Supplementary information supporting the paper: Warnatzsch et al. (2020) Climate Change Impact on Aflatoxin Contamination Risk in Malawi's Maize Crops.

Supplementary Tables

Table 1: Aflatoxin (AF) contamination of food commodities in Malawi compared to European Union (EU) regulated levels (Commission, 2006, Commission, 2010) (table adapted from Misihairabgwi et al. (2017)). NS: Not Stated

Food Commodity	Toxin	Positive samples (%)	Mean (µg/kg) [Range]	EU Regulation (µg/kg)	Source
Maize based beers from Tribal (chewa) rituals and commercial village brewers	AF	89	90 ± 96 [NS]	4	(Matumba et al., 2014c)
Maize Puffs sold in retail markets	AF	75	1.1 [0.3-2.0]	4	(Matumba et al., 2014b)
Instant maize-based baby cereals sold in local markets	AF	100	2.5 [0.5-10.4]	0.1	(Matumba et al., 2014b)
Maize sold in farmsteads and local markets	AF	100	12 [5-20]	10	(Probst et al., 2014)
Maize from rural households	AF	100	8.3 ± 8.2 [0.7-140]	10	(Mwalwayo and Thole, 2016)
	AFB_1	45.3	1.71 ± 3.17 [NS]	5	(Matumba et al., 2009)

Table 2: Regional Climate Models (RCM) sources, the original calendar format, and the climatic variables used. All of the models other than CanRCM4_r2 were accessed through The Earth System Grid Federation (ESGF) data index (ESGF, 2017). The CanRCM4_r2 model was accessed through the Canadian Centre for Climate Modelling and Analysis website (CCCma, 2017).

RCM	Institution	Lateral Boundary Conditions	Climatic Variable	Original Calendar
CCLM4-8-17_v1 (COSMO, 2017)	Climate Limited-area Modelling Community (CLMcom)	CNRM-CM5 r1i1p1	Tas, Pr	365-days
		HadGEM2-ES r1i1p1		360-days
		EC-EARTH r12i1p1		366-days
		MPI-ESM-LR r1i1p1		366-days
HIRHAM5_v2 (Christensen et al, 2007)	Danmarks Meteorologiske Insitut (DMI)	EC-EARTH r3i1p1	Tas, Pr, Hurs	366-days
RACMO22T_v1 (van Meijgaard et al, 2008)	Koninklijk Nederlands Meteorologisch Instituut (KNMI)	HadGEM2-ES r1i1p1	Tas, Pr, Hurs	360-days
		EC-EARTH r1i1p1		366-days
RCA4_v1 (Samuelsson et al, 2015)	Sveriges Meteorologiska och Hydrologiska Institut (SMHI)	CanESM2 r1i1p1	Tas, Pr, Hurs	366-days
		CNRM-CM5 r1i1p1		366-days
		CSIRO-MK3-6-0 r1i1p1		365-days
		GFDL-ESM2M r1i1p1		365-days
		IPSL-CM5A-MR r1i1p1		365-days
		HadGEM2-ES r1i1p1		360-days
		EC-EARTH r12i1p1		366-days
		MIROC5 r1i1p1		365-days
		MPI-ESM-LR r1i1p1		366-days
		NORESM1-M r1i1p1		365-days
REMO2009_v1 (Jacob et al, 2012)	Climate Service Centre Germany (CSC) and Max Planck Institut (MPI)	EC-EARTH r12i1p1	Tas, Pr	366-days
		MPI-ESM-LR r1i1p1		366-days
CanRCM4_r2 (Scinocca et al, 2016)	Canadian Centre for Climate Modelling and Analysis (CCCma)	CanESM2 r1i1p1	Tas, Pr	365-days

Table 3: Observed data sources

Dataset	Variable Used	Resolution	Time-Period Available	Data Source
Climate Research Unit (CRU) version 4.0 (Harris et al, 2014)	Tas, TasMin, TasMax and Pr	0.5° Monthly Land Only	1901-2015	Gridded Station Data
University of Delaware (UDel) version 4.01 (Willmott & Matsuura, 2001)	Tas and Pr	0.5° Monthly Land Only	1901-2010	Gridded Station Data
Global Precipitation Climatology Centre (GPCC) version 7 (Schneider et al, 2015)	Pr	1.0° Monthly	1901-2010	Satellite and Station Data

Table 4: List of data sources for the climate files used in AquaCrop. Note that all RCMs referred to in this table are listed in

Table **1:** Aflatoxin (AF) contamination of food commodities in Malawi compared to European Union (EU) regulated levels (Commission, 2006, Commission, 2010) (table adapted from Misihairabgwi et al. (2017)). NS: Not Stated

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	AFB_1	45.3	1.71 ± 3.17 [NS]	5	(Matumba et al., 2009)

Table 2 and the observed data referred to in this table are from the sources listed in Table 2. Note also that a version of each of these climate files was created for the three regions of Malawi: Northern, Central and Southern. All climate data used in AquaCrop used a 365-day calendar averaged over the relevant time period.

<table>
<tr><th>File</th><th>Time Scale</th><th>RCP</th><th>Temperature</th><th>Reference Evapotrans-piration</th><th>Precipitation Rate</th><th>CO_2 Concentration</th></tr>
<tr><td>1</td><td>1971-2000</td><td>N/A</td><td>Mean of observed monthly data for minimum and maximum temperature</td><td rowspan="5">Calculated using methodology described in Section 2</td><td>Observed monthly data for precipitation rates</td><td>AquaCrop Mauna Loa CO_2</td></tr>
<tr><td>2</td><td rowspan="2">2020-2049</td><td>4.5</td><td rowspan="4">Projected ensemble mean daily minimum and maximum temperature</td><td rowspan="4">Projected ensemble mean precipitation rate</td><td>AquaCrop IPCC RCP 4.5</td></tr>
<tr><td>3</td><td>8.5</td><td>AquaCrop IPCC RCP 8.5</td></tr>
<tr><td>4</td><td rowspan="2">2040-2069</td><td>4.5</td><td>AquaCrop IPCC RCP 4.5</td></tr>
<tr><td>5</td><td>8.5</td><td>AquaCrop IPCC RCP 8.5</td></tr>
</table>

Table 5: List of data sources for the climate files used in AFLA-maize. Note that all hindcast and projected data referred to in this table are from the RCMs listed in

Table **1:** Aflatoxin (AF) contamination of food commodities in Malawi compared to European Union (EU) regulated levels (Commission, 2006, Commission, 2010) (table adapted from Misihairabgwi et al. (2017)). NS: Not Stated

Food Commodity	**Toxin**	**Positive samples (%)**	**Mean (μg/kg) [Range]**	**EU Regulation (μg/kg)**	**Source**
Maize based beers from Tribal (chewa) rituals and commercial village brewers	AF	89	90 ± 96 [NS]	4	(Matumba et al., 2014c)
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Maize sold in farmsteads and local markets	AF	100	12 [5-20]	10	(Probst et al., 2014)
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	AFB_1	45.3	1.71 ± 3.17 [NS]	5	(Matumba et al., 2009)

Table 2 and the observed data referred to in this table are from the sources listed in Table 2. Note also that a version of each of these climate files was created for the three regions of Malawi: Northern, Central and Southern. All climate data used in AFLA-maize used a 366-day calendar with daily results for each date and year (i.e. 365/366 days (depending on leap year) x 30 years for each scenario).

<table>
<tr><th>File</th><th>Time Scale</th><th>RCP</th><th>Temperature</th><th>Relative Humidity</th><th>Precipitation Rate</th><th>Leaf Wetness</th></tr>
<tr><td>1</td><td>1971-2000</td><td>N/A</td><td>Mean of observed monthly data for minimum and maximum temperature</td><td>Hindcasted ensemble mean daily relative humidity</td><td>Observed monthly data for precipitation rates</td><td rowspan="5">Calculated using methodology described in main paper (Section 4.1)</td></tr>
<tr><td>2</td><td rowspan="2">2020-2049</td><td>4.5</td><td rowspan="4">Projected ensemble mean daily minimum and maximum temperature</td><td rowspan="4">Projected ensemble mean daily relative humidity</td><td rowspan="4">Projected ensemble mean precipitation rate</td></tr>
<tr><td>3</td><td>8.5</td></tr>
<tr><td>4</td><td rowspan="2">2040-2069</td><td>4.5</td></tr>
<tr><td>5</td><td>8.5</td></tr>
</table>

Table 6: Calibration of individual maize varieties (Sutcliffe, 2014) compared with AquaCrop default values.

Parameter (in degree days)	AquaCrop Default	Fast-Development	Slow-Development
Emergence	80	60	98
Max Canopy	705	684	720
Senescence	1400	1008	1715
Maturity	1700	1332	2267
Length building up to Harvest Index (HI)	750	636	1140
Duration of flowering	180	132	220
Degree-Days for Flowering	880	636	1078
Time to maximum rooting depth	1409	1120	1722

Table 7: Common calibration of both maize varieties compared with AquaCrop default values.

Parameter		AquaCrop Default	Calibrated Maize	Reference
Initial Canopy Cover	Initial Plant Density (plants/ha)	75 000	47 000	(Wiyo et al, 1999)
Canopy Development	Maximum Canopy Cover (%)	96	75	(Fiwa, 2015)
Root Deepening	Maximum effective rooting depth (m)	2.3	0.6	
Harvest Index	Hio (%)	48	40	
Air Temperature Stresses	Base temperature (°C)	8	13	(Benson et al, 2016)
	Upper temperature (°C)	30	32	
Soil Salinity Stress - Salt tolerance	ECe lower threshold (dS/m)	2	4	adapted from (Benson et al, 2016)
	ECe upper threshold (dS/m)	10	9	
Crop response to soil fertility stress	Crop response to soil fertility stress	Not Considered	Considered	(Fiwa, 2015)
	Biomass Production (%)		69	
	Canopy Decline in Season		medium	
	Reduction of Canopy Expansion (%)		7	
	Average decline in Canopy Cover (%/day)		0.1	
	Reduction in water productivity (%)		47	

Table 8: Development Dates for the fast-development maize variety. The date of emergence and harvest dates are listed for each climatic scenario and time period, as well as the number of days after planting (DAP) those dates occur. The difference (Δ) between the development of the crop under historic climatic and future climatic conditions is also listed.

Sowing Date	Region	Climate Scenario	Emergence			Harvest		
			Date	DAP	Δ	Date	DAP	Δ
15 Nov.	Northern	1971-2000	21 Nov.	6	N/A	09 Apr.	145	N/A
		2020-2049 RCP 4.5	20 Nov.	5	-1	20 Mar.	126	-19
		2020-2049 RCP 8.5	20 Nov.	5	-1	19 Mar.	125	-20
		2040-2069 RCP 4.5	20 Nov.	5	-1	20 Mar.	126	-19
		2040-2069 RCP 8.5	20 Nov.	5	-1	19 Mar.	125	-20
	Central	1971-2000	20 Nov.	5	N/A	22 Mar.	127	N/A
		2020-2049 RCP 4.5	20 Nov.	5	0	07 Mar.	113	-14
		2020-2049 RCP 8.5	20 Nov.	5	0	05 Mar.	111	-16
		2040-2069 RCP 4.5	20 Nov.	5	0	07 Mar.	113	-14
		2040-2069 RCP 8.5	20 Nov.	5	0	05 Mar.	111	-16
	Southern	1971-2000	20 Nov.	5	N/A	04 Mar.	109	N/A
		2020-2049 RCP 4.5	20 Nov.	5	0	22 Feb.	99	-10
		2020-2049 RCP 8.5	20 Nov.	5	0	21 Feb.	98	-11
		2040-2069 RCP 4.5	20 Nov.	5	0	22 Feb.	99	-10
		2040-2069 RCP 8.5	20 Nov.	5	0	21 Feb.	98	-11
10 Dec.	Northern	1971-2000	17 Dec.	7	N/A	12 May	153	N/A
		2020-2049 RCP 4.5	16 Dec.	6	-1	19 Apr.	131	-22
		2020-2049 RCP 8.5	16 Dec.	6	-1	16 Apr.	128	-25
		2040-2069 RCP 4.5	16 Dec.	6	-1	19 Apr.	131	-22
		2040-2069 RCP 8.5	16 Dec.	6	-1	16 Apr.	128	-25
	Central	1971-2000	16 Dec.	6	N/A	22 Apr.	133	N/A
		2020-2049 RCP 4.5	15 Dec.	5	-1	05 Apr.	117	-16
		2020-2049 RCP 8.5	15 Dec.	5	-1	03 Apr.	115	-18
		2040-2069 RCP 4.5	15 Dec.	5	-1	05 Apr.	117	-16

		2040-2069 RCP 8.5	15 Dec.	5	-1	03 Apr.	115	-18
	Southern	1971-2000	15 Dec.	5	N/A	02 Apr.	113	N/A
		2020-2049 RCP 4.5	15 Dec.	5	0	22 Mar.	103	-10
		2020-2049 RCP 8.5	15 Dec.	5	0	20 Mar.	101	-12
		2040-2069 RCP 4.5	15 Dec.	5	0	22 Mar.	103	-10
		2040-2069 RCP 8.5	15 Dec.	5	0	20 Mar.	101	-12
30 Dec.	Northern	1971-2000	06 Jan.	7	N/A	14 Jun.	166	N/A
		2020-2049 RCP 4.5	05 Jan.	6	-1	13 May	135	-31
		2020-2049 RCP 8.5	05 Jan.	6	-1	10 May	132	-34
		2040-2069 RCP 4.5	05 Jan.	6	-1	13 May	135	-31
		2040-2069 RCP 8.5	05 Jan.	6	-1	10 May	132	-34
	Central	1971-2000	05 Jan.	6	N/A	20 May	141	N/A
		2020-2049 RCP 4.5	05 Jan.	6	0	29 Apr.	121	-20
		2020-2049 RCP 8.5	05 Jan.	6	0	27 Apr.	119	-22
		2040-2069 RCP 4.5	05 Jan.	6	0	29 Apr.	121	-20
		2040-2069 RCP 8.5	05 Jan.	6	0	27 Apr.	119	-22
	Southern	1971-2000	04 Jan.	5	N/A	28 Apr.	119	N/A
		2020-2049 RCP 4.5	04 Jan.	5	0	14 Apr.	106	-13
		2020-2049 RCP 8.5	04 Jan.	5	0	12 Apr.	104	-15
		2040-2069 RCP 4.5	04 Jan.	5	0	14 Apr.	106	-13
		2040-2069 RCP 8.5	04 Jan.	5	0	12 Apr.	104	-15

Table 9: Development Dates for the slow-development maize variety. The date of emergence and harvest dates are listed for each climatic scenario and time period, as well as the number of days after planting (DAP) those dates occur. The difference (Δ) between the development of the crop under historic climatic and future climatic conditions is also listed.

Sowing Date	Region	Climate Scenario	Emergence			Harvest		
			Date	DAP	Δ	Date	DAP	Δ
15 Nov.	Northern	1971-2000	25 Nov.	10	N/A	28 Aug.	286	N/A
		2020-2049 RCP 4.5	24 Nov.	9	-1	29 Jun.	227	-59
		2020-2049 RCP 8.5	24 Nov.	9	-1	23 Jun.	221	-65
		2040-2069 RCP 4.5	24 Nov.	9	-1	29 Jun.	227	-59
		2040-2069 RCP 8.5	24 Nov.	9	-1	23 Jun.	221	-65
	Central	1971-2000	24 Nov.	9	N/A	18 Jul.	245	N/A
		2020-2049 RCP 4.5	23 Nov.	8	-1	28 May	195	-50
		2020-2049 RCP 8.5	23 Nov.	8	-1	23 May	190	-55
		2040-2069 RCP 4.5	23 Nov.	8	-1	28 May	195	-50
		2040-2069 RCP 8.5	23 Nov.	8	-1	23 May	190	-55
	Southern	1971-2000	23 Nov.	8	N/A	27 May	193	N/A
		2020-2049 RCP 4.5	22 Nov.	7	-1	01 May	168	-25
		2020-2049 RCP 8.5	22 Nov.	7	-1	29 Apr.	166	-27
		2040-2069 RCP 4.5	22 Nov.	7	-1	01 May	168	-25
		2040-2069 RCP 8.5	22 Nov.	7	-1	29 Apr.	166	-27
10 Dec.	Northern	1971-2000	21 Dec.	11	N/A	26 Sep.	290	N/A
		2020-2049 RCP 4.5	20 Dec.	10	-1	14 Aug.	248	-42
		2020-2049 RCP 8.5	20 Dec.	10	-1	09 Aug.	243	-47
		2040-2069 RCP 4.5	20 Dec.	10	-1	14 Aug.	248	-42
		2040-2069 RCP 8.5	20 Dec.	10	-1	09 Aug.	243	-47
	Central	1971-2000	20 Dec.	10	N/A	01 Sep.	265	N/A
		2020-2049 RCP 4.5	19 Dec.	9	-1	17 Jul.	220	-45
		2020-2049 RCP 8.5	18 Dec.	8	-2	10 Jul.	213	-52
		2040-2069 RCP 4.5	19 Dec.	9	-1	18 Jul.	221	-44

		2040-2069 RCP 8.5	18 Dec.	8	-2	10 Jul.	213	-52
	Southern	1971-2000	18 Dec.	8	N/A	21 Jul.	223	N/A
		2020-2049 RCP 4.5	18 Dec.	8	0	10 Jun.	183	-40
		2020-2049 RCP 8.5	18 Dec.	8	0	06 Jun.	179	-44
		2040-2069 RCP 4.5	18 Dec.	8	0	10 Jun.	183	-40
		2040-2069 RCP 8.5	18 Dec.	8	0	06 Jun.	179	-44
30 Dec.	Northern	1971-2000	10 Jan.	11	N/A	14 Oct.	288	N/A
		2020-2049 RCP 4.5	09 Jan.	10	-1	08 Sep.	253	-35
		2020-2049 RCP 8.5	09 Jan.	10	-1	03 Sep.	248	-40
		2040-2069 RCP 4.5	09 Jan.	10	-1	08 Sep.	253	-35
		2040-2069 RCP 8.5	09 Jan.	10	-1	03 Sep.	248	-40
	Central	1971-2000	09 Jan.	10	N/A	23 Sep.	267	N/A
		2020-2049 RCP 4.5	08 Jan.	9	-1	20 Aug.	234	-33
		2020-2049 RCP 8.5	08 Jan.	9	-1	14 Aug.	228	-39
		2040-2069 RCP 4.5	08 Jan.	9	-1	20 Aug.	234	-33
		2040-2069 RCP 8.5	08 Jan.	9	-1	14 Aug.	228	-39
	Southern	1971-2000	08 Jan.	9	N/A	26 Aug.	239	N/A
		2020-2049 RCP 4.5	07 Jan.	8	-1	21 Jul.	204	-35
		2020-2049 RCP 8.5	07 Jan.	8	-1	14 Jul.	197	-42
		2040-2069 RCP 4.5	07 Jan.	8	-1	21 Jul.	204	-35
		2040-2069 RCP 8.5	07 Jan.	8	-1	14 Jul.	197	-42

Table 10: AFI for slow- and fast-developing maize varieties in each region of Malawi under differing climatic conditions and sowing dates. The bold red text indicates AFI levels which are consistent with exceedances of the EU threshold for AFB_1 contamination in food.

	Sowing Date	**Region**	**Baseline (1971-2000)**	**2035 RCP 4.5**	**2035 RCP 8.5**	**2055 RCP 4.5**	**2055 RCP 8.5**
Slow-Development Maize Variety	15 Nov.	North	5.62	5.90	28.06	0.44	32.02
	10 Dec.		21.08	38.02	90.07	45.40	54.15
	30 Dec.		35.75	60.19	**101.57**	**169.69**	83.42
	15 Nov.	Central	31.46	60.43	**116.33**	47.80	93.21
	10 Dec.		**97.63**	**103.05**	**146.55**	94.04	**129.55**
	30 Dec.		81.98	**151.65**	**165.21**	**167.04**	**215.79**
	15 Nov.	South	**178.01**	**235.61**	**247.04**	**210.21**	**232.87**
	10 Dec.		**179.40**	**251.67**	**244.28**	**234.12**	**197.55**
	30 Dec.		**147.21**	**238.50**	**247.30**	**265.58**	**282.81**
Fast-Development Maize Variety	15 Nov.	North	4.14	3.43	21.85	0.00	45.61
	10 Dec.		17.20	30.68	75.75	30.32	44.53
	30 Dec.		31.57	64.15	**96.19**	**139.86**	81.83
	15 Nov.	Central	22.27	55.07	**124.70**	39.69	**110.78**
	10 Dec.		84.62	**111.70**	**127.55**	74.40	**110.26**
	30 Dec.		89.86	**156.09**	**168.65**	**154.72**	**209.15**
	15 Nov.	South	**178.60**	**231.56**	**240.76**	**215.12**	**236.56**
	10 Dec.		**185.92**	**251.83**	**243.54**	**235.35**	**180.24**
	30 Dec.		**156.20**	**238.02**	**250.55**	**268.90**	**247.19**

Supplementary Figures

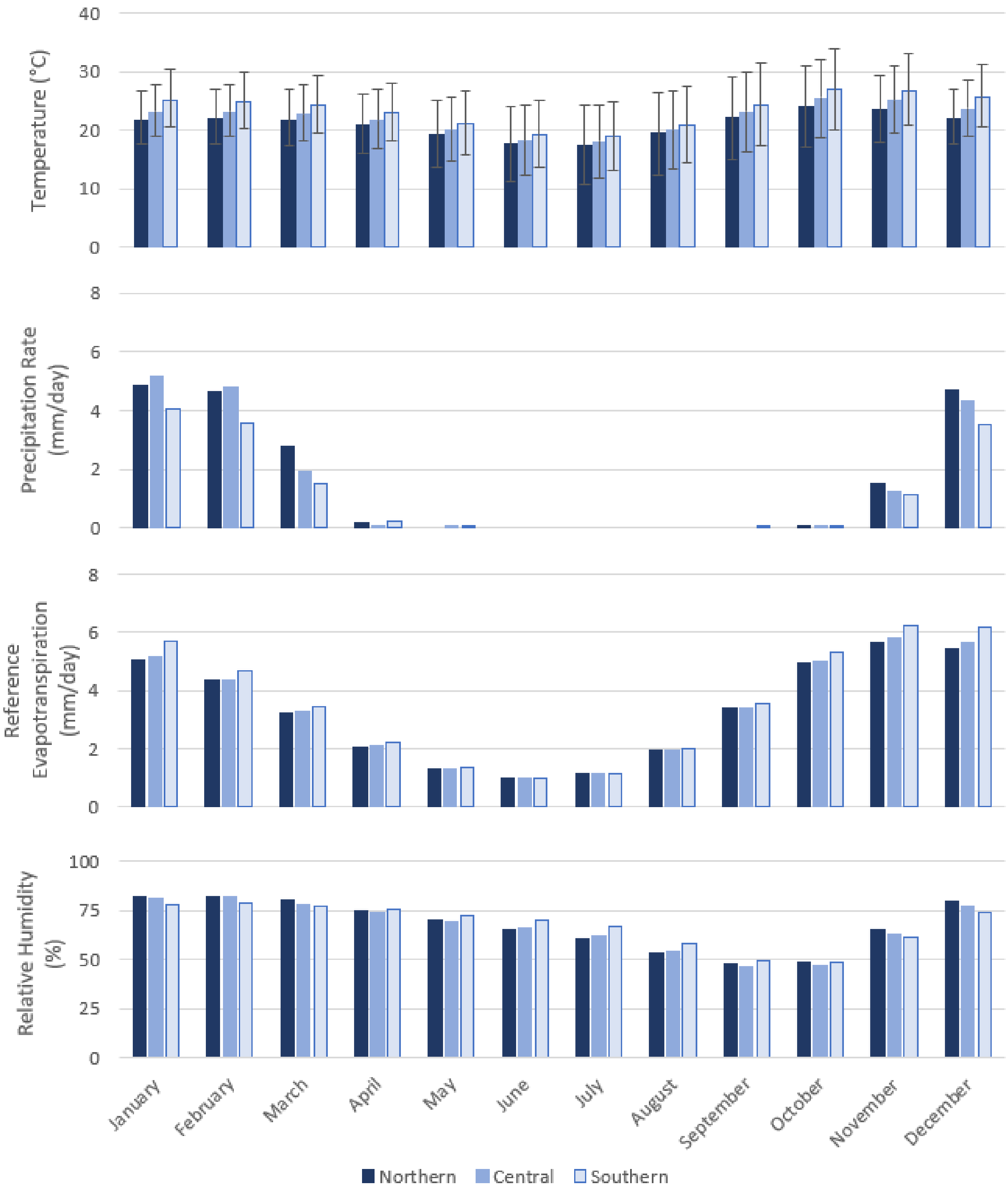

Figure 1: The top panel shows daily temperatures, the height of the bar indicates the average mean daily temperature during the relevant month over that 30 year period, with the whisker bars indicating the average daily minimum and maximum temperatures. The second, third and fourth panels down show average daily precipitation, average daily reference evapotranspiration and average daily relative humidity respectively. All four panels show this data for the three regions of Malawi in the 1971-2000 period, with the darkest blue representing the Northern Region, the middle blue representing the Central Region and the lightest blue representing the Southern Region.

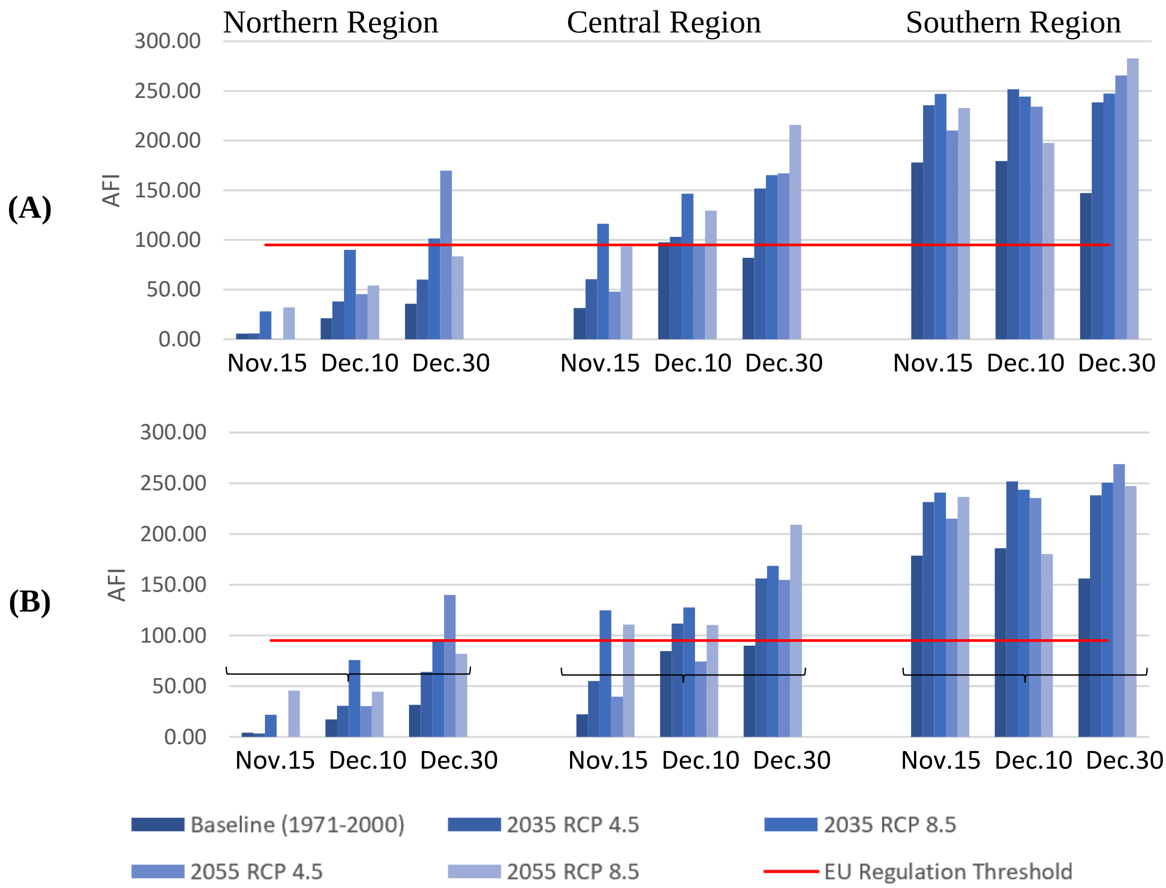

Figure 2: AFI for slow (A) and fast (B) development maize varieties in each region of Malawi under different climatic conditions and planting dates

Methodology for Calculating Reference Evapotranspiration for Central Malawi
To calculate evapotranspiration for Central Malawi, the FAO Penman Monteith (FPM) model was applied (Allen et al, 1998a).

Equation 1 $$ETo = \frac{0.408\Delta(R_n - G) + \gamma\frac{900}{T+273}u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)}$$

Where:

- ETo is the reference evapotranspiration (mm day^{-1})
- R_n is the net radiation at the crop surface (MJ m2 day^{-1}),
- G is the soil heat flux density (MJ m-2 day^{-1})
- T is the mean daily air temperature (°C)
- u_2 is wind speed at 2 m height (m s^{-1})
- e_s is the saturation vapour pressure (kPa)
- e_a is the actual vapour pressure (kPa), see Equation 10
- $e_s – e_a$ is the saturation vapour pressure deficit (kPa)
- Δ is the slope vapour pressure curve (kPa°C^{-1})
- γ is the psychrometric constant (kPa °C^{-1})

It is not possible to get data for all of the above variables for Central Malawi, either from observed data of the past, or from climate models used to hindcast the past or forecast future climates. Therefore, temperature-based calculation methods were applied for climatic variables with no primary data available (Allen et al, 1998b). This methodology has been tested for Malawi by Wang et al. (2011), and for South Malawi by Ngongondo et al. (2012) and deemed to be appropriate for use.

2.1. Net Radiation at the Crop Surface

R_n is the net radiation at the crop surface (MJ m2 day^{-1}) and can be calculated as follows:
Equation 2 $$R_n = R_{ns} - R_{nl}$$

Where:

- R_{ns} is the net incoming shortwave radiation (MJm-2 day-1) and can be calculated as follows:
  Equation 3 $$R_{ns} = (1 - \propto)R_s$$

  Where:
  - ∝ is the albedo or canopy reflection coefficient, which is 0.23 for the hypothetical grass reference crop
  - R_s is the fraction of the solar radiation not reflected from the surface (MJm-2 day-1) and can be calculated as follows:
    Equation 4 $$R_s = k_{Rs}\sqrt{T_{max} - T_{min}}\,R_a$$

    Where:
    - K_{RS} is adjustment coefficient. For inland regions not influenced by large bodies of water, K_{RS} = 0.16 ; for coastal regions, or regions where the air mass is influenced by a large nearby water body, K_{RS} = 0.19. Since Central Malawi is highly influenced by the presence of a large water body (Lake Malawi). K_{RS} is considered to be 0.19 in this study.
    - T_{max} is the maximum air temperature (ºC)
    - T_{min} is the minimum air temperature (ºC)

- R_a is extra-terrestrial radiation (MJm-2 day-1) and can be calculated as follows:

  Equation 5 $R_a = \frac{24(60)}{\pi} G_{sc} d_r [\omega_s \sin(\varphi) \sin(\delta) + \cos(\varphi) \cos(\delta) \sin(\omega_s)]$

  Where:
  - G_{Sc} is the solar constant = 0.0820 $MJm^{-2}min^{-1}$
  - d_r is the inverse relative since earth-Sun (rad) which can be calculated as follows:

    Equation 6 $d_r = 1 + 0.033 \cos\left(\frac{2\pi}{365} J\right)$

    Where:
    - J is the number of days in the year between 1 (1 January) and 365 or 266 (31 December). J at the middle of each month = 30.4M-15 where M is the month number
  - ω_s is the sunset hour angle (rad) which can be calculated as follows:

    Equation 7 $\omega_s = \arccos[-\tan(\varphi) \tan(\delta)]$

    Where:
    - φ is the latitude (rad)
    - δ is the solar declination (rad) which can be calculated as follows:

      Equation 8 $\delta = 1 + 0.409 \sin\left(\frac{2\pi}{365} J - 1.39\right)$

- R_{nl} is in the net outgoing longwave radiation (MJm-2 day-1) and can be calculated as follows:

Equation 9 $R_{nl} = \sigma \left[\frac{T_{maxK^4} + T_{minK^4}}{2}\right] \left(0.34 - 0.14\sqrt{e_a}\right) \left(1.35 \frac{R_s}{R_{so}} - 0.35\right)$

Where:
- σ is the Stefan-Boltzmann constant [4.903 x 10^{-9} MJ K^{-4} m^{-2} day^{-1}
- $T_{max,K}$ is the maximum absolute temperature during the 24-hour period [K = °C + 273.16],
- $T_{min, K}$ minimum absolute temperature during the 24-hour period [K = °C + 273.16],
- e_a actual vapour pressure [kPa], which can be calculated as follows:

  Equation 10 $e_a = e^o(T_{dew}) = 0.6108 exp\left(\frac{17.27 T_{dew}}{T_{dew} + 237.3}\right)$

  Where:
  - T_{dew} is the dew point temperature. T_{dew} is near the minimum temperature (T_{min}) when the relative humidity is nearly 100%. In semi-arid regions, T_{dew} is estimated by subtracting 2°C from T_{min}. As Central Malawi's humidity is typically under 90%, the T_{dew} can be calculated as follows:

    Equation 11 $T_{dew} = T_{min} - 2$

- R_s is the solar radiation [MJ m-2 day-1], see Equation 4.

- R_{so} is the clear-sky solar radiation [MJ m-2 day-1], which can be calculated as follows:
  Equation 12 $R_{SO} = \left(0.75 + 0.00002(h)\right)R_a$

  Where:
  - h is the elevation above sea level (m)
  - R_a is extra-terrestrial radiation, (MJm-2 day-1), see Equation 5.

2.2. Soil Heat Flux Density

G is the soil heat flux density (MJ m-2 day^{-1})

- For daily assessment, G is assumed to be zero (0) as the soil heat flux is relatively small
  Equation 13: $G_{day} = 0$

- For monthly assessments,
  Equation 14: $G = 0.07\ (T_{month,i+1} - T_{month,i-1})$

  Where:
  - $T_{mon,\ i-1}$ is the mean air temperature of the previous month (°C)
  - $T_{mon,\ i+1}$ is the mean air temperature of the next month (°C)

2.3. Mean Temperature

T is the mean daily air temperature (°C), which can be calculated as follows:
Equation 15: $T_{mean} = \frac{T_{min}+T_{max}}{2}$

Where:
- T_{max} is the maximum air temperature (ºC)
- T_{min} is the minimum air temperature (ºC)

2.4. Wind Speed at 2m height

u_2 is wind speed at 2 m height (m s^{-1}). We can use a default value of 172 km day^{-1} which is the average value over different weather stations around the globe. This was recommended by Allen et al. (1998). To convert to the correct units for the equation above (m s^{-1}) we can do the following:
Equation 16: $\frac{172km}{day}\ x\ \frac{day}{24\ hours}\ x\ \frac{hour}{60\ minutes}\ x\ \frac{minute}{60\ seconds}\ x\ \frac{1000\ meters}{km} = \frac{172{,}000\ meters}{86{,}400\ seconds}$

2.5. Vapour Pressure

To calculate ETO, various vapour pressure variables are required, including the saturation vapour pressure (e_s), the actual vapour pressure (e_a) and the slope vapour pressure curve (Δ).

- e_s is the saturation vapour pressure (kPa), it can be calculated as follows:
  Equation 17: $e_s = \frac{e^o(T_{max})+e^o(T_{min})}{2}$

  Where:
  - $e^0(T_{max})$ is the vapour pressure at maximum temperature, and can be calculated as follows:
    Equation 18: $e^o(T_{max}) = 0.6108exp\left(\frac{17.27T_{max}}{T_{max}+237.3}\right)$

Where:

- T_{max} is the maximum air temperature (ºC)

- $e^0(T_{min})$ is the vapour pressure at minimum temperature, and can be calculated as follows:

  Equation 19: $e^o(T_{min}) = 0.6108exp\left(\frac{17.27T_{min}}{T_{min}+237.3}\right)$

  Where:

  - T_{min} is the minimum air temperature (ºC)

- e_a is the actual vapour pressure (kPa), see Equation 10
- Δ is the slope vapour pressure curve (kPa°C^{-1})

  Equation 20: $\Delta = \frac{4098\left[0.6108exp\left(\frac{17.27T}{T+237.3}\right)\right]}{(T+237.3)^2}$

  Where:
  - T is the mean air temperature (°C), see Equation 15
  - exp[…] 2.7183 (base of natural logarithm) raised to the power […]

2.6. Psychrometric Constant

γ is the psychrometric constant (kPa °C^{-1}), it can be calculated as follows:

Equation 21: $\gamma = \frac{C_pP}{\varepsilon\lambda}$

Where:

- C_P is the specific heat at a constant pressure, C_P = 1.013 x 10^{-3} MJ kg^{-1} °C^{-1}
- P is atmospheric pressure (kPa), which can be calculated as follows:

  Equation 22: $P = 101.325(293 - 0.0065(h))^{5.25588}$

  Where:

  - h is the altitude above sea level in meters (m)
    - For Central Malawi, the average altitude above sea level (h) is 948.1944444m (determined using data from JISAO (2014))
  - ε is the ratio molecular weight of water vapour / dry air, ε = 0.622
  - λ is the latent heat of vaporization, λ = 2.45 MJ kg^{-1}

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