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Quantifying the impact of ozone on crops in Sub-Saharan Africa demonstrates regional and local hotspots of production loss.

Environmental Science and Pollution Research

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Supplementary Material

Table S1. Input parameterisation for land-cover definitions for EMEP-WRF Africa.

CROP	#Name	code	type	PFT	hveg	Alb	eNH4	SGS50	DSGS	EGS50	DEGS	LAImin	LAImax	SLAIlen	ELAIlen	BiomasD	Eiso	EmtI	Emtp	Eiso-m2	Emt-m2
	#				m	(%)	day	days/d	day	days/d	day	m2/m2	m2/m2	days	days	g/m2	ug/g/h	ug/g/h	ug/g/h		
Wheat	IAM_AfrWh_Irrigated	IAM_AfricaWheat_Irrigated	ECR	NOLPJ	1	20	0					3.5	3.5	1	1	0	0	0	0	0	0
Wheat	IAM_AfrWh_NonIrrig	IAM_AfricaWheat_NonIrrig	ECR	NOLPJ	1	20	0					3.5	3.5	1	1	0	0	0	0	0	0
Bean	IAM_AfrBe_Irrigated	IAM_AfricaBean_Irrigated	ECR	NOLPJ	1	20	0					4	4	1	1	0	0	0	0	0	0
Bean	IAM_AfrBe_NonIrrig	IAM_AfricaBean_NonIrrig	ECR	NOLPJ	1	20	0					4	4	1	1	0	0	0	0	0	0

IAM_AfricaWheat_Irrigated = POD_3IAM for irrigated African wheat
IAM_AfricaWheat_NonIrrig = POD_3IAM for non- irrigated African wheat
IAM_AfricaBean_Irrigated = POD_3IAM for irrigated African beans
IAM_AfricaBean_NonIrrig = POD_3IAM for non-irrigated African beans

User notes:
Start and end days of the growing season were not needed for these model runs as daily values of POD_3IAM were used for this exercise.

h = Height of vegetation, Alb = Albedo, ENH4 = Flag for possible Nhx fluxes
LAImax - give as -1 if bulk resistance
SLAIlen = days from LAImin to LAImax at start of season
ELAIlen = days from LAImax to LAImin at end of season
(Set SLAIlen and ELAIlen to 1 for vegetation with constant LAI)
BVOC biomass loosely based upon Simpson et al., (1999)
BVOC data only used outside Europe as defaults
'type' - used in deposition system, e.g, to define areas where N-dep to coniferous forest is calculated
ECF - conif forest; EDF - decid forest; SNL - seminnatural; W - Water

Table S2. Input parameterisation for DO_3SE within EMEP-WRF Africa

For explanation of parameters see EMEP user manual (http://emep.int/mscw/index_mscw.html)

CROP	# Code	Landcover	gmax	fmin	f_phen	#	#	#	#	#	Astart	Aend	flight	ftemp	#	#	Surface	Res.	fVDP	#	VPD	fSWP	#	rootd	Lw,,,,
	#Code	LU	#	#	fac	fac	fac	fac	len	len	(rel-SGS)	(rel_EGS)	#	min	opt	max	RgsS	RgsO	max	min	Crit	SWPmax	PWP	m	m,,,,
	#	#	#	#	a	b	c	d	e	f	days	days	#	#	#	#	#	#	#	#	#	#	#	#	#
Wheat	IAM_AfrWh_Irrigated	IAM_AfricaWheat_Irrigated	430	0.01	1	1	1	1	1	1	0	0	0.011	12	28	39	150	200	3.2	4.6	8	-9.99	-99.9	0.8	0.02,,,,
Wheat	IAM_AfrWh_NonIrrig	IAM_AfricaWheat_NonIrrig	430	0.01	1	1	1	1	1	1	0	0	0.011	12	28	39	150	200	3.2	4.6	8	-9.99	-99.9	0.8	0.02,,,,
Bean	IAM_AfrBe_Irrigated	IAM_AfricaBean_Irrigated	415	0.01	1	1	1	1	1	1	0	0	0.02	15	29	43	150	200	2.8	4.5	8	-9.99	-99.9	0.6	0.03,,,,
Bean	IAM_AfrBe_NonIrrig	IAM_AfricaBean_NonIrrig	415	0.01	1	1	1	1	1	1	0	0	0.02	15	29	43	150	200	2.8	4.5	8	-9.99	-99.9	0.6	0.03,,,,

Where:

IAM_AfricaWheat_Irrigated = POD_3IAM for irrigated African wheat
IAM_AfricaWheat_NonIrrig = POD_3IAM for non- irrigated African wheat
IAM_AfricaBean_Irrigated = POD_3IAM for irrigated African beans
IAM_AfricaBean_NonIrrig = POD_3IAM for non-irrigated African beans

Growing seasons used to calculate POD_3IAM

For each crop, three-month growing periods (90 days before harvest) were allocated for each country, based on information from the FAO crop calendar. Beans have more than one growing season in some African countries, so there are two sections of the table for this crop. SGS = Start day of growing season, EGS = End day of growing season, from 1 – 365.

Table S3: African wheat

Country	3 months	SGS	EGS
Somalia	April - June	91	180
Tanzania	April - June	91	180
Rwanda	April - June	91	180
Uganda	April - June	91	180
Congo DRC	April - June	91	180
Cameroon	April - June	91	180
Burundi	May - July	121	210
Malawi	May - July	121	210
Mozambique	June - Aug	152	241
Zimbabwe	June - Aug	152	241
Namibia	July - Sep	182	271
South Africa	July - Sep	182	271
Ethiopia	July - Sep	182	271
Kenya	July - Sep	182	271
Zambia	July - Sep	182	271
Angola	July - Sep	182	271
Madagascar	Aug - Oct	213	302
Swaziland	Aug - Oct	213	302
Eritrea	Aug - Oct	213	302
Lesotho	Aug - Oct	213	302
Mauritania	Dec - Feb	335	59
South Sudan	Dec - Feb	335	59
Sudan	Dec - Feb	335	59
Mali	Dec - Feb	335	59
Niger	Dec - Feb	335	59
Chad	Jan - March	1	90
Nigeria	Jan - March	1	90

Table S4: Dry beans

Season 1			
Country	**3 months**	**SGS**	**EGS**
Rwanda	March - May	60	149
Tanzania	April - June	91	180
Uganda	April - June	91	180
Kenya	April - June	91	180
Ethiopia	April - June	91	180
South Africa	April - June	91	180
Burundi	April - June	91	180
Madagascar	April - June	91	180
Congo	April - June	91	180
Congo DRC	April - June	91	180
Cameroon	April - June	91	180
Mozambique	April - June	91	180
Swaziland	April - June	91	180
Zimbabwe	April - June	91	180
Djibouti	April - June	91	180
Eritrea	April - June	91	180
Namibia	April - June	91	180
Malawi	May - July	121	210
Cote d'Ivoire	June - Aug	152	241
Ghana	June - Aug	152	241
Benin	June - Aug	152	241
Togo	June - Aug	152	241
Chad	June - Aug	152	241
Somalia	June - Aug	152	241
Mauritania	June - Aug	152	241
Niger	June - Aug	152	241

Season 2			
Country	**3 months**	**SGS**	**EGS**
Ethiopia	Aug - Oct	213	302
South Sudan	Aug - Oct	213	302
Tanzania	Oct - Dec	274	363
Uganda	Oct - Dec	274	363
Kenya	Oct - Dec	274	363
Rwanda	Oct - Dec	274	363
Burundi	Oct - Dec	274	363
Congo	Oct - Dec	274	363
Congo DRC	Oct - Dec	274	363
Cameroon	Oct - Dec	274	363
Somalia	Oct - Dec	274	363
South Africa	Dec - Feb	335	59
Madagascar	Dec - Feb	335	59
Malawi	Jan - March	1	90
Mozambique	Jan - March	1	90
Lesotho	Jan - March	1	90
Angola	Jan - March	1	90

Table S5. Wheat production per South African province for 2010, split by percentage rainfed and irrigated production, using SPAM spatial data.

Province	Total production (th. Tonnes)	% Rainfed	% Irrigated
Western Cape	670	78.2	21.8
Free State	520	95.0	5.0
Northern Cape	272	44.4	55.6
North West	123	79.9	20.1
Limpopo	109	59.7	40.3
KwaZulu-Natal	39.88	67.0	32.0
Mpumalanga	38.65	80.8	19.2
Eastern Cape	22.99	43.4	56.6
Gauteng	11.27	84.4	15.6

Table S6. 90-day accumulation periods used to calculate POD_3IAM for wheat in the provinces of South Africa. Start (SGS) and end of growing season (EGS) are expressed as day of year.

Province	Accumulation period	SGS	EGS
Free State	Aug - Sept – Oct	213	302
Gauteng	Aug - Sept – Oct	213	302
North West	Aug - Sept – Oct	213	302
Mpumalanga	Aug - Sept – Oct	213	302
KwaZulu-Natal	Aug - Sept - Oct	213	302
Western Cape	July - Aug - Sept	182	271
<u>Irrigated areas</u>			
Limpopo (warmer irrigation areas)	Sept - Oct - Nov	244	333
Northern Cape (cooler)	Oct - Nov - Dec	274	363
Eastern Cape (cooler)	Oct - Nov - Dec	274	363
<u>Non-irrigated</u>			
Limpopo	Aug - Sept – Oct	213	302
Northern Cape	Aug - Sept – Oct	213	302
Eastern Cape	Aug - Sept - Oct	213	302

Table S7. Dry bean production per South African province for 2010, split by percentage rainfed and irrigated production, using SPAM spatial data.

Province	Total production (Tonnes)	% Rainfed	% Irrigated
Free State	20568	92.7	7.3
Mpumalanga	11789	89.6	10.4
Limpopo	7894	36.1	63.9
KwaZulu-Natal	6837	69.1	30.9
North West	4957	70.4	29.6
Gauteng	3288	86.9	13.1
Eastern Cape	1800	83.3	16.8
Northern Cape	1023	10.5	89.5
Western Cape	630	64.5	35.5

Table S8. 90-day accumulation periods used to calculate POD_3IAM for beans in the provinces of South Africa. Start (SGS) and end of growing season (EGS) are expressed as day of year.

Province	Accumulation period	SGS	EGS
Free State	Dec - Jan - Feb	335	59
Mpumalanga: Highveld	Dec - Jan - Feb	335	59
Limpopo: Highveld	Dec - Jan - Feb	335	59
North West	Dec - Jan - Feb	335	59
KwaZulu-Natal: Highveld	Dec - Jan - Feb	335	59
Western Cape	Dec - Jan - Feb	335	59
Eastern Cape	Dec - Jan - Feb	335	59
Gauteng	Dec - Jan - Feb	335	59
Nothern Cape	Dec - Jan - Feb	335	59
Mpumalanga: Lowveld	March - April - May	60	149
Limpopo: Lowveld	March - April - May	60	149
KwaZulu-Natal: Lowveld	March - April - May	60	149

Yield loss calculations

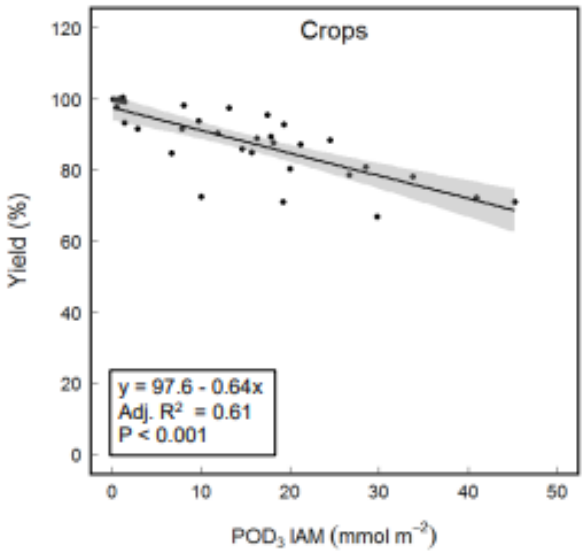

Figure S1. Flux-effect relationship for wheat, using POD_3IAM, from the Modelling and Mapping Manual (CLRTAP, 2017). The wheat data come from 13 experiments carried out on five wheat cultivars in Europe (Belgium, Finland, Italy and Sweden) (Pleijel *et al.,* 2007).The regression of yield with POD_3IAM was based on the approach followed by Fuhrer (1994). For each individual experiment, yield was calculated at zero POD_3IAM by obtaining the intercept value from the regression model. This was then used as the reference level for no effect (at the individual experiment level) when calculating relative yield ('Yield (%)' in this figure). Wheat yield under different levels of ozone flux was thus comparable between experiments, on a common relative scale.

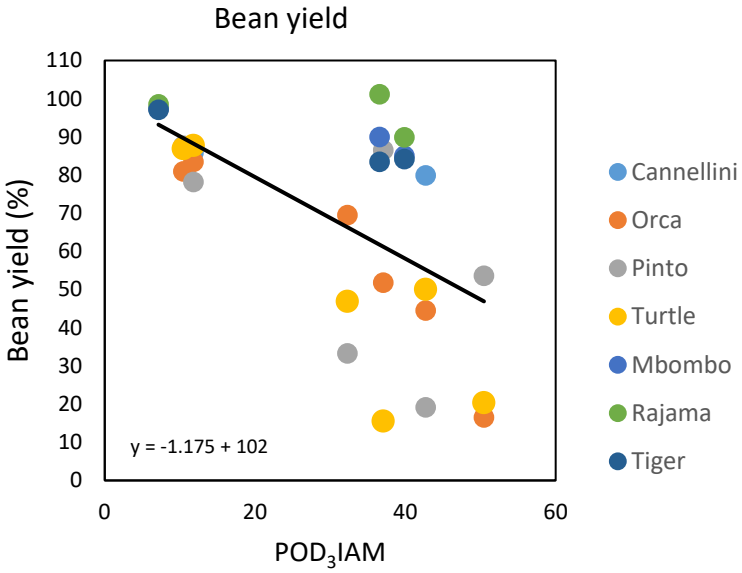

Figure S2. The relationship between the percentage bean yield and stomatal ozone flux (POD_3IAM) for common bean based on experimental data collected in the UK CEH Bangor solardomes for seven bean cultivars during the growing seasons of 2017-2019. The regression of yield with POD_3IAM followed the approach used by Fuhrer (1994). For each bean cultivar, yield was calculated at zero POD_3IAM by obtaining the intercept value from the regression model. This was then used as the reference level for no effect when calculating relative yield ('Bean yield (%)' in this figure).

Table S9. Impact of ozone on wheat production in SSA, for all wheat producing countries. Total production loss due to ozone is estimated for 2015.

Country	Wheat prod 2010 (Th. t)	Wheat prod 2015 (Th. t)	Av. POD_3IAM (mmol m^{-2})	sd	Av. % yield loss	sd	Total Prod loss (Th. t)
Ethiopia	2950	4805	9.7	3.8	6.1	2.4	233
Sudan	442	853	7.5	4.5	4.7	2.9	69
Rwanda	72	758	10.8	2.3	6.9	1.5	46
South Africa	1792	1826	4.3	2.5	2.7	1.6	46
Zambia	201	250	14.3	3.3	9.1	2.1	27
Mali	24	87	9.2	3.6	5.8	2.3	7.34
Tanzania	88	102	10.3	3.0	6.5	1.9	5.47
Kenya	331	154	6.9	3.6	4.4	2.3	4.14
Nigeria	115	63	4.1	3.8	2.5	2.4	2.99
Zimbabwe	19	49	5.8	3.7	3.7	2.4	2.50
Eritrea	23	21	14.9	3.5	9.5	2.2	2.49
Uganda	21	23	13.4	3.7	8.5	2.4	1.86
DR Congo	17	16	12.9	3.7	8.2	2.3	0.89
Niger	8.35	13	4.0	2.6	2.5	1.6	0.71
Burundi	9.12	6.71	12.8	1.1	8.1	0.7	0.59
Namibia	15	14	4.5	3.5	2.8	2.2	0.54
Mozambique	15	17	5.2	3.1	3.3	2.0	0.52
Lesotho	20	11	5.3	1.8	3.3	1.2	0.43
Mauritania	2.80	8.73	5.0	1.0	3.1	0.6	0.27
Madagascar	9.37	5.39	8.7	2.9	5.5	1.8	0.25
Angola	3.92	3.95	7.6	4.5	4.8	2.9	0.23
Cameroon	2.86	2.78	20.2	7.9	12.9	5.0	0.20
South Sudan	3.70	3.70	7.1	3.6	4.5	2.3	0.18
Chad	4.13	2.35	8.5	4.0	5.4	2.5	0.15
Somalia	1.03	1.06	16.3	1.3	10.4	0.8	0.13
Malawi	4.62	2.32	8.5	1.3	5.4	0.9	0.12
Swaziland	0.62	0.78	3.0	2.1	1.8	1.4	0.02
Sub-Saharan Africa	6196	9099	7.4	4.7	4.7	3.0	453

Table S10. Impact of ozone on bean production in SSA, for countries producing beans in S1. Total production loss due to ozone is estimated for 2015. For countries where beans were grown in two seasons, annual production and estimated production losses were divided by two.

Country	Bean prod 2010 (Th. t)	Bean prod 2015 (Th. t)	Av. POD_3IAM (mmol m^{-2})	sd	Av. % yield loss	sd	Total prod loss (Th. t)
Tanzania	382	529	10.1	2.9	11.9	3.4	55
Kenya	240	469	11.3	4.6	13.3	5.4	47
Uganda	249	266	14.0	4.3	16.5	5.1	43
Ethiopia	182	318	11.5	4.1	13.5	4.9	38
Cameroon	170	175	13.7	7.3	16.1	8.6	35
Ghana	210	212	12.9	2.5	15.1	2.9	32
Togo	76	177	14.9	2.5	17.5	3.0	28
Rwanda	156	207	8.9	2.5	10.4	3.0	20
DR Congo	75	156	15.8	4.0	18.6	4.7	18
Benin	110	101	12.1	5.0	14.2	5.9	17
Burundi	93	130	10.0	1.6	11.7	1.9	15
Malawi	83	102	6.8	1.9	8.0	2.2	8.46
Cote dIvoire	33	38	10.4	3.0	12.2	3.6	3.91
Chad	73	88	2.9	3.7	3.5	4.3	2.41
Madagascar	41	43	6.5	2.7	7.6	3.2	2.05
Mozambique	92	19	8.4	3.0	9.8	3.6	1.68
South Africa	27	38	2.9	2.0	3.5	2.4	1.17
Somalia	11	13	9.2	3.1	10.8	3.6	1.12
Zimbabwe	29	14	6.5	2.2	7.7	2.6	1.06
Congo	1.92	2.19	17.9	3.1	21.0	3.7	0.51
Namibia	5.46	5.30	4.3	2.5	5.0	3.0	0.27
Niger	14	23	0.9	0.8	1.1	0.9	0.17
Djibouti	1.82	2.42	6.0	0.1	7.1	0.1	0.16
Mauritania	10	12	0.8	0.6	0.9	0.7	0.10
Eritrea	0.28	0.28	8.7	5.4	10.2	6.4	0.03
Swaziland	1.13	0.66	2.4	1.1	2.8	1.3	0.02
Sub-Saharan Africa	2367	3141	9.1	6.0	10.7	7.1	370

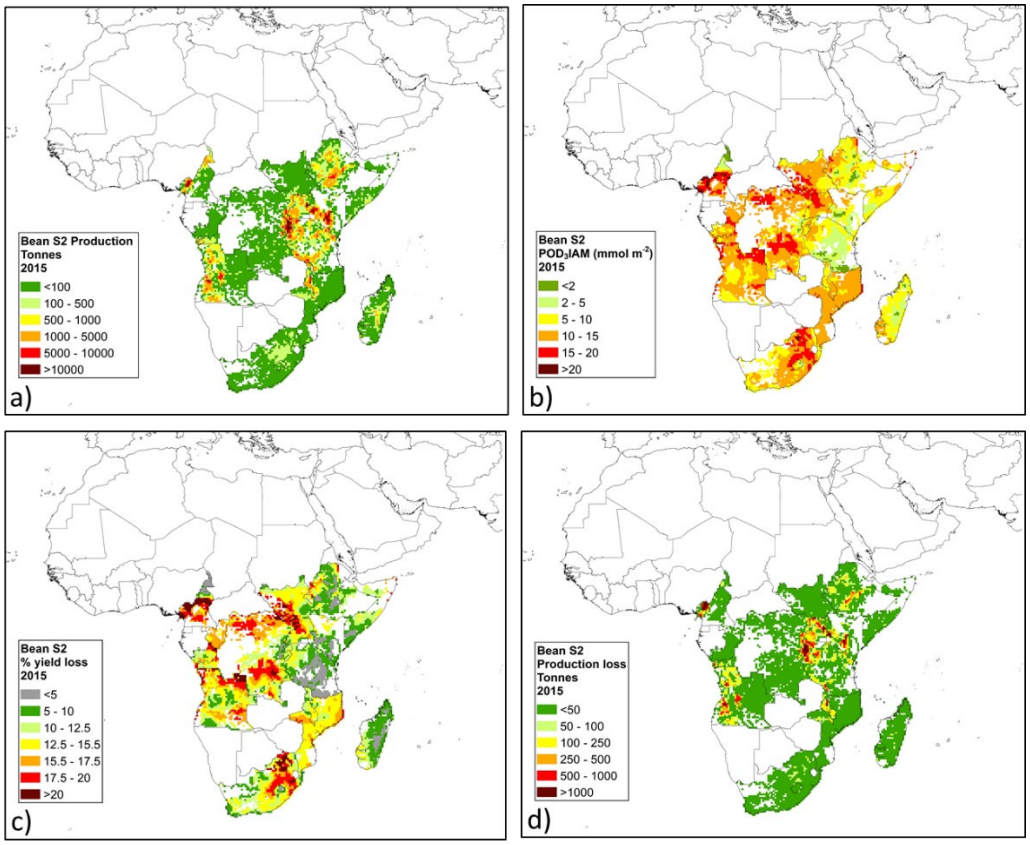

Figure S3. Ozone impact on bean production in Sub-Saharan Africa for the year 2015, season 2. a) Bean production for 2015, using spatial data from the SPAM dataset for 2010 and FAO national conversion factors for 2015; b) POD_3IAM (mmol m^{-2}) for bean, accumulated over a 90-day period during the growing season; c) Percentage yield loss for bean due to ozone; d) Production loss (tonnes) in 2015 for beans due to ozone. For countries where beans were grown in two seasons, annual production and estimated production losses were divided by two.

Table S11. Bean production and ozone-induced losses (season 2) per country in Sub-Saharan Africa for the 10 countries with the highest estimated production loss in 2015. SPAM production data are for 2010, values for 2015 have been estimated using conversion factors from FAO national totals. For countries where beans were grown in two seasons, annual production and estimated production losses were divided by two.

Country	2010 prod. (Th. t)	2015 prod. (Th. t)	Av. POD_3IAM (mmol m^{-2})	± sd	Av. % yield loss	± sd	Total prod. loss (Th. t)
Angola	262	416	12.1	3.1	14.3	3.6	60.04
Uganda	249	266	12.0	3.6	14.1	4.2	42.53
Tanzania	382	529	5.3	3.0	6.3	3.5	41.56
Cameroon	170	175	13.4	6.4	15.7	7.5	39.39
Kenya	240	469	6.7	3.6	7.9	4.3	36.25
Ethiopia	182	318	7.8	3.5	9.1	4.1	26.39
Rwanda	156	207	8.7	2.7	10.2	3.2	23.61
DR Congo	75	156	12.6	3.0	14.8	3.6	18.15
Burundi	93	130	9.6	1.4	11.2	1.7	16.93
Malawi	83	102	10.3	1.7	12.1	2.0	14.67

Table S12. Impact of ozone on bean production in SSA, for countries producing beans in S2. Total production loss due to ozone is estimated for 2015. For countries where beans were grown in two seasons, annual production and estimated production losses were divided by two.

Country	Bean prod 2010 (Th. t)	Bean prod 2015 (Th. t)	Av. POD_3IAM (mmol m^{-2})	sd	Av. % Yield loss	sd	Total prod loss (Th. t)
Angola	262	416	12.1	3.1	14.3	3.6	60
Uganda	249	266	12.0	3.6	14.1	4.2	43
Tanzania	382	529	5.3	3.0	6.3	3.5	42
Cameroon	170	175	13.4	6.4	15.7	7.5	39
Kenya	240	469	6.7	3.6	7.8	4.3	36
Ethiopia	182	318	7.7	3.5	9.1	4.1	26
Rwanda	156	207	8.7	2.7	10.2	3.2	24
DR Congo	75	156	12.6	3.0	14.8	3.5	18
Burundi	93	130	9.6	1.4	11.2	1.7	17
Malawi	83	102	10.3	1.7	12.0	2.0	15
South Africa	27	38	11.7	3.4	13.7	4.0	7.37
Mozambique	92	19	12.2	1.5	14.4	1.8	3.48
Madagascar	41	43	6.9	2.5	8.1	2.9	2.71
South Sudan	10	10	11.5	3.1	13.5	3.6	1.75
Somalia	11	13	8.3	2.5	9.7	2.9	1.34
Congo	1.92	2.19	12.7	2.3	14.9	2.7	0.37
Lesotho	5.75	1.78	8.1	4.0	9.5	4.7	0.20
Sub-Saharan Africa	2081	2897	10.51	4.08	12.35	4.8	337

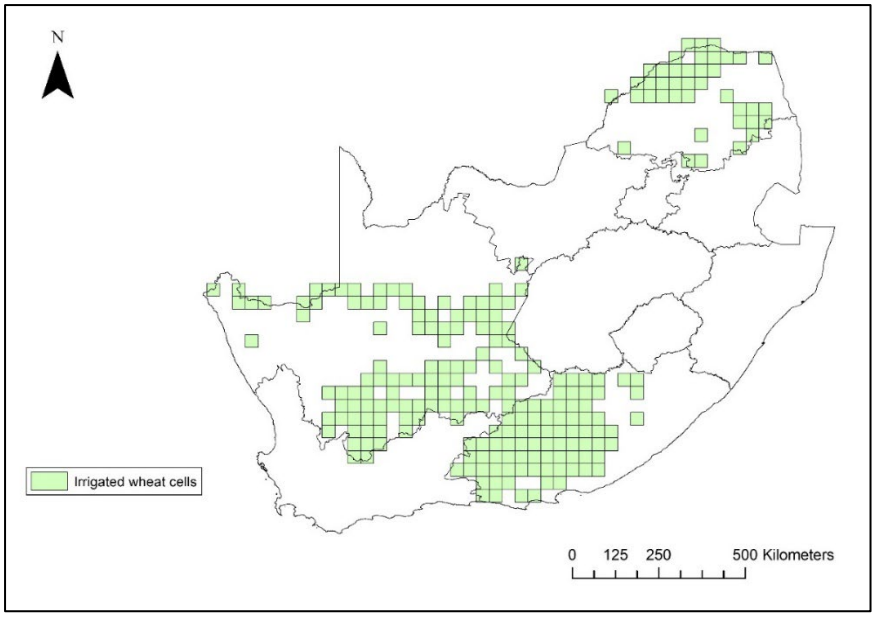

Figure S4. Irrigated wheat grid cells in the Limpopo, Eastern Cape and Northern Cape provinces of South Africa (irrigated production >75%).

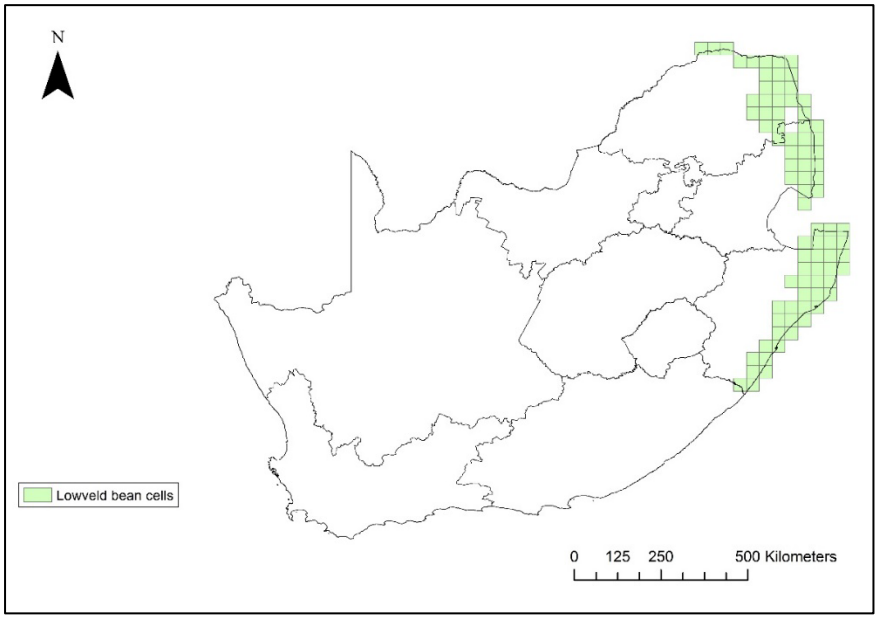

Figure S5. Lowveld grid cells in the Limpopo, Mpumalanga and KwaZulu-Natal provinces of South Africa. Elevation is 150 – 600m above sea level. These areas are frost-free so beans can be grown during the autumn (Southern hemisphere, March – April).

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