
<td>40</td>
<td>Clay loam</td>
</tr>
<tr>
<td>4</td>
<td>7</td>
<td>40</td>
<td>Sandy loam</td>
</tr>
<tr>
<td>5</td>
<td>8</td>
<td>40</td>
<td>Silt loam</td>
</tr>
<tr>
<td>6</td>
<td>9</td>
<td>40</td>
<td>Silt clay loam</td>
</tr>
<tr>
<td>7</td>
<td>≥10</td>
<td>40</td>
<td>Loam</td>
</tr>
<tr>
<td>8</td>
<td>≤4</td>
<td>75</td>
<td>Loamy sand</td>
</tr>
</tbody>
</table>
2.3. Weather data and reference weather stations

Historical daily weather data sets have been collected from the Kenya Meteorological Department. Weather sets are available for 31 locations in Kenya and contain ten or more years of data. Weather data are derived mainly from weather propagation (based on historical measured weather data) and from NASA-POWER (http://power.larc.nasa.gov/). For more information about the weather data per location, see the file weather_station_metadata.xls.

Based on crop harvested area distribution and the climate zones defined for Kenya (Van Wart et al., 2013) per crop several reference weather stations (RWS) were selected (Table 4).

Table 4. Selected weather stations and % coverage of total harvested area

<table>
<thead>
<tr>
<th>Crop</th>
<th>Selected RWS (#)</th>
<th>% coverage national harvested area (sum selected RWSs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rainfed maize</td>
<td>Dagoretti</td>
<td>26%</td>
</tr>
<tr>
<td></td>
<td>ELDORET</td>
<td></td>
</tr>
<tr>
<td></td>
<td>KAKAMEGA</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Kericho</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Kisii</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Kisumu</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Kitale</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Nakuru (8)</td>
<td></td>
</tr>
<tr>
<td>Rainfed millet</td>
<td>Dagoretti</td>
<td>21%</td>
</tr>
<tr>
<td></td>
<td>ELDORET</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Embu</td>
<td></td>
</tr>
<tr>
<td></td>
<td>KAKAMEGA</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Kericho</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Kisii</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Kisumu</td>
<td></td>
</tr>
</tbody>
</table>
2.4. Crop and management information

Management practices for each RWS buffer zone were retrieved by the local country agronomist. Requested information included: dominant crop rotations and their proportions of the total harvested area, planting windows, dominant cultivar name and maturity, and actual and optimal plant population density. The crop and management information is given in Table 5, 7 and 8.

Table 5. Crop and management information for maize, sorghum, wheat, rice and millet in different RWS buffer zones of Kenya as compiled by the country agronomist (Source: Dr. O. Adimo)

<table>
<thead>
<tr>
<th>Weather station</th>
<th>Cropping system</th>
<th>Water regime</th>
<th>Cropping cycle</th>
<th>Sowing window</th>
<th>% crop area under this system</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dagoretti</td>
<td>Single: maize</td>
<td>Rainfed</td>
<td>1</td>
<td>March 15– April 30</td>
<td>90%</td>
</tr>
<tr>
<td>Kakamega</td>
<td>Double: maize-maize</td>
<td>Rainfed</td>
<td>1</td>
<td>March 15– April 30</td>
<td>60%</td>
</tr>
<tr>
<td>Kakamega</td>
<td>Double: maize-maize</td>
<td>Rainfed</td>
<td>2</td>
<td>15 August - 15 September</td>
<td>60%</td>
</tr>
<tr>
<td>Kericho</td>
<td>Single: maize</td>
<td>Rainfed</td>
<td>1</td>
<td>1-30 April</td>
<td>70%</td>
</tr>
<tr>
<td>Kisii</td>
<td>Double: maize-maize</td>
<td>Rainfed</td>
<td>1</td>
<td>March 15– April 30</td>
<td>70%</td>
</tr>
<tr>
<td>Kisii</td>
<td>Double: maize-maize</td>
<td>Rainfed</td>
<td>2</td>
<td>March 15– April 30</td>
<td>70%</td>
</tr>
<tr>
<td>Kishu</td>
<td>Double: maize-maize</td>
<td>Rainfed</td>
<td>1</td>
<td>March 15– April 30</td>
<td>70%</td>
</tr>
<tr>
<td>Kishu</td>
<td>Double: maize-maize</td>
<td>Rainfed</td>
<td>2</td>
<td>15 August - 15 September</td>
<td>70%</td>
</tr>
<tr>
<td>Kitale</td>
<td>Single: maize</td>
<td>Rainfed</td>
<td>1</td>
<td>1-30 April</td>
<td>80%</td>
</tr>
<tr>
<td>Nakuru</td>
<td>Single: maize</td>
<td>Rainfed</td>
<td>1</td>
<td>March 15– April 30</td>
<td>70%</td>
</tr>
<tr>
<td>Eldoret</td>
<td>Single: maize</td>
<td>Rainfed</td>
<td>1</td>
<td>1-30 April</td>
<td>80%</td>
</tr>
<tr>
<td>Dagoretti</td>
<td>Single: millet</td>
<td>Rainfed</td>
<td>1</td>
<td>1-30 April</td>
<td>5%</td>
</tr>
<tr>
<td>Embu</td>
<td>Single: millet</td>
<td>Rainfed</td>
<td>1</td>
<td>1-28 February</td>
<td>20%</td>
</tr>
<tr>
<td>KAKAMEGA</td>
<td>Single: millet</td>
<td>Rainfed</td>
<td>1</td>
<td>1-30 April</td>
<td>20%</td>
</tr>
<tr>
<td>Kericho</td>
<td>Single: millet</td>
<td>Rainfed</td>
<td>1</td>
<td>1-30 April</td>
<td>20%</td>
</tr>
<tr>
<td>Kisii</td>
<td>Single: millet</td>
<td>Rainfed</td>
<td>1</td>
<td>1-30 April</td>
<td>10%</td>
</tr>
<tr>
<td>Kisumu</td>
<td>Single: millet</td>
<td>Rainfed</td>
<td>1</td>
<td>1-30 April</td>
<td>20%</td>
</tr>
</tbody>
</table>
The sowing days used for the simulations are determined as the first day within the sowing window when the cumulative rainfall exceeded 20 mm (counting starts at the first day of the sowing window).

3. Crop growth simulations and model calibration

3.1. Used crop growth models

The crop growth simulations for wheat, sorghum and millet in Kenya have been carried out with the crop growth simulation model WOFOST version 7.1.3 (release March 2011) (Supit et al., 1994, 2012; Wolf et al., 2011). For maize the crop growth model HybridMaize version 2013.4.1 has been applied (Yang et al., 2006); for rice ORYZA2000.

3.2. Data for model calibration

Based on experimental information reported in the literature, we have compiled data for the main crop characteristics for maize, sorghum, wheat and millet growing in Kenya (Table 6). These characteristics can be considered representative for optimal (i.e. no water and no nutrient limitation) growing conditions in the different zones of Kenya. These crop characteristics have been used for testing and possibly calibrating the model parameters.

Table 6. Crop characteristics for main crop types in Kenya to test and calibrate the WOFOST model parameters, being representative for a high-yield variety growing under optimal conditions with respect to water and nutrient supply and optimal management

<table>
<thead>
<tr>
<th>Crop/zones in Kenya</th>
<th>Period from emergence</th>
<th>Period fractions from LAI-max (m^2 m^-2)</th>
<th>Total biomass</th>
<th>Yield (kg dry matter)</th>
<th>Harvest index (yield /</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kitale</td>
<td>Single: millet</td>
<td>Rainfed</td>
<td>l</td>
<td>1-30 April</td>
<td>10%</td>
</tr>
<tr>
<td>Makindu</td>
<td>Single: millet</td>
<td>Rainfed</td>
<td>l</td>
<td>March 15– April 30</td>
<td>10%</td>
</tr>
<tr>
<td>Nakuru</td>
<td>Single: millet</td>
<td>Rainfed</td>
<td>l</td>
<td>March 15– April 30</td>
<td>20%</td>
</tr>
<tr>
<td>Eldoret</td>
<td>Single: millet</td>
<td>Rainfed</td>
<td>l</td>
<td>1-30 April</td>
<td>10%</td>
</tr>
<tr>
<td>Dagoretti</td>
<td>Single: sorghum</td>
<td>Rainfed</td>
<td>l</td>
<td>1-30 April</td>
<td>5%</td>
</tr>
<tr>
<td>Embu</td>
<td>Single: sorghum</td>
<td>Rainfed</td>
<td>l</td>
<td>15 March – 30 April</td>
<td>10%</td>
</tr>
<tr>
<td>Kakamega</td>
<td>Single: sorghum</td>
<td>Rainfed</td>
<td>l</td>
<td>1-30 April</td>
<td>20%</td>
</tr>
<tr>
<td>Kericho</td>
<td>Single: sorghum</td>
<td>Rainfed</td>
<td>l</td>
<td>1-30 April</td>
<td>10%</td>
</tr>
<tr>
<td>Kisii</td>
<td>Single: sorghum</td>
<td>Rainfed</td>
<td>l</td>
<td>1-30 April</td>
<td>20%</td>
</tr>
<tr>
<td>Kiseru</td>
<td>Single: sorghum</td>
<td>Rainfed</td>
<td>l</td>
<td>1-30 April</td>
<td>10%</td>
</tr>
<tr>
<td>Kitale</td>
<td>Single: sorghum</td>
<td>Rainfed</td>
<td>l</td>
<td>1-30 April</td>
<td>10%</td>
</tr>
<tr>
<td>Makindu</td>
<td>Single: sorghum</td>
<td>Rainfed</td>
<td>l</td>
<td>15 March – 30 April</td>
<td>30%</td>
</tr>
<tr>
<td>Meru</td>
<td>Single: sorghum</td>
<td>Rainfed</td>
<td>l</td>
<td>15 March – 30 April</td>
<td>10%</td>
</tr>
<tr>
<td>Nakuru</td>
<td>Single: sorghum</td>
<td>Rainfed</td>
<td>l</td>
<td>15 March – 30 April</td>
<td>10%</td>
</tr>
<tr>
<td>Eldoret</td>
<td>Single: sorghum</td>
<td>Rainfed</td>
<td>l</td>
<td>15 March – 30 April</td>
<td>10%</td>
</tr>
<tr>
<td>Kakamega</td>
<td>Single: wheat</td>
<td>Rainfed</td>
<td>l</td>
<td>15 August - 15 September</td>
<td>20%</td>
</tr>
<tr>
<td>Kericho</td>
<td>Single: wheat</td>
<td>Rainfed</td>
<td>l</td>
<td>15 August - 15 September</td>
<td>20%</td>
</tr>
<tr>
<td>Kitale</td>
<td>Single: wheat</td>
<td>Rainfed</td>
<td>l</td>
<td>15 August - 15 September</td>
<td>80%</td>
</tr>
<tr>
<td>Meru</td>
<td>Single: wheat</td>
<td>Rainfed</td>
<td>l</td>
<td>15 September-15 October</td>
<td>80%</td>
</tr>
<tr>
<td>Nakuru</td>
<td>Single: wheat</td>
<td>Rainfed</td>
<td>l</td>
<td>15 August - 15 September</td>
<td>90%</td>
</tr>
</tbody>
</table>
8

<table>
<thead>
<tr>
<th></th>
<th>to maturity (days)</th>
<th>emergence to flowering and from flowering to maturity (%)</th>
<th>above-ground (kg dry matter per ha)²</th>
<th>per ha)²</th>
<th>total biomass above ground</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grain maize, all zones</td>
<td>115 - 235</td>
<td>50% - 50%</td>
<td>4 to 7</td>
<td>10600 to 19000</td>
<td>5300 to 9500</td>
</tr>
<tr>
<td>Sorghum, all zones</td>
<td>85 - 235</td>
<td>55% - 45%</td>
<td>3 to 7</td>
<td>9600 to 15000</td>
<td>3800 to 6500</td>
</tr>
<tr>
<td>Millet, all zones</td>
<td>115 - 235</td>
<td>62% - 38%</td>
<td>3 to 7</td>
<td>9600 to 15000</td>
<td>2900 to 4500</td>
</tr>
<tr>
<td>Wheat, all zones</td>
<td>115 - 140</td>
<td>54% - 46%</td>
<td>4 to 7</td>
<td>10600 to 17000</td>
<td>4200 to 6800</td>
</tr>
</tbody>
</table>

¹ Crop characteristics are based on Crop data for Kenya (Table 5), expert knowledge and experimental information, as reported for Kenya by Beyene et al. (2011), Cheruiyot et al. (2001), Kimani et al. (2007), Mucheru et al. (2007), Mugwe et al. (2007, 2009), Onyango (2010), Smaling et al. (1991), Smaling and Janssen (1993), Hausmann et al. (2000), Achieng et al. (2010), and Maobe et al. (2010).

² Yields and total biomass productions are in general higher with longer growth periods and thus for cooler and often higher-altitude environmental zones.

3.3. WOFOST calibration and simulation

The temperature sums required for phenological development per crop type in WOFOST are calibrated on the basis of the observed crop calendars (see Tables 5 and 6) and the climate conditions per RWS buffer zone in Kenya.

We may assume that sorghum, wheat and millet are in general produced in Kenya without application of irrigation water. However, to simplify the calibration of the model parameters related to crop growth and phenological development, we have done the crop model calibration for optimal conditions (see crop characteristics in Table 6). This means that water supply and nutrient supply are optimal to attain high yield levels and that crop protection and other management activities are all optimally performed.

3.3.1. WOFOST crop parameter sets for growth simulations

We used for the simulations with WOFOST the standard crop parameter sets as compiled by Van Heemst (1988). These parameter sets were later slightly adapted for African conditions. The new crop parameter sets are given in the files SORG-med-Eth-GYGA.CAB, MILL-med-Eth-GYGA.CAB for respectively, sorghum and millet. For wheat the standard crop parameter set for Europe (Boons-Prins et al., 1993) has been adapted for simulating wheat production in Kenya. Its new parameter set for a medium growth variety is given in the file WHE-med-Eth-GYGA.CAB (Appendix B). In the indicated files the following parameters are adapted for the GYGA-simulations: (a) temperature sums (TSUM1 and TSUM2) required for the modelled phenological development from crop emergence until flowering and from flowering to maturity, as calibrated for the climate conditions and the crop data per RWS buffer zone in Table 5; the derived and applied TSUM1 and TSUM2 values for the different zones are given in Table 7; (b) maximal rooting depth, which is set at 100 cm for millet and sorghum; (c) life span of leaves growing at 35°C (SPAN) for sorghum and wheat has been increased to resp. 42 and 40, whereas SPAN for millet has kept the same and similar value (=42); (d) correction
factor for evapo-transpiration (CFET) has been increased from 1.0 to 1.1 for both sorghum and millet but remained the same for wheat (=1.0); (e) for millet the maximum leaf CO$_2$ assimilation rate, which is dependent on development stage, has been decreased from 85 kg ha$^{-1}$ hr$^{-1}$ to 50 kg ha$^{-1}$ hr$^{-1}$ for the first development stages, and for sorghum form 70 kg ha$^{-1}$ hr$^{-1}$ to 50 kg ha$^{-1}$ hr$^{-1}$ for the first development stages; (f) for wheat the pattern of assimilate allocation to the crop organs over time has been changed (see Appendix B);

Table 7. Temperature sums (TSUM1 and TSUM2) required for the modelled crop phenological development from crop emergence until flowering and from flowering to maturity as calibrated for the climate conditions and the crop data in Table 5 for maize, sorghum, millet and wheat in the different RWS buffer zones of Kenya.

<table>
<thead>
<tr>
<th>Weather station</th>
<th>Cropping system</th>
<th>Cropping cycle</th>
<th>Water regime</th>
<th>Growth duration</th>
<th>TSUM1 (°Cd)</th>
<th>TSUM2 (°Cd)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dagoretti</td>
<td>Single: maize</td>
<td>1</td>
<td>Rainfed</td>
<td>130</td>
<td>520</td>
<td>350</td>
</tr>
<tr>
<td>Kakamega</td>
<td>Double: maize-maize</td>
<td>1</td>
<td>Rainfed</td>
<td>130</td>
<td>650</td>
<td>500</td>
</tr>
<tr>
<td>Kakamega</td>
<td>Double: maize-maize</td>
<td>2</td>
<td>Rainfed</td>
<td>130</td>
<td>700</td>
<td>600</td>
</tr>
<tr>
<td>Kericho</td>
<td>Single: maize</td>
<td>1</td>
<td>Rainfed</td>
<td>210</td>
<td>730</td>
<td>730</td>
</tr>
<tr>
<td>Kisi</td>
<td>Double: maize-maize</td>
<td>1</td>
<td>Rainfed</td>
<td>180</td>
<td>920</td>
<td>870</td>
</tr>
<tr>
<td>Kisi</td>
<td>Double: maize-maize</td>
<td>2</td>
<td>Rainfed</td>
<td>180</td>
<td>820</td>
<td>870</td>
</tr>
<tr>
<td>Kisu Mun</td>
<td>Double: maize-maize</td>
<td>1</td>
<td>Rainfed</td>
<td>130</td>
<td>850</td>
<td>800</td>
</tr>
<tr>
<td>Kisu Mun</td>
<td>Double: maize-maize</td>
<td>2</td>
<td>Rainfed</td>
<td>130</td>
<td>800</td>
<td>800</td>
</tr>
<tr>
<td>Kitale</td>
<td>Single: maize</td>
<td>1</td>
<td>Rainfed</td>
<td>210</td>
<td>920</td>
<td>920</td>
</tr>
<tr>
<td>Nakuru</td>
<td>Single: maize</td>
<td>1</td>
<td>Rainfed</td>
<td>210</td>
<td>800</td>
<td>860</td>
</tr>
<tr>
<td>Eldoret</td>
<td>Single: maize</td>
<td>1</td>
<td>Rainfed</td>
<td>210</td>
<td>680</td>
<td>680</td>
</tr>
<tr>
<td>Dagoretti</td>
<td>Single: millet</td>
<td>1</td>
<td>Rainfed</td>
<td>130</td>
<td>520</td>
<td>360</td>
</tr>
<tr>
<td>Embu</td>
<td>Single: millet</td>
<td>1</td>
<td>Rainfed</td>
<td>180</td>
<td>850</td>
<td>630</td>
</tr>
<tr>
<td>KAKAMEGA A</td>
<td>Single: millet</td>
<td>1</td>
<td>Rainfed</td>
<td>130</td>
<td>690</td>
<td>530</td>
</tr>
<tr>
<td>Kericho</td>
<td>Single: millet</td>
<td>1</td>
<td>Rainfed</td>
<td>210</td>
<td>730</td>
<td>730</td>
</tr>
<tr>
<td>Kisi</td>
<td>Single: millet</td>
<td>1</td>
<td>Rainfed</td>
<td>180</td>
<td>950</td>
<td>730</td>
</tr>
<tr>
<td>Kisu Mun</td>
<td>Single: millet</td>
<td>1</td>
<td>Rainfed</td>
<td>130</td>
<td>900</td>
<td>700</td>
</tr>
<tr>
<td>Kitale</td>
<td>Single: millet</td>
<td>1</td>
<td>Rainfed</td>
<td>195</td>
<td>900</td>
<td>700</td>
</tr>
<tr>
<td>Makindu</td>
<td>Single: millet</td>
<td>1</td>
<td>Rainfed</td>
<td>120</td>
<td>850</td>
<td>630</td>
</tr>
<tr>
<td>Nakuru</td>
<td>Single: millet</td>
<td>1</td>
<td>Rainfed</td>
<td>195</td>
<td>800</td>
<td>700</td>
</tr>
<tr>
<td>ELDORET</td>
<td>Single: millet</td>
<td>1</td>
<td>Rainfed</td>
<td>195</td>
<td>650</td>
<td>600</td>
</tr>
<tr>
<td>Dagoretti</td>
<td>Single: sorghum</td>
<td>1</td>
<td>Rainfed</td>
<td>100</td>
<td>440</td>
<td>310</td>
</tr>
<tr>
<td>Embu</td>
<td>Single: sorghum</td>
<td>1</td>
<td>Rainfed</td>
<td>180</td>
<td>800</td>
<td>670</td>
</tr>
<tr>
<td>KAKAMEGA A</td>
<td>Single: sorghum</td>
<td>1</td>
<td>Rainfed</td>
<td>95</td>
<td>530</td>
<td>400</td>
</tr>
<tr>
<td>Kericho</td>
<td>Single: sorghum</td>
<td>1</td>
<td>Rainfed</td>
<td>210</td>
<td>700</td>
<td>780</td>
</tr>
<tr>
<td>Kisi</td>
<td>Single: sorghum</td>
<td>1</td>
<td>Rainfed</td>
<td>100</td>
<td>560</td>
<td>420</td>
</tr>
<tr>
<td>Kisu Mun</td>
<td>Single: sorghum</td>
<td>1</td>
<td>Rainfed</td>
<td>95</td>
<td>700</td>
<td>510</td>
</tr>
<tr>
<td>Kitale</td>
<td>Single: sorghum</td>
<td>1</td>
<td>Rainfed</td>
<td>210</td>
<td>850</td>
<td>1000</td>
</tr>
<tr>
<td>Makindu</td>
<td>Single: sorghum</td>
<td>1</td>
<td>Rainfed</td>
<td>95</td>
<td>690</td>
<td>520</td>
</tr>
<tr>
<td>Meru</td>
<td>Single: sorghum</td>
<td>1</td>
<td>Rainfed</td>
<td>210</td>
<td>750</td>
<td>780</td>
</tr>
<tr>
<td>Nakuru</td>
<td>Single: sorghum</td>
<td>1</td>
<td>Rainfed</td>
<td>210</td>
<td>700</td>
<td>1000</td>
</tr>
<tr>
<td>ELDORET</td>
<td>Single: sorghum</td>
<td>1</td>
<td>Rainfed</td>
<td>210</td>
<td>670</td>
<td>700</td>
</tr>
<tr>
<td>Location</td>
<td>Crop Type</td>
<td>Sowing Type</td>
<td>Growth Duration</td>
<td>Rainfall at Sowing</td>
<td>Rainfall at Maturity</td>
<td></td>
</tr>
<tr>
<td>----------</td>
<td>-----------</td>
<td>-------------</td>
<td>-----------------</td>
<td>-------------------</td>
<td>---------------------</td>
<td></td>
</tr>
<tr>
<td>Kakamega</td>
<td>Single: wheat</td>
<td>1</td>
<td>Rainfed</td>
<td>133</td>
<td>1150</td>
<td></td>
</tr>
<tr>
<td>Kericho</td>
<td>Single: wheat</td>
<td>1</td>
<td>Rainfed</td>
<td>133</td>
<td>1150</td>
<td></td>
</tr>
<tr>
<td>Kitale</td>
<td>Single: wheat</td>
<td>1</td>
<td>Rainfed</td>
<td>133</td>
<td>1150</td>
<td></td>
</tr>
<tr>
<td>Meru</td>
<td>Single: wheat</td>
<td>1</td>
<td>Rainfed</td>
<td>133</td>
<td>1150</td>
<td></td>
</tr>
<tr>
<td>Nakuru</td>
<td>Single: wheat</td>
<td>1</td>
<td>Rainfed</td>
<td>133</td>
<td>1150</td>
<td></td>
</tr>
</tbody>
</table>

*Growth duration is assumed to be the period from sowing to maturity, of which the period from sowing to crop emergence is estimated at about 10 days. The actual sowing date is determined as the first day within the sowing window (for calibration of the sowing window is Table 5 used) when the cumulative rainfall exceeded 20 mm (counting starts at the first day of the sowing window)*

### 3.3.2. Initialization of available soil moisture for simulation with WOFOST

For single cropping systems (i.e. one crop grown per year) and for the first crop in double cropping systems the simulation of the soil water balance has been started 90 days before the sowing date and thus generally in the dry season (before unimodal or bimodal rainfall period). At this start of the simulation the total amount of available soil moisture is set at 3.3 cm (i.e. soil moisture content being one third of the water holding capacity between field capacity and wilting point, thus: $0.33 \times (SMFC - SMWP)$).

### 3.4. HybridMaize calibration and simulation

#### 3.4.1. HybridMaize crop parameter sets for growth simulations

In HybridMaize, a single genotype specific parameter is required for simulations (Yang et al., 2006). Phenological development stages in HybridMaize progress according to the accumulation of growing degree days (GDD), calculated as daily mean temperature minus a base temperature (10 °C for maize). Total GDD (from sowing to maturity) was calculated for each site based on the site-specific crop growth duration and the actual temperature records. Through optimization, total GDD were estimated for each site so that the long-term average simulated date of maturity matches the one reported by the country agronomist. Date of silking is calculated internally in HybridMaize based on relationships between GDD to silking versus total GDD. If the calculated total GDD of a particular site was greater than ±25% of other nearby sites, this site was further investigated to determine if any errors persisted in the weather data used to calculate GDD or country agronomist partners were contacted to determine if a misspecification of cropping season had occurred. If total GDD calculations of nearby sites were within 5% of each other, a fixed GDD (roughly the average of these GDD) for all sites within the region was used. To avoid unrealistically long crop cycle lengths, the maximum GDD was set at 1900 C° based on maximum GDD values reported in the literature.

Since our objective was to estimate attainable maize production using best available technology, we simulated yields of modern hybrid cultivars while the optimal plant population density for each location was determined based on the relationship between plant population and seasonal water deficit developed for US maize (Grassini et al. 2009) (Figure C1, Appendix C), with maximum set at 80,000 plant ha$^{-1}$ (average plant density of irrigated corn in Nebraska) and a minimum set at 35,000 plant ha$^{-1}$. The rationale was that the observed plant population density gradient along the east-west water deficit gradient in the US Corn
Belt is a very good proxy for optimal planting density, for a given water deficit level, in a real farm context where crop producers do have good access to markets, inputs, and extension services. Seasonal water deficit was estimated as the difference between total precipitation and total evaporative demand (i.e., reference grass-based evapotranspiration) between sowing and physiological maturity at each location (RWS).

Table 8. Input parameters used in the HybridMaize model for simulation of rainfed maize in Kenya.

<table>
<thead>
<tr>
<th>Weather station</th>
<th>Cropping system</th>
<th>Water regime</th>
<th>% crop under this area</th>
<th>Sowing date used for model calibration and simulations</th>
<th>Growth duration (days till maturity)</th>
<th>GDD (°C, base temp = 10°)</th>
<th>Soil available water content at planting (mm)</th>
<th>Plant population (1,000 ha⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eldoret</td>
<td>single</td>
<td>Rainfed</td>
<td>100%</td>
<td>15-Apr</td>
<td>180</td>
<td>1750</td>
<td>25</td>
<td>53</td>
</tr>
<tr>
<td>Narok</td>
<td>wheat-</td>
<td>Rainfed</td>
<td>100%</td>
<td>1-Mar</td>
<td>130</td>
<td>950</td>
<td>50</td>
<td>53</td>
</tr>
<tr>
<td>Dagoretti</td>
<td>single</td>
<td>Rainfed</td>
<td>100%</td>
<td>1-Mar</td>
<td>130</td>
<td>1000</td>
<td>25</td>
<td>65</td>
</tr>
<tr>
<td>Embu</td>
<td>single</td>
<td>Rainfed</td>
<td>100%</td>
<td>1-Mar</td>
<td>180</td>
<td>1450</td>
<td>25</td>
<td>53</td>
</tr>
<tr>
<td>Kakamega</td>
<td>Double</td>
<td>Rainfed</td>
<td>50%</td>
<td>15-Apr</td>
<td>135</td>
<td>1430</td>
<td>25</td>
<td>80</td>
</tr>
<tr>
<td>Kakamega</td>
<td>Double</td>
<td>Rainfed</td>
<td>50%</td>
<td>9-Sep</td>
<td>130</td>
<td>1430</td>
<td>25</td>
<td>68</td>
</tr>
<tr>
<td>Kambi YaM awe</td>
<td>single</td>
<td>Rainfed</td>
<td>100%</td>
<td>18-Mar</td>
<td>110</td>
<td>1530</td>
<td>25</td>
<td>35</td>
</tr>
<tr>
<td>Kambi YaM awe</td>
<td>single</td>
<td>Rainfed</td>
<td>100%</td>
<td>1-Mar</td>
<td>110</td>
<td>1540</td>
<td>25</td>
<td>35</td>
</tr>
<tr>
<td>Kericho</td>
<td>single</td>
<td>Rainfed</td>
<td>100%</td>
<td>15-Apr</td>
<td>165</td>
<td>1230</td>
<td>25</td>
<td>80</td>
</tr>
<tr>
<td>Kisii</td>
<td>Double</td>
<td>Rainfed</td>
<td>50%</td>
<td>15-Apr</td>
<td>130</td>
<td>1360</td>
<td>25</td>
<td>77</td>
</tr>
<tr>
<td>Kisii</td>
<td>Double</td>
<td>Rainfed</td>
<td>50%</td>
<td>9-Sep</td>
<td>130</td>
<td>1390</td>
<td>25</td>
<td>77</td>
</tr>
<tr>
<td>Kisumu</td>
<td>Double</td>
<td>Rainfed</td>
<td>50%</td>
<td>15-Apr</td>
<td>165</td>
<td>1900</td>
<td>25</td>
<td>45</td>
</tr>
<tr>
<td>Kisumu</td>
<td>Double</td>
<td>Rainfed</td>
<td>50%</td>
<td>9-Sep</td>
<td>130</td>
<td>1790</td>
<td>25</td>
<td>54</td>
</tr>
<tr>
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<td>single</td>
<td>Rainfed</td>
<td>100%</td>
<td>15-Apr</td>
<td>180</td>
<td>1640</td>
<td>25</td>
<td>80</td>
</tr>
<tr>
<td>Makindu</td>
<td>single</td>
<td>Rainfed</td>
<td>100%</td>
<td>1-Mar</td>
<td>120</td>
<td>1590</td>
<td>25</td>
<td>53</td>
</tr>
<tr>
<td>Meru</td>
<td>single</td>
<td>Rainfed</td>
<td>100%</td>
<td>1-Mar</td>
<td>210</td>
<td>1270</td>
<td>25</td>
<td>53</td>
</tr>
<tr>
<td>Nyeri</td>
<td>single</td>
<td>Rainfed</td>
<td>100%</td>
<td>15-Apr</td>
<td>180</td>
<td>1280</td>
<td>25</td>
<td>53</td>
</tr>
<tr>
<td>rfmz1</td>
<td>single</td>
<td>Rainfed</td>
<td>100%</td>
<td>1-Mar</td>
<td>130</td>
<td>1010</td>
<td>25</td>
<td>53</td>
</tr>
<tr>
<td>rfmz2</td>
<td>single</td>
<td>Rainfed</td>
<td>100%</td>
<td>1-Mar</td>
<td>130</td>
<td>1000</td>
<td>25</td>
<td>53</td>
</tr>
<tr>
<td>Thika</td>
<td>single</td>
<td>Rainfed</td>
<td>100%</td>
<td>1-Mar</td>
<td>130</td>
<td>1000</td>
<td>25</td>
<td>53</td>
</tr>
</tbody>
</table>

3.4.2. Initialization of available soil moisture for simulation for HybridMaize

To account for variation in soil moisture at planting, the HybridMaize model was used to calculate available soil water available at planting for each system. This calculation was then used to inform decisions on available soil water at planting (as a percent of available water holding capacity of soil).
4. Calculation of mean water limited yield level and yield gap per buffer zone

Crop growth simulations for the different RWS-soil type-crop type-sowing date combinations (see some combinations in the WOFOST rerun files with resp. CLFILE-SOFILE-CRFILE-IDSOY-WYR (= year) given in Appendix C) in Kenya have been done for both potential (= irrigated) and water limited (= rainfed) conditions, to indicate the degree that yield levels may increase by application of irrigation water.

Crop production systems in Kenya are mainly rainfed. Hence, the water limited yields (Yw) have been used to calculate the yield gap. The mean Yw values per crop type per RWS buffer zone were calculated from the Yw values simulated for each crop type-sowing date-crop rotation-soil type combination per zone, weighted to their relative areas.

Next, the yield gap per RWS buffer zone is calculated as the difference between the mean Yw value per zone and the mean actual yield per zone. Note that the time period of the actual yields and that of the Yw values is partly different (i.e. mean of actual yields based on yields from 2000 up to and including 2011 and mean of simulated yields based on simulations for the available weather data between mainly 1998 and 2012).

5. References


Appendices

Appendix A Fraction of precipitation lost by surface runoff (based on literature review)

Table 9. Surface runoff fraction of total seasonal precipitation (in %) for soils that are cultivated with cereals and are mulched, used for simulations with WOFOST

<table>
<thead>
<tr>
<th>Drainage class, Slope angle, in %</th>
<th>Very poor</th>
<th>Insufficient</th>
<th>Moderate</th>
<th>Well drained</th>
<th>Extremely well drained</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-2</td>
<td>10</td>
<td>6.7</td>
<td>3.3</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2-6</td>
<td>13.3</td>
<td>10</td>
<td>6.7</td>
<td>3.3</td>
<td>0</td>
</tr>
<tr>
<td>6-10</td>
<td>16.7</td>
<td>13.3</td>
<td>10</td>
<td>6.7</td>
<td>3.3</td>
</tr>
<tr>
<td>&gt;10</td>
<td>20</td>
<td>16.7</td>
<td>13.3</td>
<td>10</td>
<td>6.7</td>
</tr>
</tbody>
</table>

Appendix B Crop data files for Kenya

Millet medium duration

** File MILL-med-Eth-GYGA.CAB
** CROP DATA FILE for use with WOFOST Version 7.0
** and universal simulation models: review and bibliography. Simulation
** reports CABO-77.
** Some changes included for Millet (medium duration) for Ethiopia for global yield gap atlas

CRPNAM='Pearl Millet, medium duration, Ethiopia, Global yield gap atlas'

** emergence

| TSUM1   | 850.     | 630.     | 0.00, 0.00, 10.00, 0.00, 20.00, 0.00, 30.00, 0.00, 40.00, 0.00 |

** phenology

| IDSL     | 0        | ! indicates whether pre-anthesis development depends!
| DLC      | 0.0      | ! on temp. (=0), daylength (=1), or both (=2)
| TSUM1    | 850.     | ! temperature sum from emergence to anthesis [cel d]
| TSUM2    | 630.     | ! temperature sum from anthesis to maturity [cel d]
| UTSMTB   | 0.00, 0.00, 10.00, 0.00, 20.00, 0.00, 30.00, 0.00, 40.00, 0.00 |

** green area

| SLATB    | 0.00, 0.000, 0.0018, 0.0020, 0.0023, 0.0025, 0.0027, 0.0029, 0.0031, 0.0033 |
| SPA      | 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000 |
| SSAATB   | 0.00, 0.00, 0.00, 0.00, 0.00, 0.00, 0.00, 0.00, 0.00, 0.00 |
| SPAN     | 42.      | ! life span of leaves growing at 35 Celsius [d]
| TBASE    | 10.0     | ! lower threshold temp. for ageing of leaves [cel]

** assimilation

| KGFTB    | 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0 |
| EFFTB    | 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0 |

15
AMAXTB = 0.00, 50.00, ! max. leaf CO2 assim. rate
1.00, 50.00, ! function of DVS [-; kg ha\(^{-1}\) hr\(^{-1}\)]
2.00, 0.00

TMPFTB = 0.00, 0.00, ! reduction factor of AMAX
8.00, 0.00, ! as function of av. temp. [\(^{\circ}\)C; -]
20.00, 1.00,
35.00, 1.00,
45.00, 0.00

TMNFTB = 5.00, 0.00, ! red. factor of gross assim. rate
20.00, 1.00,
35.00, 1.00,
45.00, 0.00

** conversion of assimilates into biomass

CVL = 0.720 ! efficiency of conversion into leaves [kg kg\(^{-1}\)]
CVO = 0.730 ! efficiency of conversion into storage org. [kg kg\(^{-1}\)]
CVR = 0.720 ! efficiency of conversion into roots [kg kg\(^{-1}\)]
CVS = 0.690 ! efficiency of conversion into stems [kg kg\(^{-1}\)]

** maintenance respiration

Q10 = 2.0 ! rel. incr. in resp. rate per 10 Cel temp. incr. [-]
RML = 0.030 ! rel. maint. resp. rate leaves [kg CH2O kg\(^{-1}\) d\(^{-1}\)]
RMO = 0.010 ! rel. maint. resp. rate stor. org. [kg CH2O kg\(^{-1}\) d\(^{-1}\)]
RMR = 0.010 ! rel. maint. resp. rate roots [kg CH2O kg\(^{-1}\) d\(^{-1}\)]
RMS = 0.015 ! rel. maint. resp. rate stems [kg CH2O kg\(^{-1}\) d\(^{-1}\)]

** partitioning

FRTB = 0.00, 0.50, ! fraction of total dry matter to roots
0.10, 0.50, ! as a function of DVS [-; kg kg\(^{-1}\)]
0.25, 0.30,
0.40, 0.17,
1.00, 0.00
2.00, 0.00

FLTB = 0.00, 1.00, ! fraction of above-gr. DM to leaves
0.10, 1.00, ! as a function of DVS [-; kg kg\(^{-1}\)]
1.00, 0.00,
2.00, 0.00

FSTB = 0.00, 0.00, ! fraction of above-gr. DM to stems
0.10, 0.00, ! as a function of DVS [-; kg kg\(^{-1}\)]
1.00, 1.00,
1.50, 0.00,
2.00, 0.00

FOTB = 0.00, 0.00, ! fraction of above-gr. DM to stor. org.
1.00, 0.00, ! as a function of DVS [-; kg kg\(^{-1}\)]
1.50, 1.00,
2.00, 1.00

** death rates

PERDL = 0.030 ! max. rel. death rate of leaves due to water stress
RDRRTB = 0.00, 0.000, ! rel. death rate of roots
1.50, 0.000, ! as a function of DVS [-; kg kg\(^{-1}\) d\(^{-1}\)]
1.5001, 0.020
2.00, 0.020

RDRSTB = 0.00, 0.000, ! rel. death rate of stems
1.50, 0.000, ! as a function of DVS [-; kg kg\(^{-1}\) d\(^{-1}\)]
1.5001, 0.020
2.00, 0.020

** water use

CFET = 1.10 ! correction factor transpiration rate [-]
DEPNR = 4.5 ! crop group number for soil water depletion [-]
IAIRDU = 0 ! air ducts in roots present (=1) or not (=0)

** rooting

KDI = 10. ! initial rooting depth [cm]
KRI = 4.0 ! maximum daily increase in rooting depth [cm d\(^{-1}\)]
RDML = 150. ! maximum rooting depth [cm]

** nutrients

** in storage organs ! in vegetative organs [kg kg\(^{-1}\)]

NMINSO = 0.0100 ; NMINVE = 0.0032
NMAXSO = 0.0300 ; NMAXVE = 0.0105
PHINSO = 0.0014 ; PHINVE = 0.0005
PMAXSO = 0.0080 ; PMAXVE = 0.0025
KMINSO = 0.0030 ; KMINVE = 0.0070
KMAXSO = 0.0080 ; KMAXVE = 0.0280
YZERO = 200. ! max. amount veg. organs at zero yield [kg ha\(^{-1}\)]

NFIG = 0.00 ! fraction of N-uptake from biol. fixation [kg kg\(^{-1}\)]

Sorghum medium duration

** File Sorg-med-ETH-GYGA.CAB
**
** CROP DATA FILE for use with WOFOST Version 7.0
** and universal simulation models: review and bibliography. Simulation
** reports CABO-TT.
**
** Some changes included for Sorghum (medium duration) for Ethiopia for global yield gap atlas

CRPNAM='Sorghum, medium duration, Ethiopia, Global yield gap atlas'

** emergence
TRASEM = 10.0  ! lower threshold temp. for emergence [cel]
TRFPW = 30.0  ! max. eff. temp. for emergence [cel]
TSUMEM = 70.  ! temperature sum from sowing to emergence [cel d]

** phenology
IDEL = 0  ! indicates whether pre-anthesis development depends
          ! on temp. (=0), daylength (=1) , or both (=2)
DLO = 1.0  ! optimum daylength for development [hr]
DLC = 0.0  ! critical daylength (lower threshold) [hr]
TSUM1 = 780.  ! temperature sum from emergence to anthesis [cel d]
TSUM2 = 700.  ! temperature sum from anthesis to maturity [cel d]

** green area
SLATB = 0.0, 0.0020, ! specific leaf area
       1.00, 0.0020, ! as a function of DVS [-; ha kg-1]
       2.00, 0.0020

SPA = 0.00  ! specific pod area [ha kg-1]
SSATB = 0.0, 0.0, ! specific stem area [ha kg-1]
        2.0, 0.0  ! as function of DVS

SPAN = 42.  ! life span of leaves growing at 35 Celsius [d]

** assimilation
KDIFTB = 0.0, 0.70, ! extinction coefficient for diffuse visible light [-]
         2.0, 0.70  ! as function of DVS
EFFTB = 0.0, 0.50, ! light-use effic. single leaf [kg ha-1 hr-1 m2 s-1]
         2.0, 0.50  ! as function of daily mean temp.

AMAXTB = 0.00, 50.00, ! max. leaf CO2 assim. rate
         1.00, 50.00, ! function of DVS [-; kg ha-1 hr-1]
         1.30, 30.00,
         1.60, 30.00,
         1.90, 20.00,
         2.00, 0.00

TMPFTB = 0.00, 0.00, ! reduction factor of AMAX
         8.00, 0.00  ! as function of av. temp. [cel; -]
         20.00, 1.00,
         35.00, 1.00,
         45.00, 0.00

TMNFTB = 5.00, 0.00, ! red. factor of gross assim. rate
         12.00, 1.00  ! as function of low min. temp. [cel; -]

** conversion of assimilates into biomass
CVL = 0.720  ! efficiency of conversion into leaves [kg kg-1]
CVO = 0.730  ! efficiency of conversion into storage org. [kg kg-1]
CVR = 0.720  ! efficiency of conversion into roots [kg kg-1]
CVS = 0.690  ! efficiency of conversion into stems [kg kg-1]

** maintenance respiration
Q10 = 2.0  ! rel. incr. in resp. rate per 10 Cel temp. incr. [-]
QML = 0.030  ! rel. maint. resp. rate leaves [kg CH2O kg-1 d-1]
NMO = 0.010  ! rel. maint. resp. rate stor.org. [kg CH2O kg-1 d-1]
NMR = 0.010  ! rel. maint. resp. rate roots [kg CH2O kg-1 d-1]
MMS = 0.015  ! rel. maint. resp. rate stems [kg CH2O kg-1 d-1]
RFSETB = 0.00, 1.00, ! red. factor for senescence
         2.00, 1.00  ! as function of DVS [-; -]

** partitioning
FRTB = 0.00, 0.55, ! fraction of total dry matter to roots
       0.20, 0.45, ! as a function of DVS [-; kg kg-1]
       0.40, 0.35,
       0.60, 0.20,
       0.80, 0.15,
       1.00, 0.00,
       1.10, 0.00,
       2.00, 0.00
** death rates**

PERDL = 0.030 ! max. rel. death rate of leaves due to water stress
RDRRTB = 0.00, 0.000, ! rel. death rate of roots
1.50, 0.000, ! as a function of DVS [-; kg kg^{-1}d]
1.5001, 0.020,
2.00, 0.020

RDRSTB = 0.00, 0.000, ! rel. death rate of stems
1.50, 0.000, ! as a function of DVS [-; kg kg^{-1}d]
1.5001, 0.020,
2.00, 0.020

** water use**

CFET = 1.10 ! correction factor transpiration rate [-]
DEPNR = 5.0 ! crop group number for soil water depletion [-]
IAIRDU = 0 ! air ducts in roots present (=1) or not (=0)

** rooting**

RRI = 10. ! initial rooting depth [cm]
KRI = 4.0 ! maximum daily increase in rooting depth [cm d^{-1}]
RDMCR = 150. ! maximum rooting depth [cm]

** nutrients**

** maximum and minimum concentrations of N, P, and K**

** in storage organs**

<table>
<thead>
<tr>
<th>Element</th>
<th>Minimum</th>
<th>Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
<td>0.0100</td>
<td>0.0320</td>
</tr>
<tr>
<td>P</td>
<td>0.0014</td>
<td>0.0060</td>
</tr>
<tr>
<td>K</td>
<td>0.0025</td>
<td>0.0075</td>
</tr>
</tbody>
</table>

** in vegetative organs**

<table>
<thead>
<tr>
<th>Element</th>
<th>Minimum</th>
<th>Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
<td>0.0035</td>
<td>0.0120</td>
</tr>
<tr>
<td>P</td>
<td>0.0005</td>
<td>0.0025</td>
</tr>
<tr>
<td>K</td>
<td>0.0070</td>
<td>0.0280</td>
</tr>
</tbody>
</table>

YZERO = 200. ! max. amount veg. organs at zero yield [kg ha^{-1}]
NFTX = 0.00 ! fraction of N-uptake from biol. fixation [kg kg^{-1}]

** Wheat medium duration**

** File WHE-med-Eth-VYGA.CAB**

** CROP DATA FILE for use with WOFPOST for Ethiopia**

** WHEAT, SPRING Medium variety, Ethiopia**

** File mainly based on spring barley data (i.e. BAR301.CAB)**

** Calibrated for use in WOFPOST model for first the Netherlands (in AgriAdapt project)**

** and next again for Ethiopia for the Global Yield Gap Atlas project for the simulation**

** of crop growth and yield on the basis of daily weather data.**

CRPNAM='Spring wheat medium duration, Ethiopia, Global yield gap atlas'

** emergence**

TBASEM = 0.0 ! lower threshold temp. for emergence [cel]
TEFFMX = 30.0 ! max. eff. temp. for emergence [cel]
TSUMEM = 100. ! temperature sum from sowing to emergence [cel d]

** phenology**

IDEL = 0 ! indicates whether pre-anthesis development depends
! on temp. (=0), daylength (=1) , or both (=2)
DLO = 99.0 ! optimum daylength for development [hr]
DLC = 99.0 ! critical daylength (lower threshold) [hr]
TSUM1 = 1325. ! temperature sum from emergence to anthesis [cel d]
TSUM2 = 1325. ! temperature sum from anthesis to maturity [cel d]
DTSMTB = 0.00, 0.00, ! daily increase in temp. sum
35.00, 35.00, ! as function of av. temp. [cel; cel d]
45.00, 35.00
DVSI = 0. ! initial DVS
DVSEND = 2.00 ! development stage at harvest (= 2.0 at maturity [-])

** initial**
\[\text{TDMI} = 60.00 \quad \text{! initial total crop dry weight [kg ha}^{-1}]\]

\[\text{LAIEM} = 0.053 \quad \text{! leaf area index at emergence [ha ha}^{-1}]\]

\[\text{MRLAI} = 0.0090 \quad \text{! maximum relative increase in LAI [ha ha}^{-1} \text{ d}^{-1}]\]

** Green area **

\[\text{SLATB} = 0.00, 0.0022, 0.17, 0.0022, 0.00, 0.0022, 0.90, 0.0022, 1.45, 0.0022, 2.00, 0.0022 \quad \text{! specific leaf area (ha ha}^{-1} \text{ kg}^{-1})\]

\[\text{SPA} = 0.00 \quad \text{! specific pod area (ha kg}^{-1})\]

\[\text{SSATB} = 0.0, 0.0, 2.0, 0.0 \quad \text{! specific stem area (ha kg}^{-1})\]

\[\text{SPAN} = 40.0 \quad \text{! life span of leaves growing at 35 Celsius [d]}\]

** Assimilation **

\[\text{KDIFTB} = 0.0, 0.60, 2.0, 0.60 \quad \text{! extinction coefficient for diffuse visible light [-]}\]

\[\text{EFFTB} = 0.0, 0.40 \quad \text{! as function of DVS [-]}\]

\[\text{AMAXTB} = 0.00, 35.00, 40.00, 35.00 \quad \text{! max. leaf CO2 assim. rate [kg ha}^{-1} \text{ hr}^{-1} \text{ m}^{-2} \text{s}^{-1} \text{]}\]

\[\text{TMPFTB} = 0.00, 0.00, 3.00, 1.00 \quad \text{! reduction factor of AMAX [kg ha}^{-1} \text{ hr}^{-1} \text{ m}^{-2} \text{ s}^{-1} \text{] as function of av. temp. [cel; -]}\]

** Conversion of assimilates into biomass **

\[\text{CVL} = 0.720 \quad \text{! efficiency of conversion into leaves [kg kg}^{-1}]\]

\[\text{CVO} = 0.740 \quad \text{! efficiency of conversion into storage org. [kg kg}^{-1}]\]

\[\text{CVR} = 0.720 \quad \text{! efficiency of conversion into roots [kg kg}^{-1}]\]

\[\text{CVS} = 0.690 \quad \text{! efficiency of conversion into stems [kg kg}^{-1}]\]

** Maintenance respiration **

\[\text{Q10} = 2.0 \quad \text{! rel. incr. in resp. rate per 10 Cel temp. incr. [-]}\]

\[\text{RML} = 0.030 \quad \text{! rel. maint. resp. rate leaves [kg CH2O kg}^{-1} \text{ d}^{-1}]\]

\[\text{RMO} = 0.010 \quad \text{! rel. maint. resp. rate stor.org. [kg CH2O kg}^{-1} \text{ d}^{-1}]\]

** Partitioning **

\[\text{FRTB} = 0.00, 0.60, 0.40, 0.55, 1.00, 0.00, 1.00, 0.00, 1.00, 0.00 \quad \text{! fraction of total dry matter to roots [kg kg}^{-1}]\]

** Water use **

\[\text{CFET} = 1.00 \quad \text{! correction factor transpiration rate [-]}\]

\[\text{DEFNR} = 4.5 \quad \text{! crop group number for soil water depletion [-]}\]

\[\text{IAIRDU} = 0 \quad \text{! air ducts in roots present (=1) or not (=0)}\]

** Rooting **

\[\text{RDI} = 10.0 \quad \text{! initial rooting depth [cm]}\]

\[\text{RRI} = 2.0 \quad \text{! maximum daily increase in rooting depth [cm d}^{-1}]\]
RDMCR = 125. ! maximum rooting depth [cm]

** nutrients
** maximum and minimum concentrations of N, P, and K
** in storage organs        in vegetative organs [kg kg⁻¹]
NMINSO = 0.0110 ;       NMINVE = 0.0035
NMAXSO = 0.0350 ;       NMAXVE = 0.0120
PMINSO = 0.0016 ;       PMINVE = 0.0004
PMAXSO = 0.0060 ;       PMAXVE = 0.0025
KMINSO = 0.0030 ;       KMINVE = 0.0070
KMAXSO = 0.0080 ;       KMAXVE = 0.0280
YZERO = 200.     ! max. amount veg. organs at zero yield [kg ha⁻¹]
NFIX = 0.00 ! fraction of N-uptake from biol. fixation [kg kg⁻¹]

Appendix C Part of the WOFOST rerun files with some of the selected soil-crop-weather-sowing dates-year combinations for Kenya

**Millet**

RUNNAM='1';
CRPNAM='Millet for YIELD GAP calcul.';
CRFILE='MILL-med-Ken-GYGA.CAB';
CLFILE='Ken0.1';
ISYR =1998;
INYEAR =1;
IDSOW=99;
ISDAY=39;
TSUM1=520.;
TSUM2=360.;
IDURMX=200;
SMW=0.100;
SMFCF=0.140;
RDMSDL=40.;
NOTINF=0.067;
WAV=0.5;
RUNNAM='2';
CRPNAM='Millet for YIELD GAP calcul.';
CRFILE='MILL-med-Ken-GYGA.CAB';
CLFILE='Ken0.1';
ISYR =1998;
INYEAR =1;
IDSOW=99;
ISDAY=39;
TSUM1=520.;
TSUM2=360.;
IDURMX=200;
SMW=0.100;
SMFCF=0.150;
RDMSDL=40.;
NOTINF=0.067;
WAV=0.7;
RUNNAM='3';
CRPNAM='Millet for YIELD GAP calcul.';
CRFILE='MILL-med-Ken-GYGA.CAB';
CLFILE='Ken0.1';
ISYR =1998;
INYEAR =1;
IDSOW=99;
ISDAY=39;
TSUM1=520.;
TSUM2=360.;
IDURMX=200;
SMW=0.100;
SMFCF=0.160;
RDMSDL=40.;
NOTINF=0.067;
WAV=0.8;
RUNNAM='4';
CRPNAM='Millet for YIELD GAP calcul.';
CRFILE='MILL-med-Ken-GYGA.CAB';
CLFILE='Ken0.1';
ISYR =1998;
INYEAR =1;
IDSOW=99;
ISDAY=39;
TSUM1=520.;
TSUM2=360.;
IDURMX=200;
SMW=0.100;
SMFCF=0.170;
RDMSDL=40.;
NOTINF=0.067;
WAV=0.9;
RUNNAM='5';
CRPNAM='Millet for YIELD GAP calcul.,'
CRFILE='MILL-med-Ken-GYGA.CAB';
CLFILE='Ken0.,'
ISYR =1998;
INYEAR =1;
IDSOW=99;
ISDAY=39;
TSUM1=520.;
TSUM2=360.;
IDURM=200;
SMW=0.100;
SMFCF=0.180;
RDM=40.;
NOTINF=0.067;
WAV=1.1;
Etc.

Sorghum
RUNNAM='1',
CRPNAM='Sorghum for YIELD GAP calcul.,'
CRFILE='SORG-med-Ken-GYGA.CAB';
CLFILE='Ken0.,'
ISYR =1998;
INYEAR =1;
IDSOW=99;
ISDAY=39;
TSUM1=440.;
TSUM2=310.;
IDURM=200;
SMW=0.100;
SMFCF=0.140;
RDM=40.;
NOTINF=0.067;
WAV=0.5;
RUNNAM='2',
CRPNAM='Sorghum for YIELD GAP calcul.,'
CRFILE='SORG-med-Ken-GYGA.CAB';
CLFILE='Ken0.,'
ISYR =1998;
INYEAR =1;
IDSOW=99;
ISDAY=39;
TSUM1=440.;
TSUM2=310.;
IDURM=200;
SMW=0.100;
SMFCF=0.150;
RDM=40.;
NOTINF=0.067;
WAV=0.7;
RUNNAM='3',
CRPNAM='Sorghum for YIELD GAP calcul.,'
CRFILE='SORG-med-Ken-GYGA.CAB';
CLFILE='Ken0.,'
ISYR =1998;
INYEAR =1;
IDSOW=99;
ISDAY=39;
TSUM1=440.;
TSUM2=310.;
IDURM=200;
SMW=0.100;
SMFCF=0.160;
RDM=40.;
NOTINF=0.067;
WAV=0.8;
RUNNAM='4',
CRPNAM='Sorghum for YIELD GAP calcul.,'
CRFILE='SORG-med-Ken-GYGA.CAB';
CLFILE='Ken0.,'
ISYR =1998;
INYEAR =1;
IDSOW=99;
ISDAY=39;
TSUM1=440.;
TSUM2=310.;
IDURM=200;
SMW=0.100;
SMFCF=0.170;
RDM=40.;
NOTINF=0.067;
WAV=0.9;
RUNNAM='5',
CRPNAM='Sorghum for YIELD GAP calcul.,'
CRFILE='SORG-med-Ken-GYGA.CAB';
CLFILE='Ken0.');
Wheat

RUNNAM = '1';
CRPNAM = 'Wheat for YIELD GAP calcul.';
CRFILE = 'WHE-med-Ken-GYGA.CAB';
CLFILE = 'Ken3.3';
ISYR = 1998;
INYEAR = 1;
IDSOW = 236;
ISDAY = 176;
TSUM1 = 1150.;
TSUM2 = 1050.;
IDURMX = 200;
SMW = 0.100;
SMFCF = 0.140;
RDMSOL = 40.;
NOTINF = 0.033;
WAV = 0.7;
RUNNAM = '2';
CRPNAM = 'Wheat for YIELD GAP calcul.';
CRFILE = 'WHE-med-Ken-GYGA.CAB';
CLFILE = 'Ken3.3';
ISYR = 1998;
INYEAR = 1;
IDSOW = 236;
ISDAY = 176;
TSUM1 = 1150.;
TSUM2 = 1050.;
IDURMX = 200;
SMW = 0.100;
SMFCF = 0.150;
RDMSOL = 40.;
NOTINF = 0.033;
WAV = 0.8;
RUNNAM = '3';
CRPNAM = 'Wheat for YIELD GAP calcul.';
CRFILE = 'WHE-med-Ken-GYGA.CAB';
CLFILE = 'Ken3.3';
ISYR = 1998;
INYEAR = 1;
IDSOW = 236;
ISDAY = 176;
TSUM1 = 1150.;
TSUM2 = 1050.;
IDURMX = 200;
SMW = 0.100;
SMFCF = 0.160;
RDMSOL = 40.;
NOTINF = 0.033;
WAV = 0.9;
RUNNAM = '4';
CRPNAM = 'Wheat for YIELD GAP calcul.';
CRFILE = 'WHE-med-Ken-GYGA.CAB';
CLFILE = 'Ken3.3';
ISYR = 1998;
INYEAR = 1;
IDSOW = 236;
ISDAY = 176;
TSUM1 = 1150.;
TSUM2 = 1050.;
IDURMX = 200;
SMW = 0.100;
SMFCF = 0.170;
RDMSOL = 40.;
NOTINF = 0.033;
WAV = 0.9;
RUNNAM = '5';
CRPNAM = 'Wheat for YIELD GAP calcul.';
CRFILE = 'WHE-med-Ken-GYGA.CAB';
CLFILE = 'Ken3.3';
ISYR = 1998;
INYEAR = 1;
IDSOW = 236;
ISDAY=176;
TSUM1=1150.;
TSUM2=1050.;
IDURMX=200;
SMN=0.100;
SMNCF=0.180;
RDMSOL=40.;
NOTINF=0.033;
WAV=1.1;
Etc.
Appendix D Relationship between maize planting density and seasonal water deficit as observed in the US Corn Belt

Figure D1. Relationship between maize planting density and seasonal water deficit as observed in the US Corn Belt. Seasonal water deficit was calculated as ETo (reference evapotranspiration) minus precipitation between sowing and physiological maturity. The grey shaded area represents the 95 % confidence interval of prediction of the linear regression. Source: Grassini et al. 2009.