Application of the GYGA approach to Ethiopia

GYGA coordination team and Dr. K. Tesfaye Fantaye

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

(by Dr. K. Tesfaye Fantaye)

Ethiopia, situated in the Horn of Africa, has a population of close to 90 million and a surface area of 1.2 million square kilometers, of which 65% is suitable for arable farming. Agriculture is the mainstay of the country’s economy, contributing about 43% of the country’s GDP and employing more than 85% of the working population. The production system is dominated by smallholder farming under rainfed conditions. Agriculture is traditional and it is characterized by subsistence mixed farming with crop cultivation and livestock husbandry practiced on most farms. Agriculture is highly dependent on rainfall, and hence the onset, duration, amount and distribution of the rainfall determines the performance of the agriculture sectors in particular and the economy of the country in general. More than 95% of the country’s agricultural output is generated by subsistence farmers who, on average, own less than 1 ha of cultivated land with poor fertility as a result of continuous cropping and low input application.

Ethiopia is known for its ecological diversity that ranges from tropical to temperate conditions. Altitude ranges from -126 meters above sea level in the Danakil Depression in the northeast to 4620 meters above sea level at the Ras Dashen Mountains in the northwest. In the central highland plateaus, where major cereal crops are grown, elevation extends from 1800 to 3000 meters above sea level, mean annual rainfall ranges from 950-1500 mm and mean annual temperature ranges from 11-21°C. Ecological and socio-cultural diversity creates favorable conditions for different types of fauna and flora to flourish such that the country is a center of origin and diversity for many cultivated crops and their wild relatives. According to the global agroecological zone classification based on length of growing period (IIASA/FAO, 2010), the major crop growing areas of the country are found in the sub-humid, humid and moist-semiarid climatic zones (Fig. 1). On the other hand, the Ministry of Agriculture and Rural Development (MoARD, 2005) classified the country into 32 major agro-ecological zones and categorized about 51% of the total land area of the country under the arid, semi-arid and sub-moist zones while the other half falls under the range of moist to humid zones. From among 18 major soil types that exist in the country, Nitosols (23%), Cambisols (19%), and Vertisols (18%) comprise more than half of the arable land area in the different agroecologies of the country (Paulos, 2001).

About 15% of the county’s area is currently used for the production of major food crops. The major staple crops of Ethiopia include cereals, pulses, oilseeds, roots and tubers, vegetables and coffee. According to the recent Ethiopian Central Statistical Agency report (CSA, 2013),
grain crops (cereals, pulses and oil crops) are cultivated on an area of 13.9 Mha with annual production of 25.1 million metric tonnes. According to the same report, cereals, pulses and oil crops constituted 78, 15, 7% of the cultivated area and 85, 12 and 3% the total grain production of the country, respectively in the main rainy season of 2012/2013. Cereals are the most important field crops and the chief element in the diet of most Ethiopians. The principal cereals are tef (an indigenous principal staple crop), wheat, barley maize, sorghum and millet. Wheat is grown mostly between 1,500 and 2,700 meters above sea level whereas maize, sorghum and millet are cultivated mostly in the warmer areas of the country. Sorghum and millet, which are drought resistant, grow well at low elevations where rainfall is less reliable. Maize is mainly grown between 1,500 and 2,200 meters above sea level and requires relatively higher seasonal rainfall to ensure good harvests. These major food crops are produced in almost all regions of the country but with large variations in terms of volume of production.

The area coverage of maize, wheat, sorghum and finger millet in Ethiopia account for 47% of cultivated grain crops area of the country in the 2012/13 cropping season (Table 1 & 2). However, the productivity of these crops is very low despite their large area coverage. The national average yield for maize, wheat and sorghum and finger millet is 3.0, 2.0 and 1.7 t ha$^{-1}$, respectively in 2012/2013 (Table 2). Available evidence suggests that yields of major crops under farmers’ management are still far lower than what can be obtained under on-station and on-farm research managed plots (Table 2). This is a clear indication of large yield gaps for major crops of the country. There are several factors believed to contribute to the low productivity including, among others, moistures stress, shortage of seeds for improved varieties, soil fertility degradation, insect pests, diseases, weeds and birds.

The most important cereal farming system zones of Ethiopia are located in the north, northwestern, central, eastern and southwestern highlands (USAID, 2010). Cereal mixed farming dominates the northern, northwestern and central highlands while maize-sorghum based cropping dominates the eastern highlands. Whilst Barley-wheat cropping dominates the Arsi and Bale highlands, coffee, maize and horticultural crops farming characterize the major farming system of the southern and southwestern highlands. The lowlands (areas below 1500 m above sea level) areas also grow short maturing maize, sorghum, wheat, and tef varieties along with some oil crops and lowland pulses.

Table 1. Area coverage of cereal crops in Ethiopia over a course of 5 decades

<table>
<thead>
<tr>
<th></th>
<th>Tef</th>
<th>Wheat</th>
<th>Maize</th>
<th>Sorghum</th>
<th>Barley</th>
<th>Finger Millet</th>
<th>Other cereals</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Cereal cultivated area (M ha)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1961/62-1969/70</td>
<td>2.11</td>
<td>0.97</td>
<td>0.8</td>
<td>1.09</td>
<td>0.96</td>
<td>-</td>
<td>0.3</td>
<td>6.23</td>
</tr>
<tr>
<td>1970/71-1979/80</td>
<td>1.67</td>
<td>0.78</td>
<td>0.83</td>
<td>0.87</td>
<td>0.84</td>
<td>-</td>
<td>0.27</td>
<td>5.25</td>
</tr>
<tr>
<td>1980/81-1989/90</td>
<td>1.23</td>
<td>0.52</td>
<td>0.84</td>
<td>0.71</td>
<td>0.86</td>
<td>-</td>
<td>0.15</td>
<td>4.3</td>
</tr>
<tr>
<td>1990/91-1999/00</td>
<td>1.76</td>
<td>0.75</td>
<td>1.12</td>
<td>0.95</td>
<td>0.73</td>
<td>-</td>
<td>0.29</td>
<td>5.6</td>
</tr>
<tr>
<td>2000/01-2008/09</td>
<td>2.17</td>
<td>1.27</td>
<td>1.59</td>
<td>1.35</td>
<td>0.96</td>
<td>-</td>
<td>0.38</td>
<td>7.72</td>
</tr>
<tr>
<td>2012/2013</td>
<td>2.73</td>
<td>1.71</td>
<td>2.01</td>
<td>1.62</td>
<td>1.02</td>
<td>0.43</td>
<td>0.08</td>
<td>9.6</td>
</tr>
<tr>
<td></td>
<td>1961/62-1969/70</td>
<td>33.9</td>
<td>15.6</td>
<td>12.8</td>
<td>17.4</td>
<td>15.4</td>
<td>4.9</td>
<td>100</td>
</tr>
</tbody>
</table>
Table 2. Nationally reported average yields and yields reported from on-station and on-farm experiments

<table>
<thead>
<tr>
<th>Crop</th>
<th>Area (M ha)*</th>
<th>Total Production (MMT)*</th>
<th>National Average Yield (t/ha)*</th>
<th>On-station yield (t/ha)#</th>
<th>On-farm yield (t/ha)#</th>
<th>Varieties considered for on-station and on-farm reports</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maize</td>
<td>2.01</td>
<td>6.16</td>
<td>3.01</td>
<td>9.0-12.0</td>
<td>6.0-8.0</td>
<td>BH-660</td>
</tr>
<tr>
<td>Wheat</td>
<td>1.63</td>
<td>3.43</td>
<td>2.11</td>
<td>3.5-5.5</td>
<td>2.5-5.0</td>
<td>Dendea</td>
</tr>
<tr>
<td>Sorghum</td>
<td>1.71</td>
<td>3.60</td>
<td>2.11</td>
<td>4.2</td>
<td>3.3</td>
<td>Chare</td>
</tr>
<tr>
<td>Finger millet</td>
<td>0.43</td>
<td>0.74</td>
<td>1.72</td>
<td>3.1</td>
<td>2.8-2.9</td>
<td>Tadesse</td>
</tr>
</tbody>
</table>


Figure 1. Major agroclimatic zones of Ethiopia.
2. Data sources and their use

Data that are used for the yield gap analyses for Ethiopia, 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 (zone)-level data on annual actual yields were retrieved from the Central Statistical Agency of Ethiopia (http://www.csa.gov.et/). We used all available actual yield data between 2005 and 2011 (2009 and 2010 missing) 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>
<tr>
<td>9</td>
<td>5</td>
<td>75</td>
<td>Sandy clay loam</td>
</tr>
<tr>
<td>10</td>
<td>6</td>
<td>75</td>
<td>Clay loam</td>
</tr>
<tr>
<td>11</td>
<td>7</td>
<td>75</td>
<td>Sandy loam</td>
</tr>
<tr>
<td>12</td>
<td>8</td>
<td>75</td>
<td>Silt loam</td>
</tr>
<tr>
<td>13</td>
<td>9</td>
<td>75</td>
<td>Silt clay loam</td>
</tr>
<tr>
<td>14</td>
<td>≥10</td>
<td>75</td>
<td>Loam</td>
</tr>
<tr>
<td>15</td>
<td>≤4</td>
<td>115</td>
<td>Loamy sand</td>
</tr>
<tr>
<td>16</td>
<td>5</td>
<td>115</td>
<td>Sandy clay loam</td>
</tr>
<tr>
<td>17</td>
<td>6</td>
<td>115</td>
<td>Clay loam</td>
</tr>
<tr>
<td>18</td>
<td>7</td>
<td>115</td>
<td>Sandy loam</td>
</tr>
<tr>
<td>19</td>
<td>8</td>
<td>115</td>
<td>Silt loam</td>
</tr>
<tr>
<td>20</td>
<td>9</td>
<td>115</td>
<td>Silt clay loam</td>
</tr>
<tr>
<td>21</td>
<td>≥10</td>
<td>115</td>
<td>Loam</td>
</tr>
<tr>
<td>22</td>
<td>≤4</td>
<td>150</td>
<td>Loamy sand</td>
</tr>
<tr>
<td>23</td>
<td>5</td>
<td>150</td>
<td>Sandy clay loam</td>
</tr>
<tr>
<td>24</td>
<td>6</td>
<td>150</td>
<td>Clay loam</td>
</tr>
<tr>
<td>25</td>
<td>7</td>
<td>150</td>
<td>Sandy loam</td>
</tr>
<tr>
<td>26</td>
<td>8</td>
<td>150</td>
<td>Silt loam</td>
</tr>
<tr>
<td>27</td>
<td>9</td>
<td>150</td>
<td>Silt clay loam</td>
</tr>
<tr>
<td>28</td>
<td>≥10</td>
<td>150</td>
<td>Loam</td>
</tr>
</tbody>
</table>

2.3. Weather data and reference weather stations

Historical daily weather data sets have been collected from the National Meteorology Agency of Ethiopia. Weather sets are available for 80 locations in Ethiopia and contain ten or more years of data. Weather data are derived mainly with help of weather propagation based on at least 3 years of actual measured data. 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 Ethiopia (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>Adet, Ambo, Arbaminch, Areka, Arse-Negele, Assosa, Ayira, Bahir Dar, Bako, Butajira, Debre Markos, Gelemso, Gore, Haramaya or Alemaya, Harar, Jimma, Kulumsa, Melkassa, Nekemte, Pawe, Shambu, Shire Endasilasse, Woliso, Wolkite (24)</td>
<td>38%</td>
</tr>
<tr>
<td>Rainfed millet</td>
<td>Adet, Assosa, Ayira, Bahir Dar, Dire Dawa, Gelemso, Gondar, Gore, Kobo, Melkassa, Nekemte, Pawe, Shambu, Shire Endasilasse, eth_rfmz5, eth_rfwt1(16)</td>
<td>39%</td>
</tr>
<tr>
<td>Rainfed sorghum</td>
<td>Assosa, Ayira, Bahir Dar, Butajira, Gelemso, Gondar, Gore, Haramaya or Alemaya, Harar, Jijiga, Kobo, Kombolacha, Melkassa, Nekemte, Pawe</td>
<td>21%</td>
</tr>
</tbody>
</table>
SPAM05 has been used to determine the locations for rainfed wheat.

### 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, millet and wheat in the different RWS buffer zones of Ethiopia as compiled by the country agronomist (Source: Dr. K. Tesfaye Fantaye)

<table>
<thead>
<tr>
<th>Weather station</th>
<th>Location</th>
<th>Cropping system</th>
<th>Water regime</th>
<th>Sowing window</th>
<th>% crop area under this system</th>
</tr>
</thead>
<tbody>
<tr>
<td>Adet</td>
<td>Adet</td>
<td>Single: maize</td>
<td>rainfed</td>
<td>1 May-30 May</td>
<td>100%</td>
</tr>
<tr>
<td>Ambo</td>
<td>Ambo</td>
<td>Single: maize</td>
<td>rainfed</td>
<td>5 May-3 June</td>
<td>100%</td>
</tr>
<tr>
<td>Arba minch</td>
<td>Arba minch</td>
<td>Single: maize</td>
<td>rainfed</td>
<td>25 March-23 April</td>
<td>100%</td>
</tr>
<tr>
<td>Areka</td>
<td>Areka</td>
<td>Single: maize</td>
<td>rainfed</td>
<td>10 March-8 April</td>
<td>100%</td>
</tr>
<tr>
<td>Arsi Negelle</td>
<td>Arsi Negelle</td>
<td>Single: maize</td>
<td>rainfed</td>
<td>15 April-15 May</td>
<td>100%</td>
</tr>
<tr>
<td>Assosa</td>
<td>Assosa</td>
<td>Single: maize</td>
<td>rainfed</td>
<td>16 April-15 May</td>
<td>100%</td>
</tr>
<tr>
<td>Ayira</td>
<td>Ayira</td>
<td>Single: maize</td>
<td>rainfed</td>
<td>1 April -30 April</td>
<td>100%</td>
</tr>
<tr>
<td>Bahir Dar</td>
<td>Bahir Dar</td>
<td>Single: maize</td>
<td>rainfed</td>
<td>15 May-14 June</td>
<td>100%</td>
</tr>
<tr>
<td>Bako</td>
<td>Bako</td>
<td>Single: maize</td>
<td>rainfed</td>
<td>01 May-14 June</td>
<td>100%</td>
</tr>
<tr>
<td>Butajira</td>
<td>Butajira</td>
<td>Single: maize</td>
<td>rainfed</td>
<td>10 April-9 May</td>
<td>100%</td>
</tr>
<tr>
<td>Debre markos</td>
<td>Debre markos</td>
<td>Single: maize</td>
<td>rainfed</td>
<td>01 April-30 April</td>
<td>100%</td>
</tr>
<tr>
<td>Gelemso</td>
<td>Gelemso</td>
<td>Single: maize</td>
<td>rainfed</td>
<td>25 March-24 April</td>
<td>100%</td>
</tr>
<tr>
<td>Gore</td>
<td>Gore</td>
<td>Single: maize</td>
<td>rainfed</td>
<td>1-30 April</td>
<td>100%</td>
</tr>
<tr>
<td>Haramaya or Alemaya</td>
<td>Haramaya</td>
<td>Single: maize</td>
<td>rainfed</td>
<td>25 March-24 April</td>
<td>100%</td>
</tr>
<tr>
<td>Harar</td>
<td>Harar</td>
<td>Single: maize</td>
<td>rainfed</td>
<td>16 April-15-May</td>
<td>100%</td>
</tr>
<tr>
<td>Jimma</td>
<td>Jimma</td>
<td>Single: maize</td>
<td>rainfed</td>
<td>01-30 April</td>
<td>100%</td>
</tr>
<tr>
<td>Location</td>
<td>Variety</td>
<td>Type</td>
<td>Dates</td>
<td>Percentage</td>
<td></td>
</tr>
<tr>
<td>------------------------------</td>
<td>--------------------------</td>
<td>---------------</td>
<td>------------------------</td>
<td>------------</td>
<td></td>
</tr>
<tr>
<td>Kulumsa</td>
<td>Single: maize</td>
<td>rainfed</td>
<td>01-30 May</td>
<td>100%</td>
<td></td>
</tr>
<tr>
<td>Melkassa</td>
<td>Single: maize</td>
<td>rainfed</td>
<td>15 June-15 July</td>
<td>100%</td>
<td></td>
</tr>
<tr>
<td>Nekemte</td>
<td>Single: maize</td>
<td>rainfed</td>
<td>15-May-13-June</td>
<td>100%</td>
<td></td>
</tr>
<tr>
<td>Pawe</td>
<td>Single: maize</td>
<td>rainfed</td>
<td>16 April-15-May</td>
<td>100%</td>
<td></td>
</tr>
<tr>
<td>Shambu</td>
<td>Single: maize</td>
<td>rainfed</td>
<td>16 April-15-May</td>
<td>100%</td>
<td></td>
</tr>
<tr>
<td>Shire Endasilasse</td>
<td>Single: maize</td>
<td>rainfed</td>
<td>01-30 June</td>
<td>100%</td>
<td></td>
</tr>
<tr>
<td>Woliso</td>
<td>Single: maize</td>
<td>rainfed</td>
<td>25 March-24 April</td>
<td>100%</td>
<td></td>
</tr>
<tr>
<td>Wolkite</td>
<td>Single: maize</td>
<td>rainfed</td>
<td>25 March-24 April</td>
<td>100%</td>
<td></td>
</tr>
<tr>
<td>Adet</td>
<td>Single: finger millet</td>
<td>rainfed</td>
<td>15 May-30 June</td>
<td>100%</td>
<td></td>
</tr>
<tr>
<td>Assosa</td>
<td>Single: finger millet</td>
<td>rainfed</td>
<td>1-30-Jun</td>
<td>100%</td>
<td></td>
</tr>
<tr>
<td>Ayira</td>
<td>Single: finger millet</td>
<td>rainfed</td>
<td>15 May-30 June</td>
<td>100%</td>
<td></td>
</tr>
<tr>
<td>Bahir Dar</td>
<td>Single: finger millet</td>
<td>rainfed</td>
<td>10 May-15 June</td>
<td>100%</td>
<td></td>
</tr>
<tr>
<td>Dire Dawa</td>
<td>Single: finger millet</td>
<td>rainfed</td>
<td>25 March-30 April 15</td>
<td>100%</td>
<td></td>
</tr>
<tr>
<td>Gelemso</td>
<td>Single: finger millet</td>
<td>rainfed</td>
<td>01 April-30 April</td>
<td>100%</td>
<td></td>
</tr>
<tr>
<td>Gonder</td>
<td>Single: finger millet</td>
<td>rainfed</td>
<td>15 May-25 June</td>
<td>100%</td>
<td></td>
</tr>
<tr>
<td>Gore</td>
<td>Single: finger millet</td>
<td>rainfed</td>
<td>1-31 May</td>
<td>100%</td>
<td></td>
</tr>
<tr>
<td>Kobo</td>
<td>Single: finger millet</td>
<td>rainfed</td>
<td>16 May-15 June</td>
<td>100%</td>
<td></td>
</tr>
<tr>
<td>Melkassa</td>
<td>Single: finger millet</td>
<td>rainfed</td>
<td>1-30 Apr</td>
<td>100%</td>
<td></td>
</tr>
<tr>
<td>Nekemte</td>
<td>Single: finger millet</td>
<td>rainfed</td>
<td>15 May-15 June</td>
<td>100%</td>
<td></td>
</tr>
<tr>
<td>Pawe</td>
<td>Single: finger millet</td>
<td>rainfed</td>
<td>1 June-10 July</td>
<td>100%</td>
<td></td>
</tr>
<tr>
<td>Shambu</td>
<td>Single: finger millet</td>
<td>rainfed</td>
<td>1-31-May</td>
<td>100%</td>
<td></td>
</tr>
<tr>
<td>Shire Endasilasse</td>
<td>Single: finger millet</td>
<td>rainfed</td>
<td>16-Jun-15-July</td>
<td>100%</td>
<td></td>
</tr>
<tr>
<td>eth_rfmz5</td>
<td>Single: finger millet</td>
<td>rainfed</td>
<td>1-30 April</td>
<td>100%</td>
<td></td>
</tr>
<tr>
<td>eth_rfwt1</td>
<td>Single: finger millet</td>
<td>rainfed</td>
<td>1-30 April</td>
<td>100%</td>
<td></td>
</tr>
<tr>
<td>Assosa</td>
<td>Single: sorghum</td>
<td>rainfed</td>
<td>1-30 June</td>
<td>100%</td>
<td></td>
</tr>
<tr>
<td>Ayira</td>
<td>Single: sorghum</td>
<td>rainfed</td>
<td>15 May-15 June</td>
<td>100%</td>
<td></td>
</tr>
<tr>
<td>Bahir Dar</td>
<td>Single: sorghum</td>
<td>rainfed</td>
<td>10 May-15 June</td>
<td>100%</td>
<td></td>
</tr>
<tr>
<td>Butajira</td>
<td>Single: sorghum</td>
<td>rainfed</td>
<td>10 April-9-May</td>
<td>100%</td>
<td></td>
</tr>
<tr>
<td>Gelemso</td>
<td>Single: sorghum</td>
<td>rainfed</td>
<td>25 March-24 April</td>
<td>100%</td>
<td></td>
</tr>
<tr>
<td>Gonder</td>
<td>Single: sorghum</td>
<td>rainfed</td>
<td>15 May-14 June</td>
<td>100%</td>
<td></td>
</tr>
<tr>
<td>Gore</td>
<td>Single: sorghum</td>
<td>rainfed</td>
<td>1-30 April</td>
<td>100%</td>
<td></td>
</tr>
<tr>
<td>Haramaya or Alemaya</td>
<td>Single: sorghum</td>
<td>rainfed</td>
<td>25 March-24 April</td>
<td>100%</td>
<td></td>
</tr>
<tr>
<td>Harar</td>
<td>Single: sorghum</td>
<td>rainfed</td>
<td>25 March-24 April</td>
<td>100%</td>
<td></td>
</tr>
<tr>
<td>Jijiga</td>
<td>Single: sorghum</td>
<td>rainfed</td>
<td>01-30 April; 15 June-14 July</td>
<td>100%</td>
<td></td>
</tr>
<tr>
<td>Kobo</td>
<td>Single: sorghum</td>
<td>rainfed</td>
<td>16 Jun-15 July</td>
<td>100%</td>
<td></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 Ethiopia 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 main crop characteristics for maize, sorghum, millet and wheat growing in Ethiopia (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 Ethiopia. These crop characteristics have been used for testing and possibly calibrating the model parameters.
Table 6. Crop characteristics for main crop types in Ethiopia 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 management¹

<table>
<thead>
<tr>
<th>Crop, zones in Ethiopia</th>
<th>Period from emergence to maturity (days)</th>
<th>Period fractions from emergence to flowering and from flowering to maturity (%)</th>
<th>LAI-max (m² m⁻²)¹</th>
<th>Total biomass above-ground (kg dry matter per ha)²</th>
<th>Yield (kg dry matter per ha)²</th>
<th>Harvest index (yield / total biomass above ground)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grain maize, all zones</td>
<td>80 - 190</td>
<td>50% - 50%</td>
<td>4 to 7</td>
<td>10600 to 19000</td>
<td>5300 to 9500</td>
<td>0.45 to 0.55</td>
</tr>
<tr>
<td>Sorghum, all zones</td>
<td>100 - 180</td>
<td>55% - 45%</td>
<td>3 to 7</td>
<td>9600 to 15000</td>
<td>3800 to 6500</td>
<td>0.35 to 0.45</td>
</tr>
<tr>
<td>Millet, all zones</td>
<td>100 - 165</td>
<td>62% - 38%</td>
<td>3 to 7</td>
<td>9600 to 15000</td>
<td>2900 to 4500</td>
<td>0.25 to 0.35</td>
</tr>
<tr>
<td>Wheat, all zones</td>
<td>90 - 140</td>
<td>54% - 46%</td>
<td>4 to 7</td>
<td>10600 to 17000</td>
<td>4200 to 6800</td>
<td>0.35 to 0.45</td>
</tr>
</tbody>
</table>

¹ Crop characteristics are based on Crop data for Ethiopia (Table 5), expert knowledge and experimental information, as reported by Erkossa et al. (2011), maize trials at Melkassa (pers. comm. K. Tesfaye Fantaye), Admassu et al. (2008), Negassa et al. (2005), Adugna (2008), Alemu & Bayu (2005), Bayu et al. (2006), Mesfine et al. (2005), Tolera et al. (1999), Geleto et al. (1995), and Tarekegne et al. (1995)

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 4 and 6) and the climate conditions per RWS buffer zone in Ethiopia.

We may assume that maize, sorghum, millet and wheat are in general produced in Ethiopia 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 6; 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 CO₂ 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 6 for maize, sorghum, millet and wheat in the different RWS buffer zones of Ethiopia

<table>
<thead>
<tr>
<th>Weather station</th>
<th>Location</th>
<th>Cropping system</th>
<th>Water regime</th>
<th>Growth duration,¹,²</th>
<th>TSUM1 (°Cd)</th>
<th>TSUM2 (°Cd)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Adet</td>
<td>Adet</td>
<td>Single: maize</td>
<td>rainfed</td>
<td>180</td>
<td>730</td>
<td>650</td>
</tr>
<tr>
<td>Ambo</td>
<td>Ambo</td>
<td>Single: maize</td>
<td>rainfed</td>
<td>200</td>
<td>750</td>
<td>800</td>
</tr>
<tr>
<td>Arbaminch</td>
<td>Arba minch</td>
<td>Single: maize</td>
<td>rainfed</td>
<td>135</td>
<td>860</td>
<td>800</td>
</tr>
<tr>
<td>Areka</td>
<td>Areka</td>
<td>Single: maize</td>
<td>rainfed</td>
<td>150</td>
<td>750</td>
<td>580</td>
</tr>
<tr>
<td>Arse-Negelle</td>
<td>Arsi Negelle</td>
<td>Single: maize</td>
<td>rainfed</td>
<td>130</td>
<td>590</td>
<td>390</td>
</tr>
<tr>
<td>Assosa</td>
<td>Assosa</td>
<td>Single: maize</td>
<td>rainfed</td>
<td>170</td>
<td>880</td>
<td>850</td>
</tr>
<tr>
<td>Ayira</td>
<td>Ayira</td>
<td>Single: maize</td>
<td>rainfed</td>
<td>145-180</td>
<td>830</td>
<td>800</td>
</tr>
<tr>
<td>Bahir Dar</td>
<td>Bahir Dar</td>
<td>Single: maize</td>
<td>rainfed</td>
<td>130</td>
<td>650</td>
<td>440</td>
</tr>
<tr>
<td>bako</td>
<td>Bako</td>
<td>Single: maize</td>
<td>rainfed</td>
<td>160</td>
<td>790</td>
<td>710</td>
</tr>
<tr>
<td>Butajira</td>
<td>Butajira</td>
<td>Single: maize</td>
<td>rainfed</td>
<td>160</td>
<td>650</td>
<td>580</td>
</tr>
<tr>
<td>Debre Markos</td>
<td>Debre markos</td>
<td>Single: maize</td>
<td>rainfed</td>
<td>160</td>
<td>570</td>
<td>390</td>
</tr>
<tr>
<td>Gelemso</td>
<td>Gelemso</td>
<td>Single: maize</td>
<td>rainfed</td>
<td>140</td>
<td>770</td>
<td>660</td>
</tr>
<tr>
<td>Gore</td>
<td>Gore</td>
<td>Single: maize</td>
<td>rainfed</td>
<td>145-180</td>
<td>720</td>
<td>580</td>
</tr>
<tr>
<td>Haramaya or Alemaya</td>
<td>Haramaya</td>
<td>Single: maize</td>
<td>rainfed</td>
<td>160</td>
<td>640</td>
<td>570</td>
</tr>
<tr>
<td>Harar</td>
<td>Harar</td>
<td>Single: maize</td>
<td>rainfed</td>
<td>150</td>
<td>730</td>
<td>610</td>
</tr>
<tr>
<td>Jimma</td>
<td>Jimma</td>
<td>Single: maize</td>
<td>rainfed</td>
<td>160</td>
<td>770</td>
<td>710</td>
</tr>
<tr>
<td>kulumsa</td>
<td>Kulumsa</td>
<td>Single: maize</td>
<td>rainfed</td>
<td>170</td>
<td>550</td>
<td>360</td>
</tr>
<tr>
<td>melkassa</td>
<td>melkassa</td>
<td>Single: maize</td>
<td>rainfed</td>
<td>120</td>
<td>780</td>
<td>530</td>
</tr>
<tr>
<td>Nekemte</td>
<td>Nekemte</td>
<td>Single: maize</td>
<td>rainfed</td>
<td>160</td>
<td>680</td>
<td>500</td>
</tr>
<tr>
<td>Pawe</td>
<td>Pawe</td>
<td>Single: maize</td>
<td>rainfed</td>
<td>170</td>
<td>1100</td>
<td>1250</td>
</tr>
<tr>
<td>Shambu</td>
<td>Shambu</td>
<td>Single: maize</td>
<td>rainfed</td>
<td>150</td>
<td>510</td>
<td>410</td>
</tr>
<tr>
<td>Shire Endasilasse</td>
<td>Shire Endasilasse</td>
<td>Single: maize</td>
<td>rainfed</td>
<td>85-120</td>
<td>560</td>
<td>350</td>
</tr>
<tr>
<td>Woliso</td>
<td>Woliso</td>
<td>Single: maize</td>
<td>rainfed</td>
<td>180</td>
<td>720</td>
<td>720</td>
</tr>
<tr>
<td>Wolkite</td>
<td>Wolkite</td>
<td>Single: maize</td>
<td>rainfed</td>
<td>145-180</td>
<td>800</td>
<td>850</td>
</tr>
<tr>
<td>Adet</td>
<td>Adet</td>
<td>Single: finger millet</td>
<td>rainfed</td>
<td>175</td>
<td>650</td>
<td>620</td>
</tr>
<tr>
<td>Assosa</td>
<td>Asosa</td>
<td>Single: finger millet</td>
<td>rainfed</td>
<td>160</td>
<td>790</td>
<td>790</td>
</tr>
<tr>
<td>Ayira</td>
<td>Ayira</td>
<td>Single: finger millet</td>
<td>rainfed</td>
<td>140-153</td>
<td>750</td>
<td>670</td>
</tr>
<tr>
<td>Bahir Dar</td>
<td>Bahir dar</td>
<td>Single: finger millet</td>
<td>rainfed</td>
<td>130</td>
<td>620</td>
<td>430</td>
</tr>
<tr>
<td>Location</td>
<td>Location</td>
<td>Crop Type</td>
<td>Method</td>
<td>Yield</td>
<td>Harvested Yield</td>
<td>Production</td>
</tr>
<tr>
<td>-------------------</td>
<td>-------------------</td>
<td>-------------------</td>
<td>------------</td>
<td>----------</td>
<td>-----------------</td>
<td>------------</td>
</tr>
<tr>
<td>Dire Dawa</td>
<td>Dire Dawa</td>
<td>Single: finger millet</td>
<td>rainfed</td>
<td>130</td>
<td>950</td>
<td>1000</td>
</tr>
<tr>
<td>Gelemso</td>
<td>Gelemso</td>
<td>Single: finger millet</td>
<td>rainfed</td>
<td>150</td>
<td>800</td>
<td>750</td>
</tr>
<tr>
<td>Gonder</td>
<td>Gonder</td>
<td>Single: finger millet</td>
<td>rainfed</td>
<td>120</td>
<td>600</td>
<td>430</td>
</tr>
<tr>
<td>Gore</td>
<td>Gore</td>
<td>Single: finger millet</td>
<td>rainfed</td>
<td>130-145</td>
<td>600</td>
<td>460</td>
</tr>
<tr>
<td>Kobo</td>
<td>Kobo</td>
<td>Single: finger millet</td>
<td>rainfed</td>
<td>110</td>
<td>790</td>
<td>670</td>
</tr>
<tr>
<td>melkassa</td>
<td>melkassa</td>
<td>Single: finger millet</td>
<td>rainfed</td>
<td>120</td>
<td>560</td>
<td>400</td>
</tr>
<tr>
<td>Nekemte</td>
<td>Nekemte</td>
<td>Single: finger millet</td>
<td>rainfed</td>
<td>150</td>
<td>580</td>
<td>500</td>
</tr>
<tr>
<td>Pawe</td>
<td>Pawe</td>
<td>Single: finger millet</td>
<td>rainfed</td>
<td>160</td>
<td>970</td>
<td>1000</td>
</tr>
<tr>
<td>Shambu</td>
<td>Shambu</td>
<td>Single: finger millet</td>
<td>rainfed</td>
<td>150</td>
<td>500</td>
<td>400</td>
</tr>
<tr>
<td>Shire Endasilasse</td>
<td>Shire Endasilasse</td>
<td>Single: finger millet</td>
<td>rainfed</td>
<td>130-145</td>
<td>650</td>
<td>660</td>
</tr>
<tr>
<td>eth_rfzm5</td>
<td>eth_rfzm5</td>
<td>Single: finger millet</td>
<td>rainfed</td>
<td>155</td>
<td>640</td>
<td>500</td>
</tr>
<tr>
<td>eth_rfwt1</td>
<td>eth_rfwt1</td>
<td>Single: finger millet</td>
<td>rainfed</td>
<td>140</td>
<td>570</td>
<td>380</td>
</tr>
<tr>
<td>Asossa</td>
<td>Asossa</td>
<td>Single: sorghum</td>
<td>rainfed</td>
<td>150</td>
<td>780</td>
<td>720</td>
</tr>
<tr>
<td>Bahir Dar</td>
<td>Bahir Dar</td>
<td>Single: sorghum</td>
<td>rainfed</td>
<td>130</td>
<td>580</td>
<td>510</td>
</tr>
<tr>
<td>Butajira</td>
<td>Butajira</td>
<td>Single: sorghum</td>
<td>rainfed</td>
<td>140</td>
<td>560</td>
<td>510</td>
</tr>
<tr>
<td>Gelemso</td>
<td>Gelemso</td>
<td>Single: sorghum</td>
<td>rainfed</td>
<td>150</td>
<td>750</td>
<td>800</td>
</tr>
<tr>
<td>Gonder</td>
<td>Gonder</td>
<td>Single: sorghum</td>
<td>rainfed</td>
<td>120</td>
<td>590</td>
<td>510</td>
</tr>
<tr>
<td>Gore</td>
<td>Gore</td>
<td>Single: sorghum</td>
<td>rainfed</td>
<td>145-180</td>
<td>660</td>
<td>660</td>
</tr>
<tr>
<td>Haramaya or Alemaya</td>
<td>Haramaya</td>
<td>Single: sorghum</td>
<td>rainfed</td>
<td>150</td>
<td>600</td>
<td>540</td>
</tr>
<tr>
<td>Harar</td>
<td>Harar</td>
<td>Single: sorghum</td>
<td>rainfed</td>
<td>150</td>
<td>680</td>
<td>660</td>
</tr>
<tr>
<td>Jijiga</td>
<td>Jijiga</td>
<td>Single: sorghum</td>
<td>rainfed</td>
<td>120</td>
<td>680</td>
<td>660</td>
</tr>
<tr>
<td>Kobo</td>
<td>Kobo</td>
<td>Single: sorghum</td>
<td>rainfed</td>
<td>110</td>
<td>770</td>
<td>710</td>
</tr>
<tr>
<td>Kombolacha</td>
<td>Kombolacha</td>
<td>Single: sorghum</td>
<td>rainfed</td>
<td>130</td>
<td>680</td>
<td>640</td>
</tr>
<tr>
<td>melkassa</td>
<td>melkassa</td>
<td>Single: sorghum</td>
<td>rainfed</td>
<td>120</td>
<td>710</td>
<td>630</td>
</tr>
<tr>
<td>Nekemte</td>
<td>Nekemte</td>
<td>Single: sorghum</td>
<td>rainfed</td>
<td>150</td>
<td>630</td>
<td>560</td>
</tr>
<tr>
<td>Pawe</td>
<td>Pawe</td>
<td>Single: sorghum</td>
<td>rainfed</td>
<td>150</td>
<td>950</td>
<td>950</td>
</tr>
<tr>
<td>Shambu</td>
<td>Shambu</td>
<td>Single: sorghum</td>
<td>rainfed</td>
<td>190</td>
<td>540</td>
<td>620</td>
</tr>
<tr>
<td>Shire Endasilasse</td>
<td>Shire Endasilasse</td>
<td>Single: sorghum</td>
<td>rainfed</td>
<td>85-120</td>
<td>500</td>
<td>410</td>
</tr>
<tr>
<td>Woliso</td>
<td>Woliso</td>
<td>Single: sorghum</td>
<td>rainfed</td>
<td>185</td>
<td>740</td>
<td>740</td>
</tr>
<tr>
<td>Wolkite</td>
<td>Wolkite</td>
<td>Single: sorghum</td>
<td>rainfed</td>
<td>160-200</td>
<td>880</td>
<td>980</td>
</tr>
<tr>
<td>eth_rfzm5</td>
<td>eth_rfzm5</td>
<td>Single: sorghum</td>
<td>rainfed</td>
<td>140</td>
<td>540</td>
<td>490</td>
</tr>
<tr>
<td>eth_rfso3</td>
<td>mieso</td>
<td>Single: sorghum</td>
<td>rainfed</td>
<td>110</td>
<td>630</td>
<td>560</td>
</tr>
<tr>
<td>Adet</td>
<td>Adet</td>
<td>Single: wheat</td>
<td>rainfed</td>
<td>150</td>
<td>1310</td>
<td>1160</td>
</tr>
<tr>
<td>Ambo</td>
<td>Ambo</td>
<td>Single: wheat</td>
<td>rainfed</td>
<td>150</td>
<td>1330</td>
<td>1180</td>
</tr>
<tr>
<td>Ayira</td>
<td>Ayira</td>
<td>Single: wheat</td>
<td>rainfed</td>
<td>120-140</td>
<td>1300</td>
<td>1150</td>
</tr>
<tr>
<td>Butajira</td>
<td>Butajira</td>
<td>Single: wheat</td>
<td>rainfed</td>
<td>130</td>
<td>1130</td>
<td>1000</td>
</tr>
<tr>
<td>Debre Zeit</td>
<td>Debre Zeit</td>
<td>Single: wheat</td>
<td>rainfed</td>
<td>130</td>
<td>1150</td>
<td>1020</td>
</tr>
<tr>
<td>kulumsa</td>
<td>Kulumsa</td>
<td>Single: wheat</td>
<td>rainfed</td>
<td>140</td>
<td>1050</td>
<td>940</td>
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<tr>
<td>mekele</td>
<td>Mekele</td>
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<td>rainfed</td>
<td>120</td>
<td>1080</td>
<td>950</td>
</tr>
<tr>
<td>melkassa</td>
<td>melkassa</td>
<td>Single: wheat</td>
<td>rainfed</td>
<td>120</td>
<td>1210</td>
<td>1080</td>
</tr>
<tr>
<td>Sheno</td>
<td>Sheno</td>
<td>Single: wheat</td>
<td>rainfed</td>
<td>140</td>
<td>890</td>
<td>790</td>
</tr>
<tr>
<td>Woliso</td>
<td>Woliso</td>
<td>Single: wheat</td>
<td>rainfed</td>
<td>145</td>
<td>1300</td>
<td>1150</td>
</tr>
<tr>
<td>eth_rfwt2</td>
<td>Bekoji</td>
<td>Single: wheat</td>
<td>rainfed</td>
<td>145</td>
<td>1200</td>
<td>1060</td>
</tr>
</tbody>
</table>
3.3.2. Initialization of available soil moisture for simulation with WOFOST

For the single cropping systems (i.e. one crop grown per year) the simulation of the soil water balance has been started 90 days before the sowing date and thus generally in the dry season. 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: \(0.33 \times (\text{SMFC}-\text{SMWP})\)).

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°Cd 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 Ethiopia.

<table>
<thead>
<tr>
<th>Weather station</th>
<th>Crop 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>Adet</td>
<td>single</td>
<td>Rainfed</td>
<td>100%</td>
<td>7-May</td>
<td>180</td>
<td>1470</td>
<td>50</td>
<td>80</td>
</tr>
<tr>
<td>Ambo</td>
<td>single</td>
<td>Rainfed</td>
<td>100%</td>
<td>1-May</td>
<td>200</td>
<td>1650</td>
<td>25</td>
<td>80</td>
</tr>
<tr>
<td>Arbaminch</td>
<td>single</td>
<td>Rainfed</td>
<td>100%</td>
<td>7 Apr</td>
<td>135</td>
<td>1800</td>
<td>25</td>
<td>48</td>
</tr>
<tr>
<td>Areka</td>
<td>single</td>
<td>Rainfed</td>
<td>100%</td>
<td>25-Mar</td>
<td>150</td>
<td>1420</td>
<td>75</td>
<td>53</td>
</tr>
<tr>
<td>Arse-Negele</td>
<td>single</td>
<td>Rainfed</td>
<td>100%</td>
<td>25 Apr</td>
<td>130</td>
<td>1080</td>
<td>50</td>
<td>80</td>
</tr>
<tr>
<td>Asebe Teferi</td>
<td>single</td>
<td>Rainfed</td>
<td>100%</td>
<td>15 Apr</td>
<td>130</td>
<td>1530</td>
<td>50</td>
<td>53</td>
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<tr>
<td>Assosa</td>
<td>single</td>
<td>Rainfed</td>
<td>100%</td>
<td>1-May</td>
<td>170</td>
<td>1750</td>
<td>75</td>
<td>80</td>
</tr>
<tr>
<td>Ayira</td>
<td>single</td>
<td>Rainfed</td>
<td>100%</td>
<td>15 Apr</td>
<td>162.5</td>
<td>1750</td>
<td>75</td>
<td>80</td>
</tr>
<tr>
<td>Bahir Dar bako</td>
<td>single</td>
<td>Rainfed</td>
<td>100%</td>
<td>1-May</td>
<td>130</td>
<td>1200</td>
<td>75</td>
<td>80</td>
</tr>
<tr>
<td>Butajira</td>
<td>single</td>
<td>Rainfed</td>
<td>100%</td>
<td>25 Apr</td>
<td>160</td>
<td>1320</td>
<td>75</td>
<td>80</td>
</tr>
<tr>
<td>Debre Markos</td>
<td>single</td>
<td>Rainfed</td>
<td>100%</td>
<td>7 Apr</td>
<td>168</td>
<td>1090</td>
<td>75</td>
<td>80</td>
</tr>
<tr>
<td>Gelemso</td>
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<td>Rainfed</td>
<td>100%</td>
<td>1-May</td>
<td>140</td>
<td>1540</td>
<td>25</td>
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<tr>
<td>Gore</td>
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<td>Rainfed</td>
<td>100%</td>
<td>15 Apr</td>
<td>162.5</td>
<td>1400</td>
<td>75</td>
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</tr>
<tr>
<td>Haramay A or Alemaya</td>
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<td>Rainfed</td>
<td>100%</td>
<td>25 Apr</td>
<td>160</td>
<td>1320</td>
<td>50</td>
<td>71</td>
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<tr>
<td>Harar</td>
<td>single</td>
<td>Rainfed</td>
<td>100%</td>
<td>15 Apr</td>
<td>150</td>
<td>1420</td>
<td>50</td>
<td>66</td>
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<tr>
<td>Jimma</td>
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<td>Rainfed</td>
<td>100%</td>
<td>7 Apr</td>
<td>160</td>
<td>1580</td>
<td>75</td>
<td>80</td>
</tr>
<tr>
<td>kulumsa</td>
<td>single</td>
<td>Rainfed</td>
<td>100%</td>
<td>21 Apr</td>
<td>185</td>
<td>1090</td>
<td>50</td>
<td>62</td>
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<tr>
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<td>Rainfed</td>
<td>100%</td>
<td>1-Jul</td>
<td>120</td>
<td>1320</td>
<td>50</td>
<td>67</td>
</tr>
<tr>
<td>Nekemte</td>
<td>single</td>
<td>Rainfed</td>
<td>100%</td>
<td>30-May</td>
<td>160</td>
<td>1260</td>
<td>50</td>
<td>80</td>
</tr>
<tr>
<td>Pave</td>
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<td>Rainfed</td>
<td>100%</td>
<td>1-May</td>
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<td>1000</td>
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<tr>
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<td>100%</td>
<td>15-Jun</td>
<td>103</td>
<td>1050</td>
<td>75</td>
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<tr>
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<td>7 Apr</td>
<td>180</td>
<td>1540</td>
<td>75</td>
<td>80</td>
</tr>
<tr>
<td>Wolkite</td>
<td>single</td>
<td>Rainfed</td>
<td>100%</td>
<td>21 Apr</td>
<td>163</td>
<td>1780</td>
<td>50</td>
<td>80</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 reported soils for each site).

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-SOFFILE-CRFILE-IDSOW-ISYR (=year) given in Appendix C) in Ethiopia have been done for both potential and water limited conditions, to indicate the degree that yield levels may increase by application of irrigation water.

Grain crop production systems in Ethiopia are mainly rain fed, except for the zones Metehara and Werer (Table 5). Hence, the simulated, mainly water limited yields (Yw) have been used to calculate the yield gap. The mean simulated yield values per crop type per RWS buffer zone were calculated from the yield values simulated for each crop type-sowing date-water regime-soil type combination per buffer zone, weighted to their relative areas.

Next, the yield gap per buffer zone is calculated as the difference between the mean simulated yield value per buffer zone and the mean actual yield per buffer zone. Note that the time period of the actual yields and that of the simulated yields is partly different (i.e. mean of actual yields based on yields from 2005 up to and including 2011 (2009 and 2010 missing) and mean of simulated yields based on simulations for the available weather data between 1998 and 2012).

5. References


Appendices

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

Table 8. 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>
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</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 Ethiopia

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-TT.
** ** 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
TRASEM = 12.0 ! lower threshold temp. for emergence [cel]
TEFFMX = 32.0 ! max. eff. temp. for emergence [cel]
TSUMM = 60. ! temperature sum from sowing to emergence [cel d]

** phenology
IDSL = 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 = 850. ! temperature sum from emergence to anthesis [cel d]
TSUM2 = 630. ! temperature sum from anthesis to maturity [cel d]
DTSMTB = 0.00, 0.00, 10.00, 0.00, 27.00, 17.00, 35.00, 17.00, 45.00, 0.00
DVSI = 0. ! initial DVS
DVSEND = 2.00 ! development stage at harvest (= 2.0 at maturity [-])

** initial
TDWI = 3.00 ! initial total crop dry weight [kg ha-1]
** ! Not used as input by WOF6_0 model
LAEM = 0.004512 ! leaf area index at emergence [ha ha-1]
RGLAI = 0.0500 ! maximum relative increase in LAI [ha ha-1 d-1]

** green area
SLATB = 0.00, 0.0018, ! specific leaf area
0.40, 0.0020, ! as a function of DVS [-; ha kg-1]
0.85, 0.0019,
2.00, 0.0019

SPA = 0.000 ! 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]

TBASE = 10.0 ! lower threshold temp. for ageing of leaves [cel]

** assimilation
KDFPFB = 0.0, 0.50, ! extinction coefficient for diffuse visible light [-]
2.0, 0.50, ! as function of DVS

EFFTB = 0.0, 0.50, ! light-use effic. single leaf [kg ha-1 hr-1 m2 s]
40.0, 0.50, ! as function of daily mean temp.

AMAXTB = 0.00, 50.00, ! max. leaf CO2 assim. rate
** File Sorg-med-ETh-GYGA.CAB

---

** CROP DATA FILE for use with WOFOST Version 7.0

---

** Sorghum medium duration

---

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
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</tr>
<tr>
<td>CVO</td>
<td>0.730</td>
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</tr>
<tr>
<td>CVR</td>
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<tr>
<td>CVS</td>
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<tr>
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</tr>
<tr>
<td>FRTB</td>
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</tr>
<tr>
<td>FLTB</td>
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<td></td>
</tr>
<tr>
<td>FSTB</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>FOTB</td>
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<tr>
<td>PERDL</td>
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<tr>
<td>RDI</td>
<td>10.</td>
<td>cm</td>
</tr>
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<td>KRI</td>
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<tr>
<td>RMCR</td>
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<td>cm</td>
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</table>

---

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

<table>
<thead>
<tr>
<th>Nutrient</th>
<th>Minimum</th>
<th>Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
<td>0.0010</td>
<td>0.0032</td>
</tr>
<tr>
<td>P</td>
<td>0.0030</td>
<td>0.0085</td>
</tr>
<tr>
<td>K</td>
<td>0.0014</td>
<td>0.0080</td>
</tr>
</tbody>
</table>

---

** maximum amount veg. organs at zero yield [kg ha-1]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>YZERO</td>
<td>200</td>
<td></td>
</tr>
</tbody>
</table>

---

** fraction of N-uptake from biol. fixation [kg kg-1]

** Some changes included for Sorghum (medium duration) for Ethiopia for global yield gap atlas

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

** phenology
IDSL = 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]

** green area
SLATB = 0.00, 0.0020, ! specific leaf area 1.00, 0.0020, ! as a function of DVS [--; ha kg-1]
SPA = 0.000 ! 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

** assimilation
KDIFTB = 0.0, 0.70, ! extinction coefficient for diffuse visible light [--; ha kg-1]
EFFTB = 0.0, 0.50, ! light-use effic. single leaf [kg ha-1 hr-1 m2 s] 40.0, 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; -]
18.00, 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. [-]
RMH = 0.0300 ! rel. maint. resp. rate leaves [kg CH2O kg-1 d-1]
RMR = 0.0100 ! rel. maint. resp. rate sto.r.org. [kg CH2O kg-1 d-1]
RMS = 0.0150 ! rel. maint. resp. rate stools [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]
FSATB = 0.00, 0.35, 0.60, 0.20, 0.80, 0.15, 1.00, 0.05, 1.10, 0.00, 2.00, 0.00
FLTB = 0.00, 1.00, ! fraction of above-gr. DM to leaves
0.40, 0.80, ! as a function of DVS [-; kg kg⁻¹]
0.60, 0.60,
0.80, 0.30,
1.00, 0.00,
1.20, 0.00,
2.00, 0.00
FSTB = 0.00, 0.00, ! fraction of above-gr. DM to stems
0.40, 0.20, ! as a function of DVS [-; kg kg⁻¹]
0.60, 0.40,
0.80, 0.70,
1.00, 1.00,
1.20, 0.85,
1.30, 0.09,
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]
1.20, 0.15,
1.30, 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
CPET = 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
RDI = 10. ! initial rooting depth [cm]
RRI = 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 ! in vegetative organs [kg kg⁻¹]
NMINSO = 0.0100 ; NMINVE = 0.0035
NMAXSO = 0.0320 ; NMAXVE = 0.0120
PMINSO = 0.0014 ; PMINVE = 0.0005
PMAXSO = 0.0060 ; PMAXVE = 0.0025
KMINSO = 0.0025 ; KMINVE = 0.0070
KMAXSO = 0.0075 ; 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]

Wheat medium duration

** File WHE-med-Eth-GYGA.CAB
** CROP DATA FILE for use with WOFOST for Ethiopia
** WHEAT, SPRING Medium variety, Ethiopia
** Calibrated for use in WOFOST 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
IDSL = 0.0 ! 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]
DTSUMTH = 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
TDWI = 60.00 ! initial total crop dry weight [kg ha⁻¹]

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LAIEM = 0.053  ! leaf area index at emergence [ha ha^{-1}]
RGLRAI = 0.0090 ! maximum relative increase in LAI [ha ha^{-1} d^{-1}]

** green area
SLATB = 0.00, 0.0022, ! specific leaf area
0.30, 0.0022, ! as a function of DVS [-; ha kg^{-1}]
0.90, 0.0022,
1.45, 0.0022,
2.00, 0.0022
SPA = 0.000 ! 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 = 40. ! life span of leaves growing at 35 Celsius [d]
TBASE = 0.0 ! lower threshold temp. for ageing of leaves [cel]

** assimilation
KDIFTB = 0.0, 0.60, ! extinction coefficient for diffuse visible light [-]
2.0, 0.60 ! as function of DVS
EFFTB = 0.0, 0.40, ! light-use effic. single leaf [kg ha^{-1} hr^{-1} m^{-2} s]
40.0, 0.40 ! as function of daily mean temp.
AMAXTB = 0.00, 35.00, ! max. leaf CO2 assim. rate
1.20, 35.00, ! function of DVS [-; kg ha^{-1} hr^{-1}]
2.00, 5.00
TMPFTB = 0.00, 0.00, ! reduction factor of AMAX
10.00, 1.00, ! as function of av. temp. [cel;]
30.00, 1.00,
35.00, 0.00
TMNFTB = 0.00, 0.00, ! red. factor of gross assim. rate
3.00, 1.00 ! as function of low min. temp. [cel;]
40.0, 0.40 ! as function of daily mean temp.

** partitioning
FRTB = 0.00, 0.60, ! fraction of total dry matter to roots
0.40, 0.55, ! as a function of DVS [-; kg kg^{-1}]
1.00, 0.00,
2.00, 0.00
FLTB = 0.00, 1.00, ! fraction of above-gr. DM to leaves
0.33, 1.00, ! as a function of DVS [-; kg kg^{-1}]
0.80, 0.10,
1.00, 0.10,
1.01, 0.00,
2.00, 0.00
FSTB = 0.00, 0.00, ! fraction of above-gr. DM to stems
0.33, 0.00, ! as a function of DVS [-; kg kg^{-1}]
0.80, 0.60,
1.00, 0.90,
1.01, 0.15,
2.00, 0.00
FOTB = 0.00, 0.00, ! fraction of above-gr. DM to stor. org.
0.33, 0.00, ! as a function of DVS [-; kg kg^{-1}]
0.80, 0.60,
1.00, 0.90,
1.01, 0.15,
2.00, 0.00

** water use
CFET = 1.00 ! 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)

** death rates
PERDL = 0.030 ! max. rel. death rate of leaves due to water stress
RDRRTB = 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, 0.000,
2.00, 0.020
RDRSTB = 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, 0.000,
2.00, 0.020

** root growth
RDI = 10. ! initial rooting depth [cm]
RRI = 2. ! 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 Ethiopia

Millet  
RUNNAM='1'; 
CRPNAM='Millet for YIELD GAP calcul.';  
CRFILE='MILL-med-Eth-GYGA.CAB'; 
CLFILE='Eth0.1';  
ISYR =1998; 
INYEAR =1; 
IDSON=135; 
ISDAY=75; 
TSM1=650.; 
TSM2=620.; 
IDURNX=200; 
SMX=0.100; 
SMFCF=0.140; 
RDMSOL=40.; 
NOTINF=0.067; 
WAV=0.5; 
RUNNAM='2'; 
CRPNAM='Millet for YIELD GAP calcul.1';  
CRFILE='MILL-med-Eth-GYGA.CAB'; 
CLFILE='Eth0.1'; 
ISYR =1998; 
INYEAR =1; 
IDSON=135; 
ISDAY=75; 
TSM1=650.; 
TSM2=620.; 
IDURNX=200; 
SMX=0.100; 
SMFCF=0.150; 
RDMSOL=40.; 
NOTINF=0.067; 
WAV=0.7; 
RUNNAM='3'; 
CRPNAM='Millet for YIELD GAP calcul.1';  
CRFILE='MILL-med-Eth-GYGA.CAB'; 
CLFILE='Eth0.1'; 
ISYR =1998; 
INYEAR =1; 
IDSON=135; 
ISDAY=75; 
TSM1=650.; 
TSM2=620.; 
IDURNX=200; 
SMX=0.100; 
SMFCF=0.160; 
RDMSOL=40.; 
NOTINF=0.067; 
WAV=0.8; 
RUNNAM='4'; 
CRPNAM='Millet for YIELD GAP calcul.1';  
CRFILE='MILL-med-Eth-GYGA.CAB'; 
CLFILE='Eth0.1'; 
ISYR =1998; 
INYEAR =1; 
IDSON=135; 
ISDAY=75; 
TSM1=650.; 
TSM2=620.; 
IDURNX=200; 
SMX=0.100; 
SMFCF=0.170; 
RDMSOL=40.; 
NOTINF=0.067; 
WAV=0.8; 
RUNNAM='5'; 
CRPNAM='Millet for YIELD GAP calcul.1';
CRFILE='MILL-med-Eth-GYGA.CAB';
CLFILE='Eth0.';
ISYR =1998;
INYEAR =1;
IDSOW=135;
ISDAY=75;
TSUM1=650.;
TSUM2=620.;
IDURMX=200;
SMW=0.100;
SMFCF=0.180;
RDMSOL=40.;
NOTINF=0.067;
WAV=1.1.
Etc.

Sorghum
RUNNAM='1';
CRPNAM='Sorghum for YIELD GAP calcul.';
CRFILE='SORG-med-Eth-GYGA.CAB';
CLFILE='Eth6.';
ISYR =1998;
INYEAR =1;
IDSOW=152;
ISDAY=92;
TSUM1=780.;
TSUM2=720.;
IDURMX=200;
SMW=0.100;
SMFCF=0.140;
RDMSOL=40.;
NOTINF=0.067;
WAV=0.5.
RUNNAM='2';
CRPNAM='Sorghum for YIELD GAP calcul.';
CRFILE='SORG-med-Eth-GYGA.CAB';
CLFILE='Eth6.';
ISYR =1998;
INYEAR =1;
IDSOW=152;
ISDAY=92;
TSUM1=780.;
TSUM2=720.;
IDURMX=200;
SMW=0.100;
SMFCF=0.150;
RDMSOL=40.;
NOTINF=0.067;
WAV=0.7.
RUNNAM='3';
CRPNAM='Sorghum for YIELD GAP calcul.';
CRFILE='SORG-med-Eth-GYGA.CAB';
CLFILE='Eth6.';
ISYR =1998;
INYEAR =1;
IDSOW=152;
ISDAY=92;
TSUM1=780.;
TSUM2=720.;
IDURMX=200;
SMW=0.100;
SMFCF=0.160;
RDMSOL=40.;
NOTINF=0.067;
WAV=0.8.
RUNNAM='4';
CRPNAM='Sorghum for YIELD GAP calcul.';
CRFILE='SORG-med-Eth-GYGA.CAB';
CLFILE='Eth6.';
ISYR =1998;
INYEAR =1;
IDSOW=152;
ISDAY=92;
TSUM1=780.;
TSUM2=720.;
IDURMX=200;
SMW=0.100;
SMFCF=0.170;
RDMSOL=40.;
NOTINF=0.067;
WAV=0.9.
RUNNAM='5';
CRPNAM='Sorghum for YIELD GAP calcul.';
CRFILE='SORG-med-Eth-GYGA.CAB';
CLFILE='Eth6.';
ISYR =1998;

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**Wheat**

RUNNAME='1';
CRPNAM='Wheat for YIELD GAP calcul.,'
CRFILE='WHE-med-Eth-GYGA.CAB';
CLFILE='Eth0.,'
ISYR =1998;
INYEAR =1;
IDSOW=166;
ISDAY=106;
TSUM1=1310.;
TSUM2=1160.;
IDURMX=200;
SMW=0.100;
SMFCF=0.140;
RDMSOL=40.;
NOTINF=0.067;
WAV=0.7;
RUNNAME='2';
CRPNAM='Wheat for YIELD GAP calcul.,'
CRFILE='WHE-med-Eth-GYGA.CAB';
CLFILE='Eth0.,'
ISYR =1998;
INYEAR =1;
IDSOW=166;
ISDAY=106;
TSUM1=1310.;
TSUM2=1160.;
IDURMX=200;
SMW=0.100;
SMFCF=0.150;
RDMSOL=40.;
NOTINF=0.067;
WAV=0.8;
RUNNAME='3';
CRPNAM='Wheat for YIELD GAP calcul.,'
CRFILE='WHE-med-Eth-GYGA.CAB';
CLFILE='Eth0.,'
ISYR =1998;
INYEAR =1;
IDSOW=166;
ISDAY=106;
TSUM1=1310.;
TSUM2=1160.;
IDURMX=200;
SMW=0.100;
SMFCF=0.160;
RDMSOL=40.;
NOTINF=0.067;
WAV=0.9;
RUNNAME='4';
CRPNAM='Wheat for YIELD GAP calcul.,'
CRFILE='WHE-med-Eth-GYGA.CAB';
CLFILE='Eth0.,'
ISYR =1998;
INYEAR =1;
IDSOW=166;
ISDAY=106;
TSUM1=1310.;
TSUM2=1160.;
IDURMX=200;
SMW=0.100;
SMFCF=0.170;
RDMSOL=40.;
NOTINF=0.067;
WAV=0.9;
RUNNAME='5';
CRPNAM='Wheat for YIELD GAP calcul.,'
CRFILE='WHE-med-Eth-GYGA.CAB';
CLFILE='Eth0.,'
ISYR =1998;
INYEAR =1;
IDSOW=166;
ISDAY=106;
TSUM1=1310.;
TSUM2=1160.;
IDNUMX=200;
SMW=0.100;
SMFCF=0.180;
ROMSG1=40.;
NOTINF=0.067;
WAV=1.1;
Etc.
Appendix D Relationship between maize planting density and seasonal water deficit as observed in the US Corn Belt

Figure 2. 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. 