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Historical simulation of maize water footprints with a new global gridded crop model ACEA

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S1 Supplementary data and methods

S1.1 ACEA's grid cell outputs

The annual outputs are divided into three groups:

- **General outputs**: 1) seeding/anthesis/harvest dates, 2) dry crop yield and above-ground biomass (both in t ha^{-1}), 3) cumulative GDDs, 4) initial and final soil moisture (both in mm), 5) elements of water balance, namely cumulative precipitation, irrigation requirement, capillary rise, groundwater inflow, evaporation, transpiration, runoff, deep percolation (all in mm).
- **Crop water use**: cumulative actual evapotranspiration (mm) split into three water types (green, blue from irrigation, and blue from capillary rise)
- **Soil moisture storage**: final soil moisture (mm) split into three water types.

The daily outputs are also divided into three groups:

- **Soil water content**: soil water content for each soil compartment (fraction of the compartment depth).
- **Water fluxes**: 1) groundwater depth (m), 2) soil moisture, 3) precipitation, 4) irrigation requirement, 5) capillary rise, 6) groundwater inflow, 7) evaporation, 8) potential evaporation, 9) transpiration, 10) runoff, 11) deep percolation (all in mm).
- **Crop growth**: 1) current and cumulative GDDs, 2) root depth (m), 3) actual canopy cover and one without stress (fraction of surface), 4) actual dry above-ground biomass and one without stress (t ha^{-1}), 5) actual harvest index and one without stress (fraction of biomass), 6) dry crop yield (t ha^{-1}).

S1.2 Changes to AquaCrop-OSPy code

Several code adjustments are implemented:

1. Collection of outputs is adjusted to have all variables listed in Sect. S1.1.
2. Fixed minor errors originating in number rounding and loop settings.
3. Tracing of green water, blue water from irrigation, and blue water from capillary rise by tracking soil moisture composition in each soil compartment after any of next water balance-related functions in *solution.py* finishes its execution: check_groundwater_table, infiltration, drainage, capillary_rise, soil_evaporation, transpiration, groundwater_inflow.
4. To better simulate water stress responses in rainfed scenarios, some changes to core functions are done:
    - We allow crop germination to be automatically triggered if there is a germination delay of more than 30 days. This happens when the topsoil moisture doesn't reach the germination TAW threshold of 20% (default value for all crops).

- The crop calendar-depended parameters are recalculated if the germination is delayed. This allows the growing season to be extended (up to 15 %) and growth stages to be shifted according to their GDDs accumulation requirements.
- The first 30 days after germination are set to be free of water stress-induced senescence. This allows crops to start growing even in arid environments assuming that farmers would use more drought-resistant crop cultivars.
- Canopy cover is not allowed to go lower than the minimum harvestable 5% until the end of the yield formation.

All these changes are also considered in irrigated scenarios. However, the impact on them is neglectable because water availability is not limited. Consequently, the germination is triggered automatically on the next day after planting.

S1.3 Plant density testing

We test the sensitivity of unit *WF* estimates of maize to three plant density values: 50 000, 75 000 and 10 000 plants ha^{-1}. As you can see from Table S1, CWU values barely change with an increase in plant density as also observed in other studies (Irmak and Djaman, 2016; Barbieri et al., 2012). On the other hand, maize yields do increase with an increase in plant density leading to smaller *WF* values. In our study, we consider the fixed density of 75 000 plants ha^{-1} as it is the most common value in literature.

Table S1. Average unit water footprint estimates for three plant densities of maize in northern Italy during 1986-2016. CWU is crop water use (g - green, b - blue).

Plant density (plants ha^{-1})	**Crop yield** ($t\ ha^{-1}\ y^{-1}$)		**CWU_g** ($mm\ y^{-1}$)		**CWU_b** ($mm\ y^{-1}$)	**Unit water footprint** ($m^3\ t^{-1}\ y^{-1}$)	
	Rainfed	Irrigated	Rainfed	Irrigated	Irrigated	Rainfed	Irrigated
50000	7.2	13.5	343.5	309	187.6	477.1	367.9
75000	7.2	14	341.7	308.3	194.1	474.6	358.9
100000	7.4	14.3	341.4	310.6	195.7	461.4	354.1

S1.4 Generic maize characteristics

Version of AquaCrop	6.1
Crop Type (1 = Leafy vegetable, 2 = Root/tuber, 3 = Fruit/grain)	3
Planting method (0 = Transplanted, 1 = Sown)	1
Calendar Type (1 = Calendar days, 2 = Growing degree days)	2
Growing degree/Calendar days from sowing to emergence/transplant recovery	80
Growing degree/Calendar days from sowing to maximum rooting	1400
Growing degree/Calendar days from sowing to senescence	1400
Growing degree/Calendar days from sowing to maturity	1700
Growing degree/Calendar days from sowing to start of yield formation	880
Duration of flowering in growing degree/calendar days (-999 for non-fruit/grain crops)	180
Duration of yield formation in growing degree/calendar days	750
Growing degree day calculation method	3

Base temperature (degC) below which growth does not progress	8
Upper temperature (degC) above which crop development no longer increases	30
Pollination affected by heat stress (0 = No, 1 = Yes)	1
Maximum air temperature (degC) above which pollination begins to fail	40
Maximum air temperature (degC) at which pollination completely fails	45
Pollination affected by cold stress (0 = No, 1 = Yes)	1
Minimum air temperature (degC) below which pollination begins to fail	10
Minimum air temperature (degC) at which pollination completely fails	5
Transpiration affected by cold temperature stress (0 = No, 1 = Yes)	1
Minimum growing degree days (degC/day) required for full crop transpiration potential	12
Growing degree days (degC/day) at which no crop transpiration occurs	0
Minimum effective rooting depth (m)	0.3
Maximum rooting depth (m)	2.3
Shape factor describing root expansion	1.3
Maximum root water extraction at top of the root zone (m3/m3/day)	0.0104
Maximum root water extraction at the bottom of the root zone (m3/m3/day)	0.0026
Soil surface area (cm2) covered by an individual seedling at 90% emergence	6.5
Number of plants per hectare	75000
Maximum canopy cover (fraction of soil cover)	0.96
Canopy decline coefficient (fraction per GDD/calendar day)	0.01
Canopy growth coefficient (fraction per GDD)	0.01245
Crop coefficient when canopy growth is complete but prior to senescence	1.05
Decline of crop coefficient due to ageing (%/day)	0.3
Water productivity normalized for ET0 and C02 (g/m2)	33.7
Adjustment of water productivity in yield formation stage (% of WP)	100
Crop performance under elevated atmospheric CO2 concentration (%)	50
Reference harvest index	0.48
Possible increase of harvest index due to water stress before flowering (%)	0
Coefficient describing positive impact on harvest index of restricted vegetative growth during yield formation	7
Coefficient describing negative impact on harvest index of stomatal closure during yield formation	3
Maximum allowable increase of harvest index above reference value	15
Crop Determinancy (0 = Indeterminant, 1 = Determinant)	1
Excess of potential fruits	50
Upper soil water depletion threshold for water stress effects on affect canopy expansion	0.14
Upper soil water depletion threshold for water stress effects on canopy stomatal control	0.69
Upper soil water depletion threshold for water stress effects on canopy senescence	0.69
Upper soil water depletion threshold for water stress effects on canopy pollination	0.8
Lower soil water depletion threshold for water stress effects on canopy expansion	0.72
Lower soil water depletion threshold for water stress effects on canopy stomatal control	1
Lower soil water depletion threshold for water stress effects on canopy senescence	1
Lower soil water depletion threshold for water stress effects on canopy pollination	1
Shape factor describing water stress effects on canopy expansion	2.9
Shape factor describing water stress effects on stomatal control	6
Shape factor describing water stress effects on canopy senescence	2.7
Shape factor describing water stress effects on pollination	1
Vol (%) below saturation at which stress begins to occur due to deficient aeration	5
Number of days lag before aeration stress affects crop growth	3

S1.5 Soil profile selection

In AquaCrop, the soil profile is divided into several compartments (Vanuytrecht et al., 2014). The thickness of a compartment is usually set to a minimum at the top of the soil profile (to increase the accuracy of soil evaporation estimations), and to a maximum at the bottom (where water fluxes are less important). By default, the model suggests using a profile with 12 compartments starting with 10 cm thickness for the first three compartments and reaching 30 cm for the last one. However, recent literature shows that the selection of compartments is task-specific, and thus there is no general rule of thumb (Mkhabela and Bullock, 2012). Therefore, the default 12 compartments setup is simplified. We test three soil profiles in this study (Table S2). A total depth of 3 meters is chosen to cover the maximum root depth of maize. The tests are performed for rainfed maize during 1993-2012 with the initial soil moisture of 50% TAW for the whole soil profile. Following the setup of Chukalla et al. (2015), four climatic zones (arid, semi-arid, semi-humid, humid) and three soil types (real reported soil in literature, sandy loam and silty clay loam) are tested for each soil profile making 36 scenarios in total. No shallow groundwater is considered.

Table S2. Selection of 3 m thick soil profiles for testing in ACEA.

Compartment number	Soil profile 1	Soil profile 2	Soil profile 3
1	0.2	0.1	0.1
2	0.3	0.1	0.1
3	0.5	0.1	0.1
4	0.8	0.3	0.2
5	1.2	0.4	0.2
6		0.6	0.2
7		0.7	0.2
8		0.7	0.2
9			0.2
10			0.2
11			0.2
12			0.2
13			0.3
14			0.3
15			0.3

Soil profile 3 has the highest number of compartments. Therefore, it is set as a benchmark for comparisons with soil profiles 1 and 2. For the comparisons, the T-test function in Excel is used. Consequently, the soil profile with the least difference from the benchmark is optimum. The parameters to compare are the soil moisture at 0.3 and 1 m depths on the crop planting and harvest dates. In total, the comparisons are made for 48 combinations of soil moisture depths with climate and soil scenarios.

According to T-test results, soil profile 1 with five compartments has a significant difference between soil moistures in 79% of the comparisons (38 out of 48) and soil profile 2 with eight compartments in only 12% of the comparisons (6 out of 48). That 12% of comparisons are always for the semi-arid and semi-humid locations at 1 m depth on the harvest date. However, the soil moisture differences in absolute terms are minor and do not affect the crop modelling outputs. Therefore, no further tests are performed and soil profile 2 is selected for further use.

S1.6 Generation of initial soil moisture

Initial soil moisture has a significant impact the crop development, especially in arid and semi-arid climate zones (Rossato et al., 2017). Consequently, it is important to provide accurate water content values when a growing season starts. In our study, we test several scenarios to identify the number of years required to generate realistic soil moisture conditions. The same setup as for the soil profile selection is considered (four climates and three soil types). The soil profile is set to eight compartments and no shallow groundwater is considered.

We see that only the soil water content of the first growing season for an arid location is affected by the initial soil moisture assumptions. Consequently, the crop modelling outputs of the first growing season are inaccurate. Therefore, to analyse the crop modelling results of the year 1986, the simulations need to start in advance. For summer crops it corresponds to a one-year spin-up period and for winter crops it corresponds to two years. To unify the modelling setup, a two-year spin-up period is selected for all crops with a 50% green water TAW on the first day of simulation (1 January 1984).

S1.7 Groundwater level limitation

To avoid crop aeration stress, we lower the minimum groundwater depth to 1 m under the assumption that farmers would drain the area to maximise crop yields. This assumption is validated by simulating rainfed maize production in the Netherlands with groundwater depth limited to 0.5, 1, and 1.5 m. While there is no difference in crop yields with two latter limits, the maize production dropped by 25-30% when the limit is 0.5 m. Moreover, this assumption is supported by literature on the optimal shallow groundwater depth for crop production (Kahlown et al., 2005).

S1.8 Extrapolation of SPAM2010

To extrapolate 5 x 5 arc minute maize harvested areas around 2010 from SPAM2010 (Yu et al., 2020) into 1986-2016, two gridded datasets on the historical cropland are used – HYDE3.2 (Klein Goldewijk et al., 2017) and HID (Siebert et al., 2015). The procedure differs for rainfed and irrigated crops.

For rainfed maize, we firstly extract the rainfed cropland from HYDE3.2 for the time period of 1980-2016. The period before 2000 is reported in 10-year timesteps. Therefore, we interpolate values between 1980 and 2000 to have annual time-series for each grid cell (using scipy.interpolate package in Python). Then, we estimate the cropland extent around the year 2010 by taking the average of 2008-2012 (HYDE2010). After, we normalize the historical cropland values to the HYDE2010 value. This allows us to extrapolate SPAM2010 by assuming that rainfed maize areas experienced the same historical changes as the normalized rainfed cropland (eq. S1). Finally, we take a lower value between the extrapolated SPAM2010 and original HYDE3.2 values to avoid two outcomes: 1) maize harvest areas being larger than the cropland, and 2) maize harvest areas being more than 0 ha in years when no rainfed cropland is reported.

$$A_{rainfed} = \min\left(SPAM2010 * \frac{HYDE3.2}{HYDE2010}, \qquad HYDE3.2\right) \tag{S1}$$

For irrigated maize, the procedure is more complex. Firstly, we extract the irrigated cropland from HYDE3.2 for the time period of 1980-2016 and from HID for the time period of 1985-2005. Same as for rainfed, we interpolate the values between 1980 and 2000 in HYDE3.2 and between the whole period in HID as it is reported with 5-year timesteps. Then, we use HYDE3.2 to extrapolate HID values until 2016. This is done by multiplying the HID value in 2005 with 2006-2016 values from HYDE3.2 normalized to the year 2005. The next steps are similar to the procedure for rainfed maize but HID values are used instead of HYDE3.2 (eq. S2). We prioritise HID dataset as it provides better coherence with globally reported statistics (Siebert et al., 2015).

$$A_{irrigated} = \min\left(SPAM2010 * \frac{HID}{HID2000}, \qquad HID\right) \tag{S2}$$

As a result, each 5 x 5 arc minute grid cell has a historical harvest area of rainfed and irrigated maize production. However, these values may not reflect the official national statistics reported by FAOSTAT (FAOSTAT, 2021). Therefore, we aggregate the extrapolated SPAM2010 data to the national level and scale it to ensure that the sum of harvest areas (both rainfed and irrigated) within a country is equal to the respective national statistic in a specific year. Note that, due to limitations on data availability, there are no new grid cells with maize production other than reported in SPAM2010. However, some cells can have no production if the corresponding country does not report it. For example, Denmark started producing maize only in 2010, and thus there were no harvested areas until that year.

S2 Supplementary results

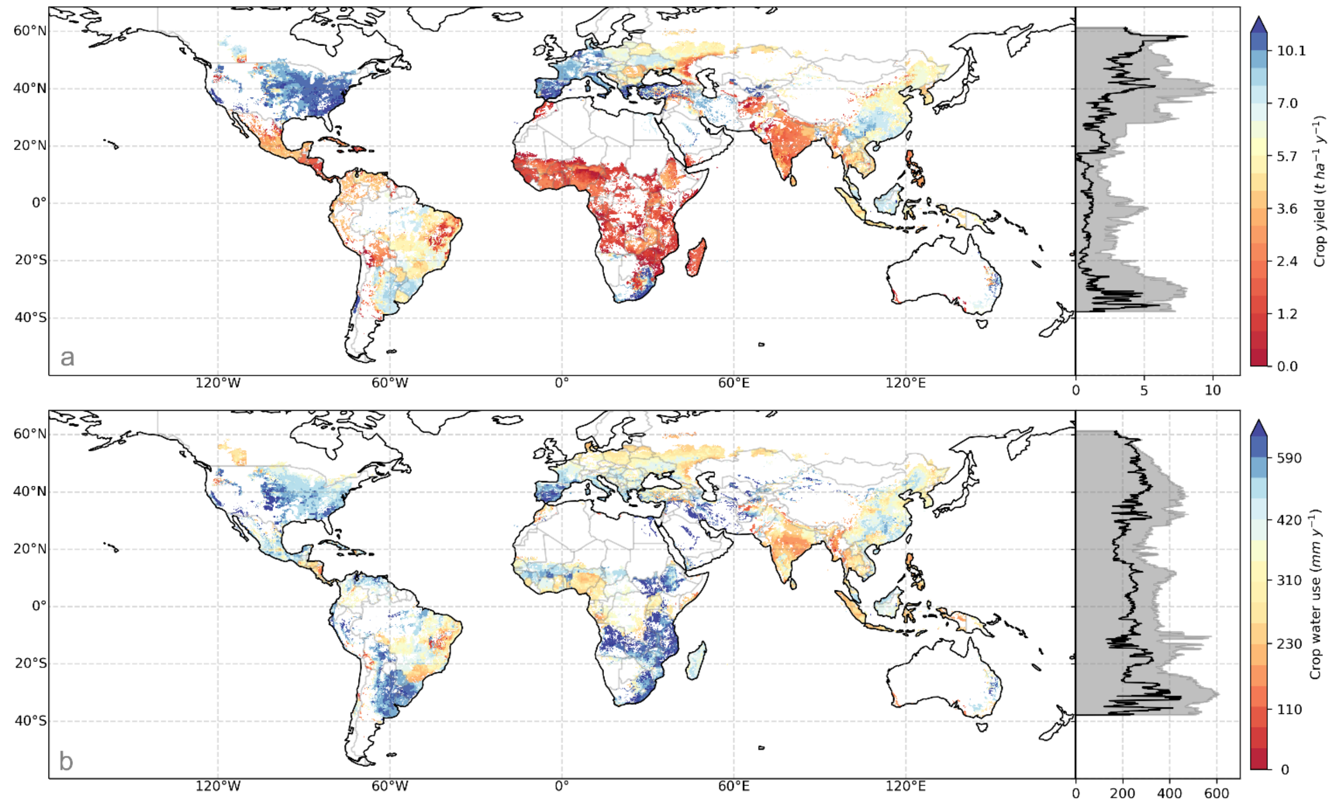

Figure S1: Average yields (a) (t ha^{-1} y^{-1}) and crop water use (c) (mm y^{-1}) of maize as the average over 2012-2016 at 5 x 5 arc minute resolution. The grey area in the side chart represents the median of all data points along the respective latitude and the black line is the 10th percentile.

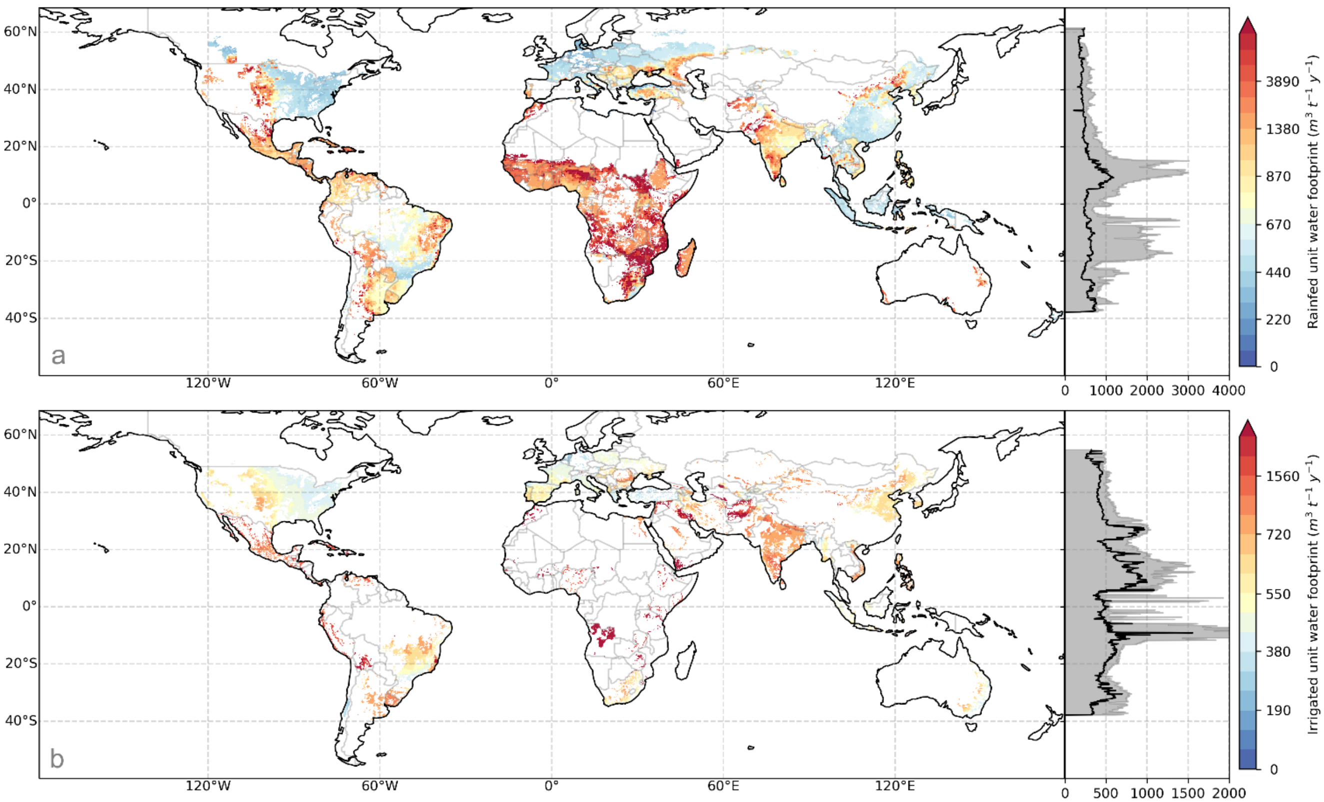

Figure S2: Average unit water footprint of rainfed (a) and irrigated (b) maize ($m^3\ t^{-1}\ y^{-1}$) as the average over 2012-2016 at 5 x 5 arc minute resolution. The grey area in the side chart represents the median of all data points along the respective latitude and the black line is the 10th percentile.

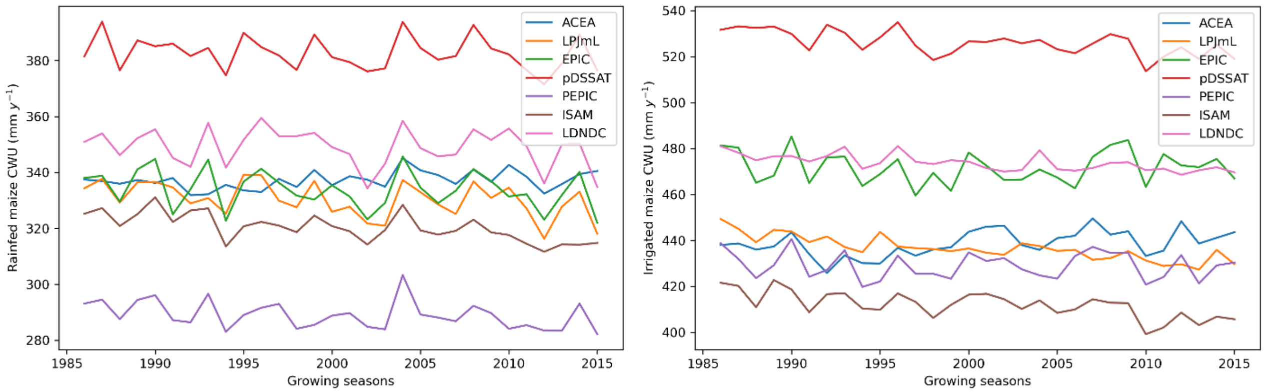

Figure S3: Global comparison of crop water use (CWU) of rainfed and irrigated maize (mm y^{-1}) with Jägermeyr et al. (2021). Each line represents an annual median value among the cells with CWU more than 10 mm simulated by one of global gridded crop models.

Table S3. National average water footprints and production of maize as the average over 2012-2016. WF is water footprint (g - green, bc - blue from capillary rise, bi - blue from irrigation).

#	Country	FAOSTAT code	Production (10^6 t y^{-1})	Harvested area (10^3 ha y^{-1})	WF_g	WF_{bc}	WF_{bi}	Unit WF (m^3 t-1 y^{-1})	Change in unit WF (relative to 1986-1990)	Change in WF of production (relative to 1986-1990)
					(% of unit WF)					
	Countries that produce 95 % of maize									
1	USA	231	343.7	34435.0	90.1 %	1.7 %	8.3 %	487.2	-28.6 %	35.8 %
2	China	41	233.1	39523.5	85.4 %	1.9 %	12.7 %	614.1	-30.7 %	99.5 %
3	Brazil	21	75.5	15057.7	99.8 %	0.1 %	0.2 %	633.2	-62.6 %	17.7 %
4	Argentina	9	31.9	4674.0	94.4 %	4.6 %	1.0 %	816.8	-48.5 %	102.2 %
5	Ukraine	230	26.3	4432.3	97.3 %	0.7 %	2.0 %	584.2	-40.2 %	108.2 %
6	Mexico	138	24.1	7155.5	89.4 %	0.1 %	10.5 %	1252.4	-46.7 %	7.2 %
7	India	100	23.7	9197.6	95.2 %	0.3 %	4.6 %	982.0	-46.1 %	57.5 %
8	Indonesia	101	19.9	3969.6	98.6 %	0.2 %	1.1 %	555.6	-60.5 %	26.7 %
9	France	68	14.9	1691.7	93.0 %	0.1 %	6.8 %	480.6	-17.0 %	-0.6 %
10	Canada	33	13.2	1383.1	98.2 %	1.8 %	0.0 %	378.7	-31.6 %	40.1 %
11	Russian Federation	185	12.0	2461.2	96.4 %	3.6 %	0.0 %	697.4	-35.8 %	133.6 %
12	South Africa	202	11.0	2553.6	87.7 %	0.0 %	12.3 %	1011.0	-61.6 %	-54.9 %
13	Nigeria	159	10.3	6388.8	99.5 %	0.2 %	0.3 %	1658.2	-16.5 %	79.2 %
14	Romania	183	10.0	2583.9	96.4 %	2.1 %	1.5 %	952.8	-19.0 %	3.5 %
15	Egypt	59	7.9	1039.9	1.0 %	0.0 %	99.0 %	1002.5	-33.3 %	28.2 %
16	Italy	106	7.8	828.9	85.5 %	6.1 %	8.4 %	456.4	-10.3 %	14.3 %
17	Ethiopia	238	7.7	2751.3	99.4 %	0.0 %	0.6 %	1918.2	-43.3 %	166.1 %
18	Philippines	171	7.4	2563.1	99.6 %	0.2 %	0.2 %	803.0	-60.4 %	-34.5 %
19	Hungary	97	7.2	1156.6	92.8 %	6.9 %	0.4 %	622.4	-8.0 %	2.5 %
20	United Republic of Tanzania	215	6.1	4014.4	99.6 %	0.1 %	0.2 %	3782.1	-12.8 %	109.8 %
21	Serbia	272	5.9	1006.9	94.4 %	5.6 %	0.0 %	706.0	-31.0 %	-32.3 %
22	Turkey	223	5.4	660.6	81.1 %	0.1 %	18.7 %	401.0	-42.2 %	45.0 %
23	Viet Nam	237	5.2	1164.3	96.0 %	0.3 %	3.6 %	829.6	-66.8 %	150.0 %
24	Pakistan	165	5.1	1182.0	70.3 %	0.0 %	29.7 %	767.3	-64.4 %	55.5 %
25	Thailand	216	4.7	1111.3	99.2 %	0.8 %	0.0 %	617.7	-45.0 %	-34.7 %
26	Germany	79	4.6	475.3	98.5 %	0.6 %	0.9 %	341.0	-22.5 %	148.7 %
27	Spain	203	4.5	401.8	42.4 %	0.0 %	57.6 %	538.0	-37.6 %	-17.2 %
28	Paraguay	169	4.2	947.0	100.0 %	0.0 %	0.0 %	1175.0	-55.8 %	449.1 %
29	Poland	173	3.9	620.0	99.4 %	0.4 %	0.2 %	477.9	-15.0 %	1589.6 %
30	Kenya	114	3.7	2166.9	99.8 %	0.0 %	0.2 %	2073.4	12.7 %	56.7 %
31	Malawi	130	3.3	1676.3	99.5 %	0.5 %	0.0 %	3120.5	-42.0 %	33.9 %
32	Zambia	251	2.9	1059.9	99.9 %	0.1 %	0.1 %	2237.1	-26.0 %	43.0 %
33	Uganda	226	2.7	1076.8	99.9 %	0.1 %	0.0 %	1248.1	-49.0 %	193.7 %
34	Bulgaria	27	2.5	441.8	99.1 %	0.2 %	0.8 %	678.4	-32.7 %	-11.8 %
35	Democratic People's Republic of Korea	116	2.2	538.8	99.9 %	0.1 %	0.0 %	789.3	32.2 %	-22.3 %
36	Nepal	149	2.1	884.8	98.3 %	0.0 %	1.6 %	1195.4	-38.0 %	26.7 %
37	Democratic Republic of the Congo	250	2.0	2591.8	100.0 %	0.0 %	0.0 %	3001.1	9.7 %	141.7 %
38	Venezuela (Bolivarian Republic of)	236	2.0	552.2	97.1 %	0.3 %	2.6 %	1255.4	-43.4 %	-1.7 %
39	Austria	11	2.0	204.4	98.3 %	0.7 %	1.0 %	353.9	-14.4 %	3.8 %
40	Cameroon	32	2.0	1071.9	99.2 %	0.6 %	0.2 %	1718.6	0.9 %	425.0 %
	Countries that produce the rest 5 % of maize									
41	Mali	133	2.0	789.2	100.0 %	0.0 %	0.0 %	2003.0	-41.4 %	453.9 %
42	Bangladesh	16	1.9	279.9	89.8 %	0.7 %	9.6 %	421.9	-84.6 %	9381.2 %
43	Greece	84	1.9	174.8	59.9 %	0.0 %	40.1 %	423.6	-12.1 %	-22.6 %
44	Guatemala	89	1.8	867.3	99.6 %	0.0 %	0.3 %	1583.6	-10.9 %	33.7 %
45	Croatia	98	1.8	271.2	95.7 %	4.2 %	0.1 %	625.7	-33.8 %	-24.5 %
46	Ghana	81	1.8	969.6	100.0 %	0.0 %	0.0 %	1712.1	-32.7 %	84.4 %
47	Myanmar	28	1.7	455.0	94.7 %	1.5 %	3.8 %	486.6	-58.7 %	222.5 %
48	Colombia	44	1.7	520.5	99.5 %	0.5 %	0.0 %	1132.1	-56.8 %	-26.1 %
49	Peru	170	1.6	496.0	59.2 %	0.0 %	40.8 %	1582.2	-36.8 %	18.5 %
50	Burkina Faso	233	1.6	848.4	99.9 %	0.0 %	0.1 %	2833.9	-45.3 %	310.4 %
51	Angola	7	1.6	1560.9	99.3 %	0.1 %	0.6 %	5516.7	-65.3 %	112.4 %
52	Iran (Islamic Republic of)	102	1.5	227.8	11.2 %	0.0 %	88.8 %	1045.8	-45.5 %	1406.1 %
53	Mozambique	144	1.5	1646.1	98.9 %	0.3 %	0.8 %	6492.6	-60.6 %	62.7 %
54	Republic of Moldova	146	1.5	468.6	99.9 %	0.0 %	0.1 %	1281.7	31.5 %	49.8 %
55	Ecuador	58	1.4	438.9	97.3 %	0.4 %	2.3 %	1461.0	-69.4 %	-5.4 %
56	Chile	40	1.4	125.3	50.0 %	0.0 %	49.9 %	320.3	-28.2 %	32.5 %
57	Lao People's Democratic Republic	120	1.4	233.0	100.0 %	0.0 %	0.0 %	572.8	-74.5 %	616.1 %
58	Slovakia	199	1.3	205.3	90.9 %	8.1 %	1.0 %	573.8	-17.2 %	79.2 %

59	Benin	53	1.3	983.4	99.9 %	0.1 %	0.0 %	2716.0	-38.0 %	117.2 %
60	Bolivia (Plurinational State of)	19	1.0	418.4	99.1 %	0.1 %	0.9 %	2065.1	-33.6 %	52.9 %
61	El Salvador	60	0.9	295.8	99.8 %	0.1 %	0.1 %	959.4	-26.6 %	12.8 %
62	Portugal	174	0.8	101.6	58.3 %	0.0 %	41.7 %	598.8	-66.0 %	-56.9 %
63	Zimbabwe	181	0.8	1192.8	98.7 %	0.0 %	1.3 %	6258.0	117.4 %	-13.3 %
64	Bosnia and Herzegovina	80	0.8	188.1	97.9 %	2.1 %	0.0 %	895.4	-2.4 %	-28.9 %
65	Togo	217	0.8	677.3	99.9 %	0.1 %	0.0 %	2821.6	-26.3 %	163.7 %
66	Côte d'Ivoire	107	0.8	381.0	100.0 %	0.0 %	0.0 %	1809.3	-60.9 %	-34.5 %
67	Belarus	57	0.7	135.6	99.2 %	0.8 %	0.0 %	556.9	-31.6 %	39.2 %
68	Czechia	167	0.7	96.3	99.9 %	0.1 %	0.0 %	432.6	-37.2 %	42.5 %
69	Guinea	90	0.7	564.5	100.0 %	0.0 %	0.0 %	3657.5	-21.5 %	486.2 %
70	Cambodia	115	0.7	152.7	99.5 %	0.5 %	0.0 %	604.7	-77.4 %	200.4 %
71	Belgium	255	0.7	63.2	92.4 %	4.1 %	3.6 %	318.2	-21.5 %	922.4 %
72	Kazakhstan	108	0.6	121.3	38.6 %	2.3 %	59.0 %	865.2	-37.8 %	45.7 %
73	Kyrgyzstan	113	0.6	96.6	60.9 %	0.0 %	39.1 %	561.9	-54.0 %	72.8 %
74	Honduras	95	0.6	338.5	99.0 %	0.0 %	0.9 %	1552.2	-13.2 %	2.0 %
75	Uruguay	234	0.5	108.8	96.9 %	0.2 %	3.0 %	1151.0	-73.3 %	56.4 %
76	Rwanda	184	0.5	251.7	100.0 %	0.0 %	0.0 %	1462.2	-34.2 %	225.6 %
77	Australia	10	0.4	62.7	63.7 %	0.4 %	35.9 %	604.5	-43.0 %	11.0 %
78	Uzbekistan	235	0.4	37.5	21.7 %	0.0 %	78.3 %	490.5	-66.6 %	46.9 %
79	Nicaragua	157	0.4	339.5	99.8 %	0.1 %	0.1 %	1860.7	27.2 %	102.4 %
80	Iraq	103	0.4	111.2	16.6 %	0.0 %	83.3 %	1359.8	-41.3 %	142.4 %
81	Cuba	49	0.4	167.5	99.0 %	0.4 %	0.6 %	1462.7	-53.6 %	117.1 %
82	Chad	39	0.4	322.7	91.3 %	7.8 %	0.8 %	3479.5	-25.1 %	1114.9 %
83	Albania	3	0.4	55.0	89.0 %	0.3 %	10.7 %	643.1	-41.4 %	-21.9 %
84	Madagascar	129	0.4	219.1	99.5 %	0.5 %	0.0 %	2399.6	-39.5 %	39.3 %
85	Slovenia	198	0.3	38.7	99.8 %	0.2 %	0.0 %	476.0	-46.4 %	-19.2 %
86	Afghanistan	2	0.3	141.8	38.2 %	0.0 %	61.8 %	1967.0	38.1 %	-13.8 %
87	Haiti	93	0.3	351.0	99.6 %	0.0 %	0.4 %	3500.2	6.8 %	51.4 %
88	Georgia	73	0.3	116.4	93.3 %	3.2 %	3.5 %	1577.7	60.1 %	-12.4 %
89	Senegal	195	0.2	159.7	99.8 %	0.0 %	0.2 %	2609.7	-18.7 %	51.3 %
90	Sri Lanka	38	0.2	65.1	98.3 %	0.1 %	1.5 %	825.5	-69.6 %	85.2 %
91	New Zealand	156	0.2	19.5	100.0 %	0.0 %	0.0 %	377.1	-4.1 %	31.9 %
92	Azerbaijan	52	0.2	36.7	48.5 %	0.4 %	51.1 %	737.7	-42.1 %	52.7 %
93	Namibia	147	0.2	31.1	99.1 %	0.0 %	0.9 %	1344.8	-54.6 %	297.0 %
94	South Sudan	277	0.2	222.7	99.9 %	0.1 %	0.0 %	7362.7	-40.8 %	270.1 %
95	Burundi	29	0.2	125.0	100.0 %	0.0 %	0.0 %	1264.6	-3.3 %	-5.3 %
96	Tajikistan	208	0.2	15.7	42.5 %	0.5 %	57.0 %	386.7	-74.5 %	20.2 %
97	Switzerland	211	0.2	14.8	99.9 %	0.1 %	0.0 %	332.9	-15.1 %	-38.9 %
98	Netherlands	150	0.1	12.6	91.7 %	7.2 %	1.1 %	266.3	-15.2 %	1336.4 %
99	Syrian Arab Republic	212	0.1	40.4	18.5 %	0.0 %	81.5 %	1987.0	-48.3 %	-30.4 %
100	North Macedonia	154	0.1	31.5	97.9 %	0.1 %	2.0 %	897.0	-25.0 %	-43.1 %
101	Panama	166	0.1	58.8	99.1 %	0.1 %	0.9 %	1377.1	-38.9 %	-21.0 %
102	Somalia	201	0.1	133.4	72.3 %	0.3 %	27.4 %	2353.3	13.3 %	-56.4 %
103	Morocco	143	0.1	139.7	68.6 %	2.4 %	29.0 %	2468.9	6.0 %	-69.0 %
104	Central African Republic	37	0.1	101.4	100.0 %	0.0 %	0.0 %	3547.7	-0.4 %	57.0 %
105	Timor-Leste	176	0.1	46.0	93.7 %	0.0 %	6.3 %	1863.3	-44.1 %	-7.2 %
106	Lithuania	126	0.1	14.6	99.6 %	0.4 %	0.0 %	425.8	-50.5 %	98.4 %
107	Eswatini	209	0.1	65.5	99.6 %	0.0 %	0.4 %	4535.8	-8.2 %	-25.2 %
108	Republic of Korea	117	0.1	15.9	98.8 %	0.0 %	1.2 %	661.1	-5.9 %	-35.2 %
109	Lesotho	122	0.1	101.1	100.0 %	0.0 %	0.0 %	6191.0	28.9 %	-27.8 %
110	Bhutan	18	0.1	24.2	100.0 %	0.0 %	0.0 %	842.1	-71.3 %	-51.0 %
111	Malaysia	131	0.1	9.8	99.8 %	0.2 %	0.0 %	590.2	-75.6 %	-46.0 %
112	Denmark	54	0.1	10.0	97.7 %	2.3 %	0.0 %	340.7	-	-
113	Yemen	249	0.1	43.4	44.9 %	0.0 %	55.1 %	2732.1	0.0 %	88.9 %
114	Turkmenistan	213	0.1	37.8	6.9 %	0.0 %	93.1 %	5018.4	0.0 %	0.0 %
115	Sudan	276	0.0	35.5	100.0 %	0.0 %	0.0 %	3546.3	-76.8 %	3251.7 %
116	Israel	105	0.0	4.2	70.7 %	0.0 %	29.3 %	198.5	11.5 %	-30.5 %
117	Gabon	74	0.0	27.5	99.9 %	0.1 %	0.0 %	1905.7	-3.2 %	85.5 %
118	Saudi Arabia	194	0.0	7.7	8.0 %	0.0 %	92.0 %	688.2	-71.7 %	255.2 %
119	Dominican Republic	56	0.0	25.7	85.7 %	0.4 %	13.9 %	2437.3	3.7 %	-14.0 %
120	Niger	158	0.0	24.4	99.6 %	0.0 %	0.4 %	2272.7	-54.9 %	206.2 %
121	Belize	23	0.0	19.9	100.0 %	0.0 %	0.0 %	344.3	-9.3 %	47.3 %
122	Gambia	75	0.0	36.9	100.0 %	0.0 %	0.0 %	3935.2	37.9 %	191.1 %
123	Sierra Leone	197	0.0	29.2	99.9 %	0.1 %	0.0 %	3542.3	13.6 %	188.2 %
124	Eritrea	178	0.0	20.0	100.0 %	0.0 %	0.0 %	2190.9	-50.2 %	-16.4 %
125	Armenia	1	0.0	3.1	74.3 %	0.0 %	25.6 %	512.6	-56.0 %	-28.0 %
126	Mauritania	136	0.0	20.2	91.1 %	0.0 %	8.9 %	3827.7	46.0 %	677.4 %

127	Botswana	20	0.0	54.8	76.8 %	0.0 %	23.2 %	5519.1	14.1 %	-21.7 %
128	Oman	221	0.0	1.5	100.0 %	0.0 %	0.0 %	92.3	-	-
129	Papua New Guinea	168	0.0	2.2	99.9 %	0.1 %	0.0 %	560.9	-68.3 %	127.0 %
130	Costa Rica	48	0.0	5.8	99.8 %	0.2 %	0.0 %	1368.6	-13.3 %	-89.6 %
131	Congo	46	0.0	13.4	99.7 %	0.3 %	0.0 %	2472.1	-11.1 %	-39.4 %
132	Guinea-Bissau	175	0.0	7.0	100.0 %	0.0 %	0.0 %	3889.8	-5.5 %	-37.0 %
133	Jordan	112	0.0	0.9	83.1 %	0.0 %	16.9 %	117.6	-2.7 %	272.1 %
134	Kuwait	118	0.0	1.0	1.6 %	0.0 %	98.4 %	772.5	-1.8 %	1556.0 %
135	Trinidad and Tobago	220	0.0	1.5	100.0 %	0.0 %	0.0 %	1385.0	47.3 %	77.9 %
136	Guyana	91	0.0	2.9	99.5 %	0.5 %	0.0 %	2499.7	-10.5 %	34.9 %
137	Lebanon	121	0.0	0.9	52.1 %	0.0 %	47.9 %	1325.0	-55.9 %	-47.3 %
138	Libya	124	0.0	1.5	90.8 %	9.2 %	0.0 %	176.7	-42.2 %	3.2 %
139	Montenegro	273	0.0	0.6	99.9 %	0.1 %	0.0 %	749.9	-27.1 %	-82.4 %
140	Jamaica	109	0.0	2.3	100.0 %	0.0 %	0.0 %	3754.3	-4.8 %	-19.2 %
141	Algeria	4	0.0	0.7	32.5 %	0.3 %	67.2 %	487.4	-45.7 %	-31.2 %
142	Luxembourg	256	0.0	0.2	100.0 %	0.0 %	0.0 %	404.7	-3.0 %	83.5 %
143	Fiji	66	0.0	0.3	100.0 %	0.0 %	0.0 %	1036.6	-15.2 %	-49.4 %
144	Bahamas	12	0.0	0.1	100.0 %	0.0 %	0.0 %	338.4	-79.5 %	-84.3 %
145	Vanuatu	155	0.0	1.5	100.0 %	0.0 %	0.0 %	225.6	-81.7 %	-84.6 %
146	Qatar	179	0.0	0.1	2.2 %	0.0 %	97.8 %	515.8	-0.9 %	2226.2 %
147	Mauritius	137	0.0	0.1	100.0 %	0.0 %	0.0 %	394.4	-37.4 %	-91.9 %
148	Japan	110	0.0	0.1	90.5 %	9.5 %	0.0 %	1453.2	-15.7 %	-84.3 %
149	Suriname	207	0.0	0.0	99.4 %	0.6 %	0.0 %	1749.3	-36.0 %	-81.5 %

Table S4. Annual average global maize simulation outputs and water footprints during 1986-2016. CWU is crop water use and WF is unit water footprint (g - green, bc - blue from capillary rise, bi - blue from irrigation).

Year	Rainfed systems					Irrigated systems					Yield scaling factor	Weighted average				
	Harvested area (10^6 ha y^{-1})	Simulated yield (t ha^{-1} y^{-1})	CWU (mm y^{-1})	WF_g (m^3 t^{-1} y^{-1})	WF_{bc} (m^3 t^{-1} y^{-1})	Harvested area (10^6 ha y^{-1})	Simulated yield (t ha^{-1} y^{-1})	CWU (mm y^{-1})	WF_g (m^3 t^{-1} y^{-1})	WF_{bi} (m^3 t^{-1} y^{-1})		Actual yield (t ha^{-1} y^{-1})	WF_g (m^3 t^{-1} y^{-1})	WF_{bc} (m^3 t^{-1} y^{-1})	WF_{bi} (m^3 t^{-1} y^{-1})	Unit WF (m^3 t^{-1} y^{-1})
1986	113.1	13.28	385.8	1053.9	11.1	18.7	14.85	459.7	693.4	355.0	26.6 %	3.67	992.6	9.2	60.3	1062.2
1987	111.1	12.77	383.4	1138.6	15.0	18.9	14.69	457.9	718.9	366.8	25.4 %	3.4	1062.9	12.3	66.2	1141.3
1988	111.1	12.56	375.5	1190.8	22.1	18.9	14.59	450.9	682.6	384.5	25.5 %	3.22	1093.9	17.9	73.3	1185.1
1989	112.4	13.40	385.1	1095.9	15.5	19.4	14.85	452.5	648.0	366.1	26.3 %	3.59	1013.9	12.7	67.0	1093.6
1990	111.5	12.90	387.1	1079.7	13.0	19.6	14.58	459.5	653.1	354.3	27.4 %	3.66	1000.2	10.5	66.0	1076.8
1991	113.5	12.76	382.1	1061.0	14.3	20.1	14.53	456.7	629.9	333.0	28.1 %	3.7	978.0	11.6	64.2	1053.7
1992	115.9	12.74	364.0	957.6	14.2	20.8	14.90	449.1	607.7	310.8	27.9 %	3.82	889.5	11.5	60.5	961.5
1993	111.0	12.86	376.2	1012.7	11.9	20.4	14.98	450.3	606.4	303.9	28.1 %	3.82	931.1	9.5	61.0	1001.7
1994	116.8	13.06	378.3	981.0	12.1	21.5	14.38	453.2	618.7	329.3	28.7 %	3.92	912.5	9.8	62.3	984.6
1995	114.1	12.64	373.9	982.4	13.2	21.7	14.55	449.5	587.9	320.2	29.1 %	3.87	901.9	10.5	65.4	977.8
1996	116.0	13.81	387.8	946.7	12.1	23.3	14.89	433.1	575.9	268.9	29.7 %	4.2	871.0	9.6	54.9	935.5
1997	117.4	13.75	390.9	933.1	12.8	23.4	14.51	458.8	578.5	306.2	30.2 %	4.27	861.5	10.3	61.8	933.6
1998	114.3	13.35	383.8	907.8	9.3	24.4	14.35	439.5	564.5	277.6	31.4 %	4.33	835.1	7.3	58.8	901.2
1999	112.7	13.31	390.2	893.4	12.1	24.6	14.55	454.9	560.0	277.5	32.1 %	4.46	820.6	9.4	60.6	890.6
2000	112.9	13.03	381.3	896.7	15.5	24.1	14.46	466.7	504.9	354.9	32.5 %	4.35	811.0	12.1	77.7	900.8
2001	112.9	13.21	387.8	889.9	14.2	24.5	14.45	461.7	521.5	320.8	32.9 %	4.46	809.2	11.1	70.3	890.5
2002	112.8	12.53	384.8	896.2	13.7	24.8	14.48	469.6	494.5	350.2	33.6 %	4.41	804.9	10.6	79.6	895.1
2003	118.9	12.84	383.7	880.1	13.2	25.7	14.72	456.9	483.7	311.7	33.7 %	4.5	790.5	10.2	70.4	871.2
2004	120.7	13.80	393.3	813.2	10.4	26.9	14.82	451.6	498.3	254.1	34.7 %	4.97	743.9	8.1	55.9	807.9
2005	121.1	12.94	394.5	855.1	10.6	27.2	14.36	459.9	487.2	281.6	35.9 %	4.77	770.7	8.1	64.6	843.4
2006	120.8	13.06	386.2	834.3	12.0	27.6	14.23	449.2	479.0	274.7	35.9 %	4.79	752.1	9.2	63.6	824.8
2007	129.9	13.06	390.7	808.9	15.5	29.4	14.44	445.6	469.6	251.6	37.2 %	4.96	731.0	12.0	57.8	800.7
2008	134.0	13.71	398.7	799.4	10.3	29.7	14.62	446.4	479.8	239.1	36.5 %	5.12	729.0	8.1	52.6	789.7
2009	129.7	13.45	389.9	771.1	10.8	29.7	14.62	454.7	468.9	247.7	37.3 %	5.2	702.4	8.4	56.3	767.1
2010	133.7	13.32	390.5	790.2	8.8	31.0	14.19	437.3	481.4	229.6	37.7 %	5.09	720.2	6.8	52.1	779.0
2011	140.0	13.35	393.8	763.5	10.6	31.8	14.35	443.0	450.5	241.1	38.9 %	5.28	693.1	8.2	54.2	755.5
2012	147.0	12.09	373.5	816.1	17.3	33.4	14.26	457.7	414.5	291.0	39.9 %	4.8	715.8	13.0	72.6	801.5
2013	152.9	13.17	387.2	728.5	10.8	34.7	14.18	446.2	450.0	231.8	40.6 %	5.41	666.3	8.4	51.8	726.5
2014	151.5	13.49	389.1	715.7	8.9	34.9	14.62	447.0	429.3	234.9	40.6 %	5.58	651.1	6.9	53.0	710.9
2015	152.8	12.97	382.9	699.5	10.6	38.5	14.34	440.1	433.9	225.8	41.7 %	5.58	635.6	8.1	54.3	698.0
2016	157.7	13.01	384.9	707.7	8.9	38.9	14.00	435.4	463.1	196.3	42.1 %	5.56	650.3	6.8	46.1	703.2

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