Supplementary Materials: The environmental mitigation potential of photovoltaic-powered irrigation in the production of South African maize

Sarah Wettstein[1], Karen Muir [1]*, Deborah Scharfy[1], Matthias Stucki[1]

[1] Zurich University of Applied Sciences, Institute of Natural Resource Sciences, 8820 Wädenswil, Switzerland; sarah.wettstein@zhaw.ch; karen.muirwendel@zhaw.ch; d.scharfy@gmx.de; matthias.stucki@zhaw.ch

* Correspondence: karen.muirwendel@zhaw.ch; Tel.: +41 58 934 54 56

1 Maize Production Inputs

1.1 Pesticides

The active ingredients of pesticides used in the production of South African rainfed and irrigated maize can be seen in Table S 1. "Pesticides, unspecified" refers to active ingredients not included in the ecoinvent database.

Table S 1: Active ingredients [g/ha] in pesticides used in rainfed and irrigated maize production in South Africa [1–3].

		Quantity applied [g/ha]	
Pesticide	**Active ingredient**	**Maize, rainfed**	**Maize, irrigated**
Organophosphorous-compounds	glyphosate-isopropylamine	180	0
Acetamide-anillide-compounds	s-metolachlor	1 673	305
Triazine-compounds	atrazine	653.8	50
	therbuthylazine	504.9	50
Cyclic N-compounds	difenoconazole	20.8	16.7
	flusilazole	0	83.3
Pyrethroid-compounds	lambda-cyhalothrin	3.5	9.3
	alpha-cypermethrin	20	10
Phenoxy-compounds	fenvalerate	6.7	6.7
	carbendazim	0	41.7
Pesticides, unspecified	azoxystrobine	251.3	26.7
	benfuracarb	66.7	66.7
	ammonium sulphate	346.7	0
	imidacloprid	0.6	0.6
	mesotrione	18.8	0.1
	tiamethoxam	443.5	11.5

1.2 Fertilisers

Table S 2 shows the quantity of organic and mineral fertilisers used in South African maize production and the total mass of nutrients applied.

Table S 2: Fertilisers and nutrients applied [kg/ha] in the production of rainfed and irrigated maize production in South Africa [1–3].

	Quantity applied [kg/ha]	
Fertiliser/Nutrient	**Maize, rainfed**	**Maize, irrigated**
Cattle manure	2 500	2 500
N	27.5	27.5
P	10	10
K	25	25
Mineral Fertilisers		
Lime	889	1 000
N	65.6	202
P	11.1	32.9
K	7	45.5
Nutrients- Total		
N	93.1	229.5
P	21.1	42.9
K	32	70.5

1.3 Transport

Transport distances and the origin of inputs and equipment included in this study are shown in Table S 3.

Table S 3: Transport distances [km] and origin of transported products.

Material	**Vehicle**	**From… to…**	**Distance [km]**
Harvested maize	Tractor and trailer	Field to farm	5.0^{+}
	Tractor and trailer	Farm to silo	40^{+}
Fertilisers	Tractor and trailer	Retailer to farm	650^{+}
Pesticides	Tractor and trailer	Retailer to farm	650^{+}
Tractor and trailer	Lorry	Within country of production	1 687†
	Transoceanic ship	Export country to Durban	14 401*
	Lorry	Durban to production region	650^{+}
	Freight train	Durban to production region	650^{+}

+ [4], † [5], * [6]

1.4 Irrigation

A dataset for a centre pivot irrigation system in South Africa was created using country-specific electricity and water data (Table S 4).

Table S 4: Dataset for irrigation in South Africa with a centre pivot system.

Irrigation	Unit	
Centre pivot irrigation, operation, per ha and year, maize, national average {ZA}| processing	ha*a	
Water, unspecified natural origin, ZA	m^3	7 000
Electricity, low voltage {ZA}| market for	kWh	1 840
Centre pivot irrigation, construction, per ha and year {ZA}| processing	ha*a	
Steel, unalloyed {GLO}| market for	kg	13
Metal working, average for steel product manufacturing {RoW}| processing	kg	13
Zinc coat, coils {RoW}| zinc coating, coils	m^2	0.667

The sources of data used to calculate average water consumption for irrigated maize production in South Africa are shown in Table S 5.

Table S 5: Water consumption for irrigation in South Africa [m^3/ha/a].

Source	Water consumption [m^3/ha/a]
Maize producer [7]	6 100
Grain SA [1–3]	8 000
GWK [8]	6 900
Average water consumption	**7 000**

2 Emissions Arising from Maize Production

2.1 Ammonia

Table S 6 shows the quantity of fertiliser applied and the ammonia emissions associated with the production of South African maize.

Table S 6: Fertiliser application and ammonia emissions [kg/ha] associated with the production of South African rainfed and irrigated maize [1–3,8].

Quantity [kg/ha]	Grain maize, rainfed	Grain maize, irrigated
Cattle manure	2 500	2 500
NPK fertiliser	65.6	202
Ammonia emissions	**8.5**	**25**

2.2 Dinitrogen Monoxide

Table S 7 gives an overview of the parameters used in the calculation of the dinitrogen monoxide emissions arising from maize production in South Africa.

Table S 7: Nitrogen inputs, removals, and dinitrogen monoxide emissions associated with the production of South African rainfed and irrigated maize [9].

Parameter	Unit	Grain maize, rainfed	Grain maize, irrigated
N from fertiliser input	kg N	77.9	214.5
N in C-N-pool	kg N	21.2	27
Atmospheric deposition	kg N	25	25
N fixation	kg N	0	0
N immobilisation	%	0	0
N_2O emissions	kg/ha	**1.9**	**4.7**

2.3 Nitrate

The nitrate emissions occurring as a result of maize production in South Africa are shown in Table S 8.

Table S 8: Nitrogen inputs, losses, and nitrate emissions associated with the production of South African rainfed and irrigated maize [9].

Parameter [kg/ha]	Grain maize, rainfed	Grain maize, irrigated
N in ammonia	7	20.6
N in above ground plant residues	9.2	14.1
N in below ground plant residues	1.7	2.6
Leaching	0.3	0.3
NO_3 emissions	**134.1**	**285**

2.4 Nitrous Oxide

The NO_x emissions arising from the production of South African dryland and irrigated maize are shown in Table S 9.

Table S 9: Dinitrogen oxide and nitrogen oxide emissions arising from South African rainfed and irrigated maize production [9].

Emissions [kg/ha]	Grain maize, rainfed	Grain maize, irrigated
N_2O	1.9	4.7
NO_x	**0.4**	**1**

2.5 Phosphate and Phosphorus

The phosphate emissions to groundwater through leaching associated with the production of South African maize are shown in Table S 10.

Table S 10: Phosphate leaching to groundwater [kg/ha/a] associated with the production of South African rainfed and irrigated maize.

Parameter	Unit	Grain maize, rainfed	Grain maize, irrigated
P_{gwl}†	kg/ha/a	0.07	0.07
F_{gw}	-	1	1
P_2O_{5sl}	kg/ha	0	0
P_{gw}	kg/ha/a	**0.07**	**0.07**

† Average value for arable land [10].

Phosphate runoff to surface waters for South African maize production is shown in Table S 11.

Table S 11: Phosphate run-off to surface water [kg/ha/a] associated with the production of South African rainfed and irrigated maize.

Parameter	Unit	Grain maize, rainfed	Grain maize, irrigated
P-Fertilisation	kg/ha	11.1	32.9
P_{rol}*	kg/ha/a	0.175	0.175
F_{ro}	-	1.08	1.13
P_2O_{5min}†	kg/ha	11.1	32.9
P_2O_{5sl}	kg/ha	0	0
P_2O_{5man}†	kg/ha	10	10
P_{ro}	kg/ha/a	**0.19**	**0.2**

* Average value for arable land [10], † Average values [11]

Phosphorous emissions to surface waters resulting from erosion in South Africa are shown in Table S 12.

Table S 12: Phosphorous emissions through erosion to surface water [kg/ha/a] associated with the production of South African rainfed and irrigated maize.

Parameter	Unit	Grain maize, rainfed	Grain maize, irrigated
S_{er}†	kg/ha/a	2 200	2 200
P_{cs}*	kg P/kg soil	0.00095	0.00095
F_r+	-	1.86	1.86
F_{erw}‡	-	0.05	0.05
P_{er}	kg P/ha/a	**0.78**	**0.78**

† Average erosion rate for South Africa [12–14], * Average value [10], + Average value [15], ‡ [10]

2.6 Heavy Metal Emissions

2.6.1 Heavy Metal Leaching into Groundwater

The leaching values was used to calculate the heavy metal emissions to groundwater can be seen in Table S 13.

Table S 13: Heavy metal leaching to groundwater [mg/ha/a] [16].

	Cd	Cu	Zn	Pb	Ni	Cr	Hg
Leaching [mg/ha/a]	50	3 600	33 000	600	n.a.	21 200	1.3

The heavy metal deposition values used in this study can be seen in Table S 14.

Table S 14: Heavy metal deposition [17].

	Cd	Cu	Zn	Pb	Ni	Cr	Hg
Deposition [mg/ha/a]	700	2 400	90 400	18 700	5 475	3 650	50

Table S 15 shows the heavy metals emissions to groundwater through leaching associated with maize production in South Africa.

Table S 15: Heavy metal emissions to ground water through leaching [mg/ha/a] associated with the production of South African rainfed and irrigated maize.

Emissions into groundwater [mg/ha/a]	Grain maize, rainfed	Grain maize, irrigated
Cd	24.9	36.3
Cu	2 615	3 027
Zn	6 910	13 228
Pb	109	158
Ni	n. a.	n. a.
Cr	20 934	20 974

The soil heavy metal contents used in this study can be seen in Table S 16.

Table S 16: Heavy metal contents of the soil [mg/kg soil] [18].

	Soil heavy metal content [mg/kg soil]						
Land use	**Cd**	**Cu**	**Zn**	**Pb**	**Ni**	**Cr**	**Hg**
Arable land	0.24	21.1	49.6	19.5	23	24.1	0.073

2.6.2 Heavy Metal Emissions into Surface Water through Erosion

Table S 17 shows the heavy metal emissions to surface water through erosion in South Africa.

Table S 17: Heavy metal emissions to surface water due to erosion [mg/ha/a] associated with the production of South African rainfed and irrigated maize.

Emissions into surface water [mg/ha/a]	Grain maize, rainfed	Grain maize, irrigated
Cd	31	46
Cu	5 827	6 743
Zn	3 003	5 749
Pb	927	1 339
Ni	3 582	3 954
Cr	5 455	5 465

2.6.3 Heavy Metal Emissions into Soil

The heavy metal emissions to agricultural soils associated with the production of maize in South Africa are shown in Table S 18.

Table S 18: Emissions of heavy metals to agricultural soil [m/ha/a] associated with the production of South African rainfed and irrigation maize.

Emissions into agricultural soils [mg/ha/a]	Grain maize, rainfed	Grain maize, irrigated
Cd	665	1 796
Cu	242	4 456
Zn	21 865	52 870
Pb	3 969	6 277
Ni	n. a.	n. a.
Cr	260 681	312 841

2.7 Water Scarcity

The monthly water scarcity index (WSI) and water scarcity for the six catchment areas corresponding to the main maize production areas in South Africa are shown in Table S 19.

Table S 19: Water scarcity index (WSI) [-] [19] *and water scarcity [m³/ha/a] of the six catchment areas in the main maize production regions in South Africa. The WSI was multiplied by the volume of irrigation water per ha and year to calculate water scarcity. Months when irrigation occurs are shaded in dark grey; no maize cultivation takes places in August and September (font grey).*

	Catchment area											
	1		**2**		**3**		**4**		**5**		**6**	
	WSI [-]	**Water scarcity [m³/ha/a]**	**WSI [-]**	**Water scarcity [m³/ha/a]**	**WSI [-]**	**Water scarcity [m³/ha/a]**	**WSI [-]**	**Water scarcity [m³/ha/a]**	**WSI [-]**	**Water scarcity [m³/ha/a]**	**WSI [-]**	**Water scarcity [m³/ha/a]**
Jan	0.9974	1746	0.0109	19	0.0109	19	0.0137	24	0.0512	90	0.011	19
Feb	0.011		0.0105		0.0108		0.0137		0.0197		0.0104	
Mar	0.0126		0.0108		0.0112		0.0137		0.0241		0.0107	
Apr	0.014		0.0113		0.0119		0.0137		0.0379		0.0109	
May	0.0167		0.0123		0.0135		0.0137		0.0578		0.0118	
Jun	0.0206		0.0134		0.0157		0.0137		0.1632		0.0126	
Jul	0.0356		0.0168		0.0217		0.0137		0.5836		0.0151	
Aug	*0.1223*		*0.0274*		*0.0452*		*0.0137*		*0.9899*		*0.023*	
Sep	*0.6251*		*0.0642*		*0.085*		*0.0137*		*0.9999*		*0.0266*	
Oct	0.9911	1734	0.2214	387	0.0387	68	0.0137	24	0.9999	1750	0.0439	77
Nov	0.9994	1749	0.0548	96	0.0151	27	0.0137	24	1	1750	0.0315	55
Dec	1	1750	0.0119	21	0.0115	20	0.0137	24	1	1750	0.0158	28
Average	0.4038	2827	0.0388	272	0.0142	170	0.0137	95.56	0.4954	3468	0.0186	130
Total		**6979**		**523**		**133**		**96**		**5340**		**179**

3 Discussion

3.1 Maize Production Area

The total maize production area, the proportion under irrigation, and the total area of irrigated maize production can be seen in Table S 20.

Table S 20: Production area, proportion of maize production under irrigation, and area of irrigated maize production in South Africa in the production year 2015/16 [20,21].

	White maize	Yellow maize	Total
Production area 2015/16 [1000 ha/a]	1 015	932	1 947
Proportion under irrigation [%]	8.1%	17.0%	
Irrigated production area 2015/16 [1000 ha]	82	158	**241**

3.2 Photovoltaic Module

Photovoltaic electricity production for solar powered irrigation in South Africa was modelled based on the 570 kW_p open ground multi-crystalline silicon power plant in the ecoinvent database v3.3 [22]. Table S 21 below shows the monthly yield of this type of system with a nominal power of 1.0 kW for the city of Welkom (Free State, South Africa), located at 28°0'16" south, 26°46'23" east, with an elevation of 1339 m a.s.l. A fixed system with optimal orientation was assumed and combined PV system losses were assumed to be 26.3% [23].

Table S 21: Photovoltaic yield for the city of Welkom, South Africa for a fixed optimal system with an inclination of 31° and an orientation of 177° [23].

Month	**Average daily electricity production from the given system [kWh]**	**Average monthly electricity production from the given system [kWh]**	**Average daily sum of global irradiation per square meter received by the modules of the given system [kWh/m²]**	**Average sum of global irradiation per square meter received by the modules of the given system [kWh/m²]**
January	4.48	139	6.31	196
February	4.81	135	6.77	189
March	5.07	157	7.06	219
April	4.7	141	6.34	190
May	4.66	144	6.16	191
June	4.65	139	5.96	179
July	4.91	152	6.34	196
August	5.14	159	6.82	211
September	5.26	158	7.18	215
October	4.95	154	6.93	215
November	4.77	143	6.68	200
December	4.51	140	6.34	197
Yearly average	**4.82**	**147**	**6.57**	**200**
Yearly total	**1760**		**2400**	

In compliance with the recommendations in the methodology guidelines for LCA of the IEA Photovoltaic Power Systems Program [24], a module lifetime of 30 years, with a degradation of 0.7% per year, corresponding to an average decrease in annual yield of 10.5% for a lifetime of 30 years, were assumed. An area of 7.366 m^2/kW_p is needed for a photovoltaic power plant with a nominal power of 1 kW_p for this type of module with 13.5% efficiency [25]. Table S 22 shows the parameters necessary for the calculation of the photovoltaic module area necessary for the generation of electricity for the irrigation of one hectare of maize.

Table S 22: Parameters needed for the calculation of photovoltaic module area requirements.

	Utilisation of annual electricity production, including degradation	**Utilisation of electricity production from October-January, including degradation**
Total annual electricity production [kWh/kWp]	1760	1760
Electricity production, October-January [kWh/kWp]	576	576
Degradation [%]	10.5	10.5
Annual yield, including degradation [kWh/kWp]	1575	1575
Electricity production, October-January, including degradation [kWh/kWp]	516	516
Volume of water used for irrigation [m^3/a]	7000	7000
Electricity requirements [$kWh/m^3/a$]	0.26	0.26
Electricity requirements for irrigation [kWh/a]	1820	1820
Peak power for PV system [kWp]	1.16	3.53
Efficiency of PV Module [%]	13.5	13.5
Required PV module area [m^2]	8.5	26.0

4 References

1. Grain SA Operational planning of white maize grain production in the production year 2011/2012 in Eastern Highveld, South Africa; Lynnwood Ridge, South Africa, 2014;
2. Grain SA Operational planning of white maize grain production in the production year 2011/2012 in Northwest, South Africa; Lynnwood Ridge, South Africa, 2014;
3. Grain SA Operational planning of white maize grain production in the production year 2011/2012 in Central and Northern Free State, South Africa; Lynnwood Ridge, South Africa, 2014;
4. Coetzee, J. (South African Breweries, Johannesburg, South Africa) Personal communication 2016.
5. DistanceFromTo Available online: http://www.distancefromto.net (accessed on Apr 15, 2015).
6. SeaRates.com Available online: http://www.searates.com/de/reference/portdistance (accessed on Apr 15, 2015).
7. Hall, W. (Maize producer, South Africa) Personal communication 2015.
8. Rechtus, S. (GWK Beperk, South Africa) Personal communication 2016.
9. Meier, M. S.; Schader, C.; Berner, A.; Gattinger, A. Modelling N2O emissions from organic fertilisers for LCA inventories. 2012.
10. Prasuhn, V. Erfassung der PO4-Austräge für die Ökobilanzierung. SALCA-Phosphor; Agroscope FAL Reckenholz: Zurich, Switzerland, 2006;
11. Coetzee, J. (South A. B. (South African Breweries, Johannesburg, South Africa) Personal communication 2015.
12. Kooman, G.; Critchley, W. R. S. GIS-Assisted Modelling of Soil Erosion in a South African Catchment: Evaluating the USLE and SLEMSA Approach. In Water Resources Planning, Development and Management; Breetzke, G. D., Ed.; InTech, 2013 ISBN 978-953-51-1092-7.
13. Le Roux, J. J.; Morgenthal, T. L.; Malherbe, J.; Pretorius, D. J.; Sumner, P. D. Water erosion prediction at a national scale for South Africa. Water SA 2008, 34, 305–314.
14. UWC Erosion Available online: http://www.botany.uwc.ac.za/envfacts/facts/erosion.htm (accessed on Apr 28, 2015).
15. Wilke, B.; Schaub, D. Phosphatanreicherung bei Bodenerosion. Mitt Dtsch. Bodenkd. Gesellsch 1996, 435–438.
16. Wolfensberger, U.; Dinkel, F.; Gaillard, G.; Hirs, B.; Lips, A.; Nentwig, W.; Waldeck, B. Beurteilung nachwachsender Rohstoffe in der Schweiz in den Jahren 1993-1996. Vergleichende Betrachtung von Produkten aus ausgewählten NWR und entsprechenden konventionellen Produkten bezüglich Umweltwirkungen und Wirtschaftlichkeit; Bern/Tänikon, 1997;
17. Freiermuth, R. Modell zur Berechnung der Schwermetallflüsse in der landwirtschaftlichen Ökobilanz; 2006; pp. 1–42;.
18. Keller, T.; Desaules, A. NABO: Böden der Schweiz: Schadstoffgehalte und Orientierungswerte (1990-1996); Bundesamt für Umwelt, Wald und Landschaft, 2001;
19. Pfister, S.; Baumann, J. Monthly characterization factors for water consumption and application to temporally explicit cereals inventory. In LCA food 2012: VII international conference on life assessment in the agri-food sector; Bari, Italy, 2010.
20. Grain SA Report Documents Available online: http://www.grainsa.co.za/upload/report_files/NOK-Wit-geelmielies---white-and-yellow-maize-per-provinsie.xls (accessed on Apr 13, 2017).
21. DAFF Trends in the Agricultural Sector 2016; Department of Agriculture, Forestry and Fisheries (DAFF), Republic of South Africa: Pretoria, South Africa, 2017;
22. ecoinvent Centre ecoinvent data v3.3; Swiss Centre for Life Cycle Inventories: Zürich, 2016;
23. JRC-EC PV potential estimation utility Available online: http://re.jrc.ec.europa.eu/pvgis/apps4/pvest.php?lang=en&map=africa (accessed on Apr 25, 2015).

24. Frischknecht, R.; Heath, G.; Raugei, M.; Sinha, P.; de Wild-Scholten, M. Methodology Guidelines on Life Cycle Assessment of Photovoltaic Electricity: 3rd Edition; National Renewable Energy Laboratory (NREL): Golden, CO, United States, 2016;
25. Jungbluth, N.; Stucki, M.; Flury, K.; Frischknecht, R.; Büsser, S. Life cycle inventories of photovoltaics. ESU-Serv. Ltd Uster Switz. 2012.