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Yield gap of the double-crop system of main-season soybean with off-season maize in Brazil

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Supplementary material

Table S1. Locations, and they respective states, from where the weather stations (WS) were selected, their codes, geographical coordinates, Köppen's climate classification (Alvares *et al.* 2013) and soil classification, according to Brazilian soil classification system (IBGE 2019).

State	Location	Latitude (degrees)	Longitude (degrees)	Altitude (meters)	Köppen's climatic	Soil classification
BA	Cocos (COC)	-14.40	-44.40	520	Aw	Oxisol
GO	Chapadão do Céu (CHA)	-18.80	-52.60	821	Am	Ultisol
GO	Rio Verde (RIV)	-17.80	-50.91	774	Aw	Oxisol
GO	Formosa (FOR)	-15.54	-47.33	935	Aw	Oxisol
MA	São Raimundo das Mangabeiras (SRM)	-7.53	-46.03	259	Aw	Oxisol
MG	Uberaba (UBE)	-19.73	-47.95	737	Cwa	Oxisol
MG	Buritis (BUR)	-15.52	-46.40	894	Aw	Oxisol
MS	Ponta Porã (POP)	-22.55	-55.71	650	Cfa	Oxisol
MS	Rio Brilhante (RIB)	-21.77	-54.52	324	Am	Oxisol
MS	S. Gabriel do Oeste (SGO)	-19.42	-54.55	646	Am	Oxisol
MS	Coxim (COX)	-18.51	-54.73	251	Aw	Oxisol
MT	Rondonópolis (RON)	-16.45	-54.56	284	Aw	Ultisol
MT	Primavera do Leste (PRL)	-15.83	-54.38	450	Aw	Oxisol
MT	Nova Xavantina (NOX)	-14.70	-52.35	316	Aw	Oxisol
MT	Campo Novo do Parecis (CNP)	-13.78	-57.83	525	Aw	Oxisol
MT	Sorriso (SOR)	-12.55	-55.72	379	Aw	Oxisol
MT	Querência (QUE)	-12.62	-52.22	361	Aw	Oxisol
PA	Altamira (ALT)	-3.21	-52.21	74.0	Am	Oxisol
PA	Bom Jesus do Tocantins (BJT)	-5.36	-49.13	95	Aw	Oxisol
PI	Uruçuí (URU)	-7.44	-44.34	399	Aw	Oxisol
PR	Campo Mourão (CAM)	-24.04	-52.40	616	Cfa	Oxisol
PR	Londrina (LON)	-23.30	-51.15	610	Cfa	Ultisol
RO	Vilhena (VIL)	-12.73	-60.15	615	Am	Oxisol
RO	Rio Crespo (RIC)	-9.75	-62.75	157	Am	Oxisol
SP	Taquarituba (TAQ)	-23.19	-49.38	561	Cfa	Oxisol
SP	Ibirarema (IBI)	-22.74	-50.38	484	Cfa	Ultisol
SP	Barretos (BAR)	-20.55	-48.54	534	Aw	Oxisol
TO	Figueirópolis (FIG)	-12.10	-49.10	291	Aw	Ultisol

Table S2. Silt, clay, sand, pH, carbon and nitrogen contents (%), of soils in the 28 Brazilian locations where soybean and maize off season yields were simulated.

State	Location	Silt (%)	Clay (%)	Sand (%)	pH	Carbon (%)	Nitrogen (%)
BA	Cocos (COC)	10	41	49	5.9	0.20	0.02
GO	Chapadão do Céu (CHA)	9	37	54	5.4	0.70	0.08
GO	Rio Verde (RIV)	17	26	57	5.3	4.80	0.44
GO	Formosa (FOR)	24	45	31	5.3	1.21	0.12
MA	São R. das Mangabeiras (SRM)	13	32	55	5.5	0.43	0.06
MG	Uberaba (UBE)	5	27	68	5.5	0.35	0.03
MG	Buritis (BUR)	5	22	73	5.7	0.26	0.02
MS	Ponta Porã (POP)	15	59	26	5.0	1.47	0.11
MS	Rio Brilhante (RIB)	8	52	40	5.0	1.97	0.14
MS	S. Gabriel do Oeste (SGO)	37	24	39	5.2	1.60	0.09
MS	Coxim (COX)	7	27	66	5.2	1.18	0.11
MT	Rondonópolis (RON)	46	27	27	5.30	0.59	0.06
MT	Primavera do Leste (PRL)	12	32	56	5.6	1.50	0.09
MT	Nova Xavantina (NOX)	18	32	50	6.4	0.19	0.03
MT	Campo N. do Parecis (CNP)	7	30	63	5.6	0.80	0.06
MT	Sorriso (SOR)	10	56	34	5.2	3.20	0.30
MT	Querência (QUE)	8	49	43	5.5	2.10	0.20
PA	Altamira (ALT)	12	27	61	5.3	1.55	0.13
PI	Uruçuí (URU)	26	24	50	5.1	0.99	0.08
PR	Campo Mourão (CAM)	17	76	7	5.4	2.83	0.25
PR	Londrina (LON)	9	49	42	5.32	0.50	0.05
RO	Vilhena (VIL)	8	39	53	5.6	2.90	0.10
RO	Rio Crespo (RIC)	34	37	29	6.2	1.40	0.10
SP	Taquarituba (TAQ)	10	55	35	4.9	0.66	0.06
SP	Ibirarema (IBI)	17	64	19	6.0	2.74	0.27
SP	Barretos (BAR)	18	61	21	5.5	2.39	0.16
TO	Figueirópolis (FIG)	18	49	33	5.3	0.75	0.04
TO	Bom J. do Tocantins (BJT)	15	39	46	5.3	0.26	0.02

Table S3. Crop models´ performance for simulating soybean yield at the calibration and validation phases.

Adapted from Battisti et al. (2017).

Models	RMSE (kg ha^{-1})	d	R^2
	Calibration		
FAO	650	0.91	0.79
DSSAT	548	0.93	0.79
APSIM	550	0.90	0.69
	Validation		
FAO	752	0.77	0.21
DSSAT	511	0.89	0.54
APSIM	732	0.79	0.43

RMSE = Root mean error square; d = Wilmott agreement index; R^2 = coefficient of determination.

Table S4. Crop models´ performance for simulating maize off season yield at the calibration and validation phases.

Adapted from Duarte (2018) (*) and Bender (2017) (**).

Models	RMSE (kg ha^{-1})	d	R^2
		Calibration	
FAO*	1459	0.72	0.28
DSSAT**	576	0.86	0.69
APSIM**	1205	0.76	0.31
		Validation	
FAO*	2008	0.71	0.28
DSSAT**	337	0.93	0.77
APSIM**	1554	0.81	0.49

RMSE = Root mean error square; d = Wilmott agreement index; R^2 = coefficient of determination.

Table S5. Average actual (Ya), water-limited (Yw) and potential (Yp) soybean yields, and the respective yield gaps, caused by water deficit (YGw) and by sub-optimal crop management (YG_M), in different Brazilian locations.

The interannual variability of soybean Ya, Yw and Ya are presented in Figure S3 at supplementary material.

States	Location	Yp	Yw	Ya	YGw	YG_M
				kg ha^{-1}		
BA	Cocos (COC)	5148.6	3113.2	3045.2	2035.4	67.9
GO	Chapadão do Céu (CHA)	4807.6	4554.6	3220.5	253.0	1334.1
GO	Rio Verde (RIV)	5090.2	4081.6	3025.2	1008.5	1056.4
GO	Formosa (FOR)	5147.7	3668.1	3050.8	1479.6	617.3
MA	São Raimundo das Mangabeiras (SRM)	4260.4	3299.1	2707.0	961.2	592.1
MG	Uberaba (UBE)	4881.4	4079.4	3047.5	802.0	1031.9
MG	Buritis (BUR)	5063.4	3657.7	2594.1	1405.5	1063.5
MS	Ponta Porã (POP)	5108.7	4094.6	3231.0	1014.0	863.6
MS	Rio Brilhante (RIB)	5071.7	3682.3	3010.2	1389.3	672.1
MS	S. Gabriel do Oeste (SGO)	4840.6	3993.8	3089.4	846.8	904.4
MS	Coxim (COX)	4754.8	4016.3	3380.2	738.5	636.1
MT	Rondonópolis (RON)	4803.6	4143.3	3190.5	660.3	952.7
MT	Primavera do Leste (PRL)	4746.6	3965.4	3259.2	781.1	706.2
MT	Nova Xavantina (NOX)	4890.9	4016.1	2981.3	874.7	1034.7
MT	Campo Novo do Parecis (CNP)	4470.7	4189.5	3086.9	281.2	1102.6
MT	Sorriso (SOR)	4288.6	3954.9	3197.3	333.7	757.5
MT	Querência (QUE)	4446.8	4170.4	3156.4	276.4	1014.0
PA	Altamira (ALT)	3868.4	3570.8	3355.1	297.6	215.6
PA	Bom Jesus do Tocantins (BJT)	3931.7	3444.9	3044.5	486.8	400.3
PI	Uruçuí (URU)	4275.1	3429.2	2607.0	845.9	822.2
PR	Campo Mourão (CAM)	5163.2	4003.3	3193.4	1159.9	809.9
PR	Londrina (LON)	4990.0	3998.4	3121.6	991.6	876.7
RO	Vilhena (VIL)	4492.4	4274.4	3145.0	217.9	1129.3
RO	Rio Crespo (RIC)	4207.9	4121.6	3106.8	86.3	1014.8
SP	Taquarituba (TAQ)	5100.3	4107.4	3235.3	992.8	872.1
SP	Ibirarema (IBI)	4943.9	4166.0	2910.0	777.9	1255.9
SP	Barretos (BAR)	4702.0	4180.7	2897.8	521.3	1282.8
TO	Figueirópolis (FIG)	4238.8	3633.3	2906.6	605.5	726.7
	Average	4704.9	3914.7	3064.2	790.2	850.5
	Standard deviation	388.0	329.7	194.6	448.3	299.0

Table S6. Average actual (Ya), water-limited (Yw) and potential (Yp) maize off-season yields, and the respective yield gaps, caused by water deficit (YGw) and by sub-optimal crop management (YG_M), in different Brazilian locations.

The interannual variability of maize off-season Ya, Yw and Ya are presented in Figure S4 at supplementary material.

States	Location	Yp	Yw	Ya	YGw	YG_M
				kg ha^{-1}		
BA	Cocos (COC)	10557.0	4904.2	4250.0	5652.7	654.2
GO	Chapadão do Céu (CHA)	10294.4	7771.7	4909.9	2522.7	2861.7
GO	Rio Verde (RIV)	10269.7	6452.4	3707.0	3817.3	2745.3
GO	Formosa (FOR)	11171.7	6286.3	4530.8	4885.4	1755.4
MA	São Raimundo das Mangabeiras (SRM)	8047.9	6416.4	2978.9	1631.5	3437.4
MG	Uberaba (UBE)	10413.8	7397.5	4575.5	3016.2	2822.0
MG	Buritis (BUR)	10379.0	5409.6	4205.9	4969.4	1203.6
MS	Ponta Porã (POP)	9252.7	6662.7	4728.6	2589.9	1934.1
MS	Rio Brilhante (RIB)	9613.6	7526.3	4967.0	2087.2	2559.3
MS	S. Gabriel do Oeste (SGO)	10193.7	7145.4	4752.0	3048.3	2393.4
MS	Coxim (COX)	10088.1	6687.0	5753.8	3401.1	933.1
MT	Rondonópolis (RON)	9281.6	7596.2	5996.3	1685.4	1599.8
MT	Primavera do Leste (PRL)	9403.5	5352.1	5282.2	4051.4	69.8
MT	Nova Xavantina (NOX)	10057.0	5497.6	4861.6	4559.4	635.9
MT	Campo Novo do Parecis (CNP)	9033.2	6563.9	5348.3	2469.2	1215.6
MT	Sorriso (SOR)	8860.9	6615.7	5933.0	2245.1	682.6
MT	Querência (QUE)	9156.7	6615.7	5357.7	2541.0	1258.0
PA	Altamira (ALT)	8014.5	7666.2	3621.4	348.3	4044.7
PA	Bom Jesus do Tocantins (BJT)	7778.7	6979.7	3130.8	798.9	3848.9
PI	Uruçuí (URU)	9079.7	5816.6	3501.5	3263.2	2315.0
PR	Campo Mourão (CAM)	7657.2	6675.3	4970.1	981.8	1705.1
PR	Londrina (LON)	8502.2	7797.3	4958.1	704.8	2839.1
RO	Vilhena (VIL)	8674.1	7291.9	4760.0	1382.1	2531.9
RO	Rio Crespo (RIC)	8001.1	6729.5	2290.4	1271.5	4439.0
SP	Taquarituba (TAQ)	9626.7	7964.3	5233.3	1662.3	2731.0
SP	Ibirarema (IBI)	9846.1	8280.5	3856.2	1565.6	4424.3
SP	Barretos (BAR)	10388.8	7167.5	4735.5	3221.2	2432.0
TO	Figueirópolis (FIG)	7992.9	6282.7	4480.2	1710.1	1802.5
	Average	9344.2	6769.8	4559.9	2574.4	2209.9
	Standard deviation	982.2	850.3	894.3	1389.3	1169.5

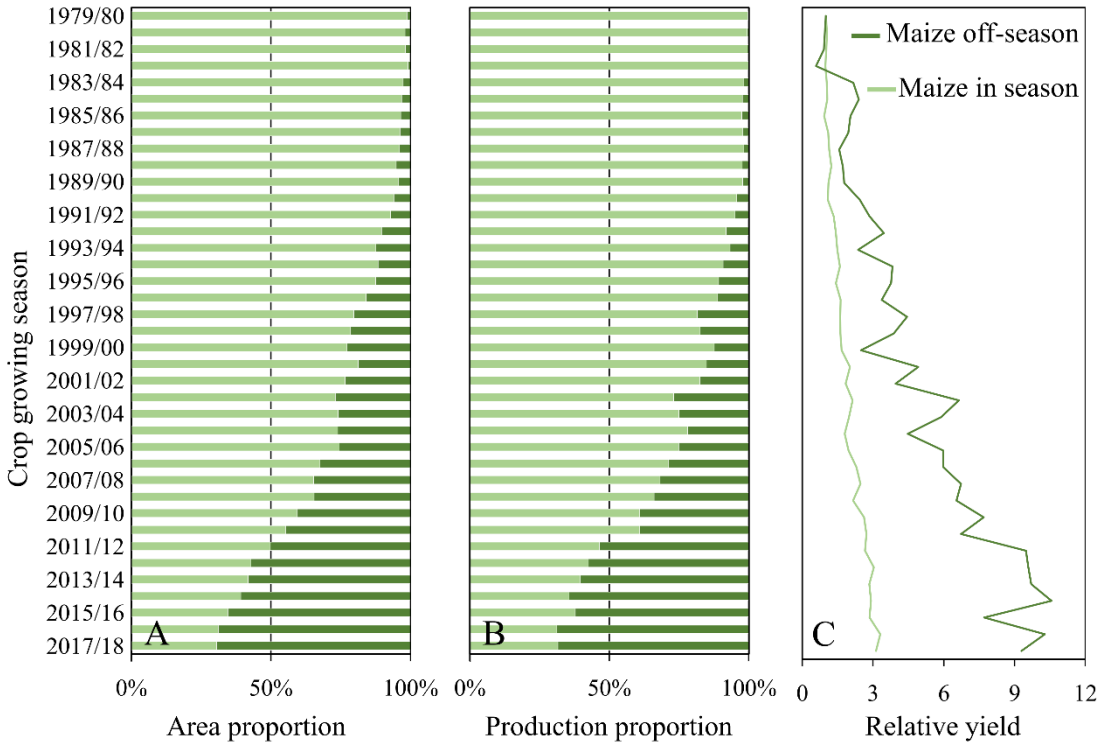

Figure S1. Historical series (1979-2018) of contribution, in proportion (%), of maize off season and maize in season for total maize cultivated area (A) and production (B) in Brazil; Historical changes in the relative yield in maize off season and summer maize (relative yield scaled to 1 in the first crop growing season - 1979/80) (C). Adapted from Conab (2019).

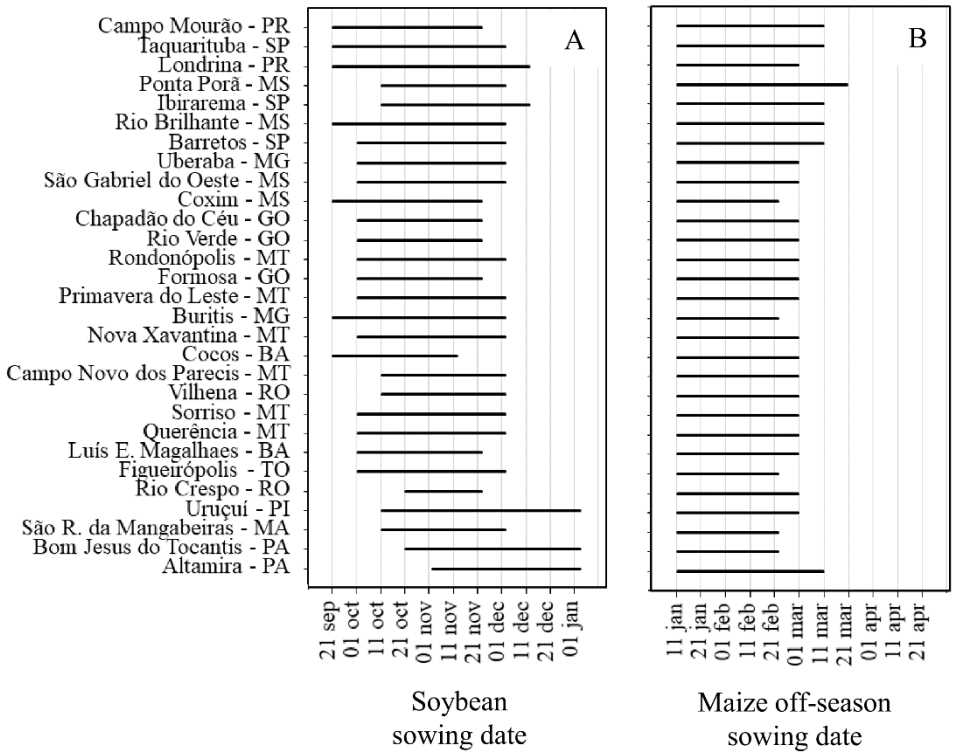

Figure S2. Best sowing windows for soybean (A) and for maize off-season (B), in different Brazilian locations. The criteria used to determine the best sowing dates are presented by Nóia Júnior and Sentelhas (2019).

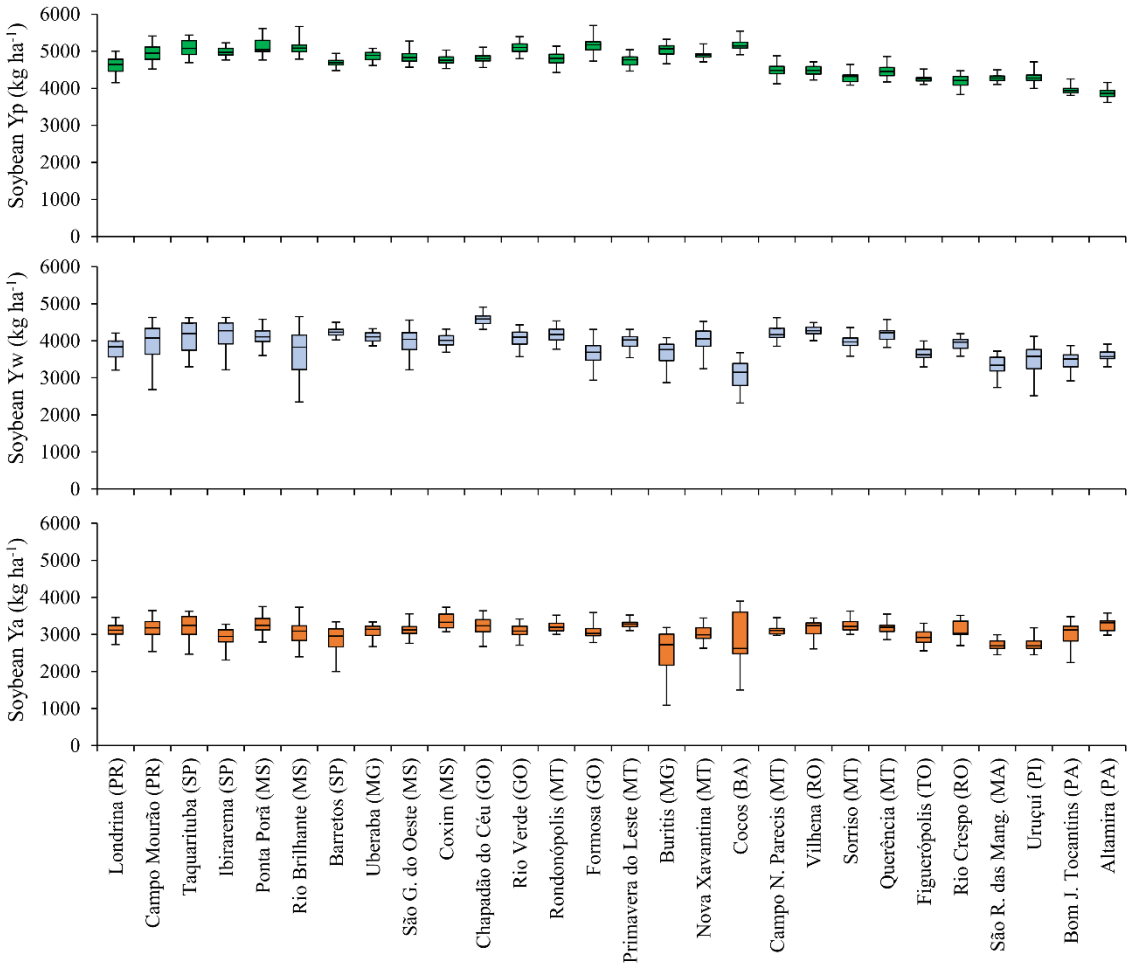

Figure S3. Inter-annual variability of soybean potential (Yp), water-limited (Yw) and actual (Ya) yields for different Brazilian locations. The error bars present the variation of all dataset.

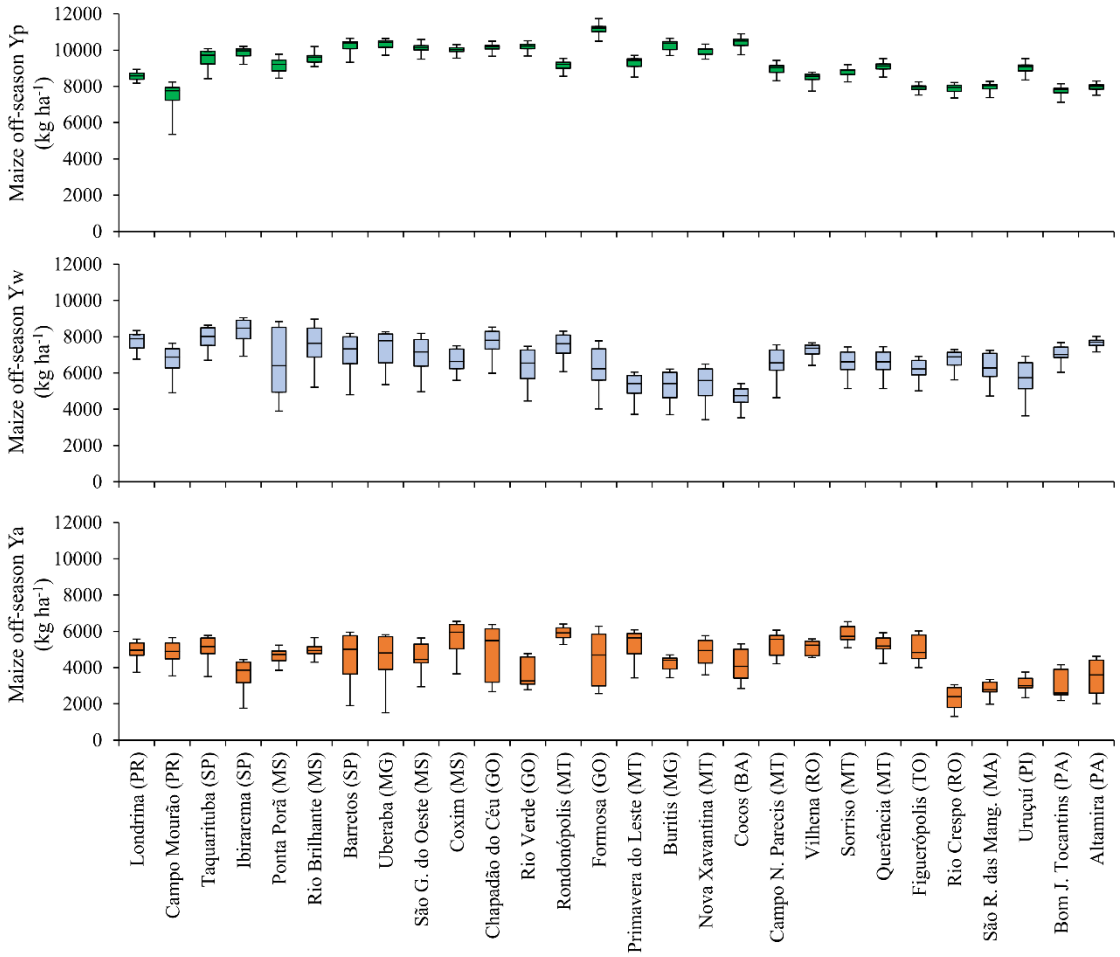

Figure S4. Inter-annual variability of maize off-season potential (Yp), water-limited (Yw) and actual (Ya) yields for different Brazilian locations. The error bars present the variation of all dataset.

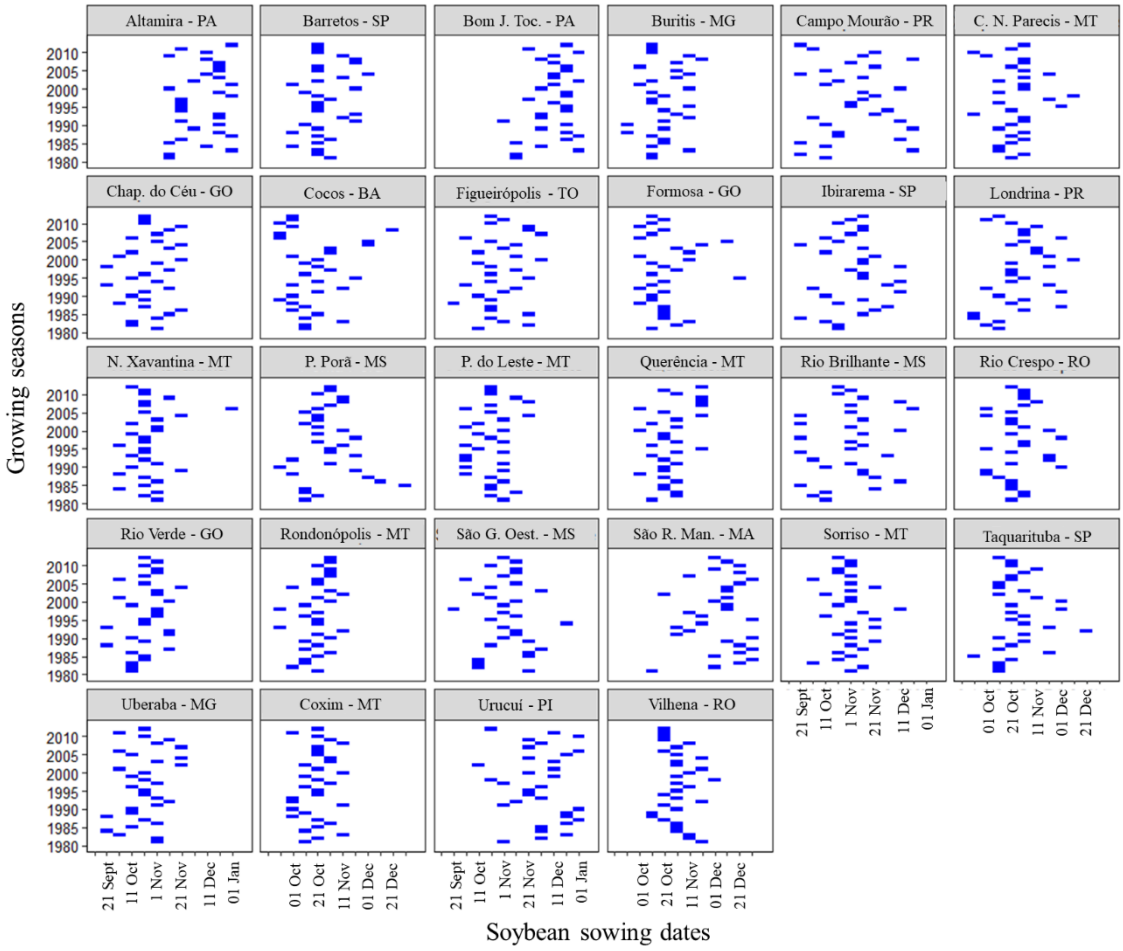

Figure S5. Best sowing date highlighted in blue for soybean in 28 different Brazilian locations for 34 growing seasons (1981-2013). The criteria used to determine the best sowing dates were based in highest water-limited yield.

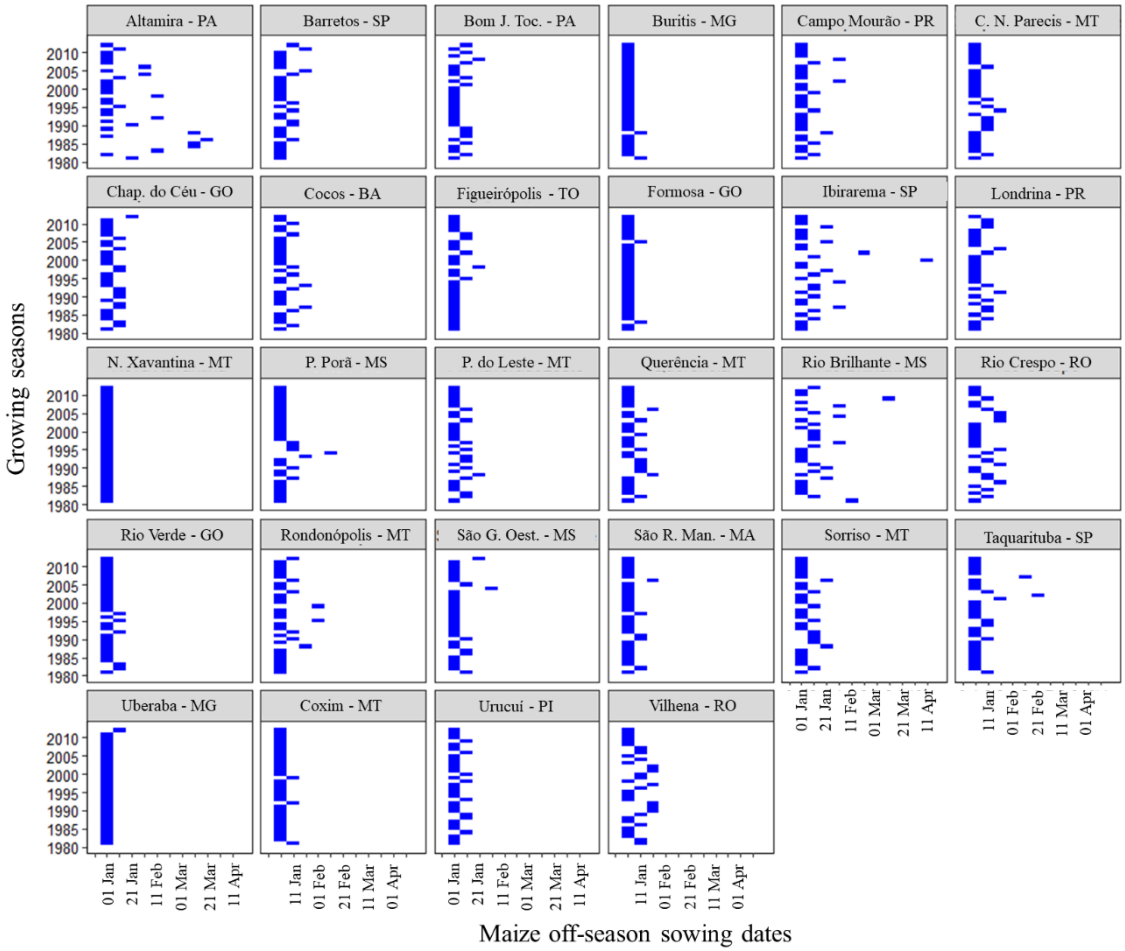

Figure S6. Best sowing date highlighted in blue for maize of season in 28 different Brazilian locations for 34 growing seasons (1981-2013). The criteria used to determine the best sowing dates were based in highest water-limited yield.

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