Appendix A Crop yield gap data from the Global Yield Gap and Water Productivity Atlas (www.yieldgap.org accessed 30-April-2020) that includes maize data for 64 countries, rice data for 21 countries, and wheat data for 52 countries. Yp represents potential yield (water-restricted yield under rainfed conditions); Ya represents actual yield; Yg represents yield difference (yield gap); Relative yield was calculated as Ya/Yp. Yp and Ya were obtained by weighted average of the corresponding yield and planting area under rainfed and irrigated conditions in a country.

Crop	Location	Yp (t/ha)	Ya (t/ha)	Yg (t/ha)	Relative yield
Maize	Albania	12.49	5.95	6.54	0.48
	Argentina	11.59	6.78	4.81	0.58
	Australia	12.46	10.11	2.34	0.81
	Bangladesh	10.10	5.73	4.37	0.57
	Belarus	11.45	5.44	6.01	0.48
	Belgium	12.58	11.00	1.58	0.87
	Bosnia and Herzegovina	6.55	4.42	2.13	0.67
	Brazil	10.81	5.99	4.82	0.55
	Bulgaria	7.33	5.87	1.46	0.80
	Burkina Faso	6.25	1.48	4.77	0.24
	China	11.90	7.55	4.35	0.63
	Croatia	9.97	6.70	3.27	0.67
	Czech Republic	9.68	7.37	2.31	0.76
	Ethiopia	12.49	2.23	10.25	0.18
	France	11.62	9.20	2.42	0.79
	Germany	10.95	9.65	1.30	0.88
	Ghana	8.64	1.69	6.95	0.20
	Greece	13.32	9.70	3.61	0.73
	Hungary	8.55	6.15	2.40	0.72
	India	9.35	1.57	7.78	0.17
	Indonesia	12.07	5.25	6.82	0.43
	Iran	16.51	6.56	9.95	0.40
	Italy	13.83	11.24	2.59	0.81
	Kenya	7.86	1.92	5.94	0.24
	Kosovo	5.51	3.00	2.51	0.54
	Macedonia, the Former Yugoslav Republic of	6.10	4.29	1.81	0.70
	Mali	9.68	1.89	7.79	0.20
	Moldova	8.05	2.94	5.11	0.36
	Montenegro	8.07	3.69	4.38	0.46
	Netherlands	12.97	11.76	1.21	0.91
	Nigeria	10.77	1.64	9.13	0.15
	Poland	10.99	6.15	4.85	0.56
	Portugal	15.08	8.49	6.58	0.56
	Serbia	9.68	6.06	3.62	0.63
	Romania	9.01	3.42	5.59	0.38

	Slovakia	9.99	5.49	4.50	0.55
	Slovenia	11.77	7.71	4.05	0.66
	Spain	14.74	10.76	3.98	0.73
	Switzerland	12.70	9.11	3.59	0.72
	Tanzania	5.96	1.20	4.77	0.20
	Uganda	6.85	1.61	5.24	0.23
	Ukraine	8.15	4.66	3.50	0.57
	United States	12.78	10.09	2.68	0.79
	Uruguay	8.08	5.14	2.93	0.64
	Zambia	11.33	2.32	9.01	0.20
Rice	Bangladesh	8.91	4.20	4.71	0.47
	Brazil	11.80	4.98	6.83	0.42
	Burkina Faso	6.24	2.00	4.24	0.32
	China	9.47	6.46	3.00	0.68
	Cote D'Ivoire	6.10	1.25	4.86	0.20
	Egypt	11.87	9.60	2.27	0.81
	Ghana	6.92	1.49	5.43	0.22
	India	6.82	3.18	3.65	0.47
	Indonesia	9.41	5.38	4.04	0.57
	Iran	7.34	4.36	2.98	0.59
	Madagascar	10.27	2.42	7.85	0.24
	Mali	7.99	3.69	4.30	0.46
	Niger	9.18	4.35	4.83	0.47
	Nigeria	6.12	2.10	4.02	0.34
	Rwanda	10.69	5.20	5.49	0.49
	Senegal	8.07	3.20	4.87	0.40
	Tanzania	6.94	1.76	5.18	0.25
	Uganda	4.08	1.77	2.31	0.43
	United States	12.41	8.13	4.28	0.66
	Uruguay	14.05	8.07	5.98	0.57
	Zambia	7.89	1.21	6.68	0.15
Wheat	Albania	8.70	3.83	4.86	0.44
	Argentina	5.16	3.02	2.14	0.59
	Australia	3.63	1.73	1.90	0.48
	Austria	8.64	5.26	3.38	0.61
	Bangladesh	4.94	2.21	2.73	0.45
	Belarus	9.20	3.60	5.60	0.39
	Belgium	11.31	8.74	2.57	0.77
	Bosnia and Herzegovina	9.22	3.41	5.81	0.37
	Bulgaria	8.11	3.64	4.47	0.45
	Croatia	8.04	4.93	3.11	0.61
	Cyprus	4.64	2.32	2.32	0.50
	Czech Republic	9.27	5.17	4.09	0.56

Denmark	8.09	7.13	0.96	0.88
Estonia	7.86	3.14	4.72	0.40
Ethiopia	8.28	2.23	6.06	0.27
Finland	7.44	3.69	3.76	0.50
France	9.81	7.17	2.64	0.73
Germany	9.73	7.63	2.10	0.78
Greece	6.06	3.07	3.00	0.51
Hungary	7.36	4.19	3.17	0.57
India	6.08	2.45	3.63	0.40
Iran	4.81	1.86	2.94	0.39
Ireland	11.82	8.73	3.09	0.74
Italy	6.49	3.82	2.66	0.59
Jordan	3.44	0.95	2.48	0.28
Kenya	6.04	2.51	3.53	0.42
Kosovo	8.21	3.00	5.21	0.37
Latvia	8.60	3.94	4.66	0.46
Lithuania	8.99	4.10	4.89	0.46
Luxemburg	9.04	6.16	2.87	0.68
Macedonia, the Former Yugoslav Republic of	7.99	3.07	4.92	0.38
Mexico	9.35	5.95	3.40	0.64
Moldova	6.97	2.46	4.52	0.35
Montenegro	7.57	3.09	4.48	0.41
Morocco	5.88	2.85	3.03	0.48
Netherlands	11.58	8.82	2.76	0.76
Norway	7.20	4.02	3.18	0.56
Poland	9.44	4.16	5.28	0.44
Portugal	5.38	1.53	3.84	0.29
Serbia	8.61	4.06	4.55	0.47
Romania	8.35	3.58	4.77	0.43
Slovakia	8.39	3.85	4.54	0.46
Slovenia	9.11	4.70	4.41	0.52
Spain	6.49	3.06	3.43	0.47
Sweden	8.73	6.21	2.52	0.71
Switzerland	9.66	5.94	3.72	0.61
Tanzania	4.45	1.21	3.24	0.27
Tunisia	5.91	2.13	3.77	0.36
Ukraine	8.25	3.06	5.19	0.37
United Kingdom	11.51	7.84	3.67	0.68
Uruguay	6.08	3.00	3.07	0.49

Appendix B Crop yield gap data from published papers. Water refers to the water management of the crop (R is rainfed, I is irrigation, RS is rainy season, and DS is dry season). Location abbreviations: NCP, North China Plain; NEC, Northeast China; NWC, Northwest China; MLRYR, Middle and Lower Reaches of the Yangtze River. Brazilian maize has two growing seasons (FGS is the first growing season, SGS is the second growing season). Rice is divided into early rice (E), late rice (L), and single-season rice (S). Yp represents potential yield (water-restricted yield under rainfed conditions); Ya represents actual yield; Yg represents yield difference (yield gap); Relative yield was calculated as Ya/Yp.

Crop	Location	Water	Ya (t/ha)	Yp (t/ha)	Yg (t/ha)	Relative yield (t/ha)	Reference
Wheat	Argentina	R	3.02	5.16	2.14	41	Aramburu Merlos et al. 2015
	Australia	R	1.7	3.7	2	47	Gobbett et al. 2016
	Australia	I	3.9	6.9	3	57	Gobbett et al. 2016
	Europe	I	5	9.5	4.5	53	Boogaard et al. 2013
	Europe	R	5	8	3	63	Boogaard et al. 2013
	Golestan (Iran)	R	4	5.8	1.8	69	Hajjarpoor et al. 2018
	Gujranwala (Pakistan)	I	3.7	6.6	2.9	56	Khaliq et al. 2019
	Narowal (Pakistan)	I	3	6.2	3.2	48	Khaliq et al. 2019
	NCP	I	5.7	8.4	2.7	68	Lu and Fan 2013
	NCP	I	4.5	8.1	3.6	56	Li et al. 2014
	NCP	I	8.9	10.5	1.6	85	Cao et al. 2019
	NWC	I	4.9	7.3	2.4	67	Fang et al. 2017
	Oklahoma (USA)	R	2.1	6.9	4.8	30	Patrignani et al. 2014
Maize	Argentina	R	6.79	11.6	4.81	59	Aramburu Merlos et al. 2015
	Argentina	R	10	15.3	5.3	65	Carciochi et al. 2020
	Bangladesh	I	5.8	12.87	7.07	45	Schulthess et al. 2013
	Brazil (FGS)	I	7.4	15.6	8.2	45	Maria Carolina et al. 2018
	Brazil (FGS)	R	7.4	13.1	5.7	56	Maria Carolina et al. 2018
	Brazil (SGS)	I	6	10.3	4.3	58	Maria Carolina et al. 2018
	Brazil (SGS)	R	6	9.2	3.2	65	Maria Carolina et al. 2018

	China	I	8.2	14.2	6	58	Liu et al. 2017
	China	R	7	10.7	3.7	65	Liu et al. 2017
	Indonesia	I	6	13.6	7.6	44	Agus et al. 2019
	Nebraska (USA)	I	13.2	14.9	1.6	89	van Ittersum et al. 2013
	NEC	I	5.6	10.9	5.3	51	Liu et al. 2012
	NEC	R	5.6	9.1	3.5	60	Liu et al. 2012
	Nkoranza (Ghana)	R	2.2	14.7	12.5	15	van Loon et al. 2019
	NWC	I	7.2	14.2	7	51	Fang et al. 2017
	Savelugu (Ghana)	R	2.3	14	11.7	16	van Loon et al. 2019
	Victoria (Australia)	R	1.9	2.6	0.8	73	van Ittersum et al. 2013
	Kenya	R	1.7	5.4	3.7	31	van Ittersum et al. 2013
	U.S.A	I	10.9	15	4.1	73	Balboa et al. 2019
Rice	Can Tho (Vietnam)	RS	3.9	7.8	3.9	50	Laborte et al. 2012
	Can Tho (Vietnam)	DS	6	8	2	75	Laborte et al. 2012
	Central Luzon (Philippines)	RS	3.8	7	3.2	54	Silva et al. 2017
	Central Luzon (Philippines)	DS	4.4	9.2	4.8	48	Silva et al. 2017
	Central Luzon (Philippines)	RS	3.7	8.7	5	43	Laborte et al. 2012
	Central Luzon (Philippines)	DS	4.6	9.6	5	48	Laborte et al. 2012
	Gujranwala, Pakistan	I	4.1	6.1	2	67	Khaliq et al. 2019
	Indonesia	I	6	9.5	3.5	63	Agus et al. 2019
	Indonesia	R	4.8	9.2	4.4	52	Agus et al. 2019
	MLRYR (E)	-	5.7	6.8	1.1	84	Zhang, ~~Tao,~~ et al. 2019a
	MLRYR (L)	-	6.4	7.1	0.7	90	Zhang, ~~Tao,~~ et al. 2019a
	MLRYR (S)	-	7.4	8.6	1.2	86	Zhang, ~~Tao,~~ et al. 2019a
	Narowal	I	2.4	6.5	4.1	40	Khaliq et al. 2019

	(Pakistan)						
	NEC	I	7.8	10.4	2.6	75	~~Espe et al. 2016~~ Zhang, et al. 2019a
	NEC (S)	-	7.4	10.4	3	71	Zhang, ~~Tao,~~ et al. 2019a
	Suphan Buri (Thailand)	RS	5	8	3	63	Laborte et al. 2012
	Suphan Buri (Thailand)	DS	5.1	8.2	3.1	61	Laborte et al. 2012
	USA		7.4-9.6	11.5-14.5	1.1-3.5	60-76	Espe et al. 2016
	West Java (Indonesia)	RS	5.6	8.4	2.8	67	Laborte et al. 2012
	West Java (Indonesia)	DS	4.2	7.7	3.5	55	Laborte et al. 2012

Appendix C Yield-limiting factors from published papers. Crop management is a comprehensive concept, it covers almost all factors that affect yield and yield gaps, except for climate conditions. Agro-technical service, government support, risk aversion of farmers, farm size, labor and expertise r elevant to farmers' decision-making, so classify them as socio-economic factors

Crop	Location	Limit factor	Reference
Wheat	Argentina	climate	Aramburu Merlos et al. 2015
	Australia	crop management, varieties	Gobbett et al. 2016
	Australia		Gobbett et al. 2016
	Europe	varieties, water supply	Boogaard et al. 2013
	Europe		Boogaard et al. 2013
	Golestan (Iran)	sowing dates, seeding rate, fertilize, irrigation	Hajjarpoor et al. 2018
	Gujranwala (Pakistan)	sowing dates, varieties,	Khaliq et al. 2019
	Narowal (Pakistan)	N deficiency	Khaliq et al. 2019
	NCP	fertilize, irrigation, agro-technical service, government support	Lu and Fan 2013
	NCP	climatic, varieties, sowing dates, soil, irrigation, agro-technical service, government support	Li et al. 2014
	NCP	seeding date, basal N input, seeding rate	Cao et al. 2019
	NWC	crop rotation, pests and weeds, water supply	Fang et al. 2017
	Oklahoma (USA)	soil, growing season rainfall	Patrignani et al. 2014

Maize	Argentina	climate	Aramburu Merlos et al. 2015
	Argentina	N and S supply	Carciochi et al. 2020
	Bangladesh	crop management	Schulthess et al. 2013
	Brazil (FGS)	water supply, temperature, crop management, climate, risk aversion of farmers	Maria Carolina et al. 2018
	Brazil (FGS)		Maria Carolina et al. 2018
	Brazil (SGS)		Maria Carolina et al. 2018
	Brazil (SGS)		Maria Carolina et al. 2018
	China	water supply, climate, plastic film, farm	Liu et al. 2017
	China	size, crop management	Liu et al. 2017
	Indonesia	water supply, pesticide and fertilizer, labor, expertise	Agus et al. 2019
	Nebraska (USA)	-	van Ittersum et al. 2013
	NEC	fertilize, irrigation, varieties, water	Liu et al. 2012
	NEC	supply, climate, sowing dates, density, soil	Liu et al. 2012
	Nkoranza (Ghana)	varieties, fertilize, density, crop management, government support, pest management	van Loon et al. 2019
	NWC	crop rotation, pests and weeds, water supply	Fang et al. 2017
	Savelugu (Ghana)	varieties, fertilize, density, crop management, government support, pest management	van Loon et al. 2019
	Victoria (Australia)		van Ittersum et al. 2013
	Kenya		van Ittersum et al. 2013
	U.S.A	intensification, irrigation, N fertilization, density, crop management, climate	Balboa et al. 2019
Rice	Can Tho (Vietnam)	seeding date, economically attractive, fertilization, water supply, farmer skills, varieties	Laborte et al. 2012
	Can Tho (Vietnam)		Laborte et al. 2012
	Central Luzon (Philippines)	varieties, irrigation, N fertilization, economically attractive, farmers' preferences	Silva et al. 2017
	Central Luzon (Philippines)		Silva et al. 2017
	Central Luzon (Philippines)	seeding date, economically attractive, fertilization, water supply, farmer skills, varieties	Laborte et al. 2012
	Central Luzon (Philippines)		Laborte et al. 2012
	Gujranwala (Pakistan)	sowing dates, varieties, N deficiency	Khaliq et al. 2019
	Indonesia	water supply, pesticide and fertilizer,	Agus et al. 2019

Indonesia	labor, expertise	Agus et al. 2019
MLRYR (E)	water supply, N supply, transplanting date, varieties, climate	Zhang et al. 2019a
MLRYR (L)		Zhang et al. 2019a
MLRYR (S)		Zhang et al. 2019a
Narowal (Pakistan)	sowing dates, varieties, N deficiency	Khaliq et al. 2019
NEC	water supply, N supply, transplanting date, varieties, climate	Zhang et al. 2019a
NEC (S)		Zhang et al. 2019a
Suphan Buri (Thailand)	seeding date, economically attractive, fertilization, water supply, farmer skills, varieties	Laborte et al. 2012
Suphan Buri (Thailand)		Laborte et al. 2012
USA	precision land-leveling, varieties	Espe et al. 2016
West Java (Indonesia)	seeding date, economically attractive, fertilization, water supply, farmer skills, varieties	Laborte et al. 2012
West Java (Indonesia)		Laborte et al. 2012

Appendix D Avergae NPFP of wheat, maize and rice from 2002-2017. Crop yield and nitrogen application rate were obtained from Food and Agriculture Organization Statistics.

Location	N rate	Yield			NPFP		
		wheat	maize	rice	wheat	maize	rice
Albania	50.09	3706.94	5681.99	-	74.01	113.44	-
Argentina	20.67	2695.85	6722.86	-	130.40	325.19	-
Australia	36.52	1767.02	6180.79	-	48.38	169.24	-
Austria	81.45	5232.93	-	-	64.25	-	-
Bangladesh	132.09	2425.14	5958.31	4170.66	18.36	45.11	31.57
Belarus	78.96	3318.07	4772.98	-	42.02	60.45	-
Belgium	186.37	8620.57	11289.36	-	46.26	60.58	-
Bosnia and Herzegovina	51.61	3430.89	4365.11	-	66.48	84.58	-
Brazil	52.67	-	4225.42	4455.50	-	80.22	84.59
Bulgaria	77.81	3728.63	5169.08	-	47.92	66.43	-
Burkina Faso	6.54	-	1641.21	2090.76	-	250.88	319.60

China	229.92	4754.89	5517.56	6551.69	20.68	24.00	28.50
Croatia	136.45	4827.99	6469.95	-	35.38	47.42	-
Cyprus	59.20	1853.76	-	-	31.32	-	-
Denmark	82.30	7305.52	-	-	88.77	-	-
Egypt	368.24	-	-	9597.46	-	-	26.06
Estonia	46.40	3163.13	-	-	68.18	-	-
Ethiopia	8.62	1983.89	2646.47	-	230.15	307.01	-
Finland	73.59	3773.60	-	-	51.28	-	-
France	111.94	6976.19	8885.63	-	62.32	79.38	-
Germany	140.70	7541.03	9415.69	-	53.60	66.92	-
Ghana	3.91	-	1717.22	2401.49	-	439.47	614.59
Greece	53.41	2593.39	10610.35	-	48.56	198.65	-
Hungary	67.50	4330.54	6216.31	-	64.15	92.09	-
India	88.49	2875.68	2333.85	3367.07	32.50	26.37	38.05
Indonesia	60.15	-	4247.40	4906.29	-	70.61	81.57
Italy	68.70	3695.18	9238.90	-	53.79	134.49	-
Kenya	15.56	2249.68	1646.04	-	144.56	105.77	-
Madagascar	1.73	-	-	3375.59	-	-	1952.62
Mali	17.23	-	2203.83	2934.98	-	127.88	170.31
Latvia	47.31	3691.17	-	-	78.03	-	-
Lithuania	44.27	4059.84	-	-	138.87	-	-
Mexico	46.66	5082.69	-	-	108.93	-	-

Morocco	26.99	1650.57	-	-	61.15	-	-
Netherlands	234.66	8571.49	11085.99	-	36.53	47.24	-
Niger	0.34	-	-	3803.83	-	-	11187.74
Nigeria	4.84	-	1679.38	1715.66	-	347.16	354.66
Norway	118.88	4515.99	-	-	37.99	-	-
Pakistan	95.87	2634.26	-	3418.93	27.48	-	35.66
Philippines	51.55	-	-	3712.46	-	-	72.01
Poland	88.16	4191.84	6156.09	-	47.55	69.83	-
Portugal	56.72	1693.57	6943.74	-	29.86	122.43	-
Romania	31.94	3078.46	3780.09	-	96.38	118.35	-
Rwanda	2.16	-	-	4360.51	-	-	2020.00
Senegal	5.31	-	-	3355.18	-	-	631.79
Serbia	91.91	3963.78	5282.23	-	43.13	57.47	-
Slovakia	70.00	4371.84	6143.01	-	62.46	87.76	-
Slovenia	128.70	4672.25	7711.83	-	36.30	59.92	-
Spain	55.73	2964.25	10460.48	-	53.19	187.68	-
Sweden	65.67	6123.37	-	-	93.24	-	-
Switzerland	113.05	5772.49	9562.44	-	51.06	84.59	-
Thailand	68.10	-	-	3006.13	-	-	44.14
Tunisia	18.22	1781.60	-	-	97.77	-	-
Uganda	0.69	-	2116.26	2016.37	-	3061.50	2916.99
Ukraine	22.67	3254.11	4914.94	-	143.54	216.80	-

Uruguay	60.03	-	4639.87	7514.78	-	77.30	125.19
Zambia	27.55	-	2299.66	1415.80	-	83.46	51.38