sustainability

MDPI

Article

The Environmental Mitigation Potential of Photovoltaic-Powered Irrigation in the Production of South African Maize

Sarah Wettstein, Karen Muir *, Deborah Scharfy and Matthias Stucki

Institute of Natural Resource Sciences, Zurich University of Applied Sciences, 8820 Wädenswil, Switzerland; sarah.wettstein@zhaw.ch (S.W.); xsfy@zhaw.ch (D.S.); matthias.stucki@zhaw.ch (M.S.)

* Correspondence: muir@zhaw.ch; Tel.: +41-58-934-5456

Received: 14 August 2017; Accepted: 22 September 2017; Published: 30 September 2017

Abstract: Agriculture is under pressure to reduce its environmental impact. The use of renewable energy sources has potential to decrease these impacts. Maize is one of the most significant crops in South Africa and approximately 241,000 hectares are irrigated. This irrigation is most commonly powered by grid electricity generated using coal. However, South Africa has high solar irradiation, which could be used to generate photovoltaic electricity. The aim of this study was to determine the environmental mitigation potential of replacing grid-powered irrigation in South African maize production with photovoltaic irrigation systems using Life Cycle Assessment. The study included the value chain of maize production from cultivation to storage. Replacing grid electricity with photovoltaic-generated electricity leads to a 34% reduction in the global warming potential of maize produced under irrigation, and—applied at a national level—could potentially reduce South Africa's greenhouse gas emissions by 536,000 t CO_2-eq. per year. Non-renewable energy demand, freshwater eutrophication, acidification, and particulate matter emissions are also significantly lowered. Replacing grid electricity with renewable energy in irrigation has been shown to be an effective means of reducing the environmental impacts associated with South African maize production.

Keywords: photovoltaic; greenhouse gas emissions; crop production; life cycle assessment; maize; corn; LCA

1. Introduction

Agriculture is associated with significant environmental repercussions and is one of the largest contributors to global anthropogenic greenhouse gas (GHG) emissions. It is responsible for around 70% of global water use [1], and an estimated 3–8% of total final energy consumption is used directly in this sector [2]. The global population growth rate between 2000 and 2015 was 1.2% [3] and, according to the United Nations [4], the population is expected to reach 9.7 billion by 2050. This increase in population, combined with rising income levels, means that food production will have to increase by 70% [5]. Along with mounting concerns about climate change and other environmental problems, agriculture is increasingly under pressure not only to produce more food, but also to simultaneously lower its environmental impacts and resource use.

The majority of the predicted population growth is expected to occur in developing and emerging countries and the population of South Africa is expected to increase by nearly 8% by 2100 [6]. Maize (*Zea mays*) is by far the most significant crop in South Africa: it constitutes a significant part of the staple diet of the country's population, and is its most important feed grain. Between 2006 and 2015, nearly 2.6 million hectares were used for the production of maize, with an average production of 11 million tonnes per year [7]. Due to the arid climatic conditions in South Africa, with an annual rainfall of approximately 450 mm [8], irrigation is used in some regions to enable or to enhance crop production. Around 1.3 million hectares [9], or just under 10% of all arable land in South Africa, is irrigated [10]. Although this constitutes only a small proportion of the total land area, irrigated agriculture contributes over 30% of the gross value of South Africa's crop production [11]. In South Africa, around 8% of white maize and 17% of yellow maize produced is grown under irrigation [12], and irrigation systems are most commonly powered by grid electricity produced using fossil fuels, such as coal. However, South Africa has high solar irradiation, which could potentially be used for the generation of photovoltaic (PV) electricity as a renewable energy supply for irrigation. As irrigation in South Africa is likely to become even more widespread in the future, finding ways of minimising its environmental impacts are of utmost importance.

The term "clean technology" refers to products, processes, or services that help reduce negative environmental impacts by, for example, increasing energy efficiency or reducing emissions. These technologies are becoming more widespread in a number of sectors, including agriculture. Along with water-saving and energy efficient irrigation systems, such as wireless sensor irrigation networks, drip irrigation, and the use of frequency converters for irrigation pumps, replacing the source of electricity for irrigation with renewable energy is a potential means of reducing its environmental impact.

Solar energy is the most abundant energy resource at our disposal: more solar energy reaches the earth in one hour than is consumed by all human activities over the course of a year [13]. Solar PV systems convert solar energy into electricity and have been associated with a range of environmental benefits, such as reduced GHG emissions [14]. Between 2003 and 2013, total installed capacity increased by 49% per year on average [15], with total global capacity reaching an estimated 303 GW by the end of 2016, meeting 1.8% of total global electricity demand [16]. This trend is likely to continue and according to the International Energy Agency (IEA), 16% of global electricity demand will be met by solar PV by 2050 [15]. First-generation solar cells (crystalline silicon) account for 90% of the commercial market [17]. Disadvantages, such as high production costs and toxicity [17,18], led to the development of alternative second-generation (thin-film) solar cells. Advantages include lower raw material and energy inputs during production. However, a number of disadvantages, such as toxicity and instability, have prevented these from becoming more widespread, although they are considered to have potential [19]. The average efficiency of both first and second-generation solar cells has improved over time, with the best performing silicon modules reaching efficiencies of around 20% and thin-film technologies reaching 15% [15]. To address the disadvantages of first- and second-generation solar cells, third-generation solar cells, which include a wide range of technologies, have also been developed. High efficiencies have been achieved, although high production costs for some of these cells mean that they are often not able to compete with alternatives for most applications. Other third-generation solar cells are still unable to compete with earlier technologies due to low efficiency, short service life, or instability. However, research in this area is continuing and third-generation solar cells appear to have a great deal of potential [19].

A number of studies highlighting the environmental impacts associated with irrigation have been carried out [20,21], but few studies have specifically compared the effect of altering the means of electricity generation for irrigation. It has been demonstrated, however, that the global warming potential (GWP) of electricity produced using PV is markedly lower than that of electricity generated using hard coal [22–24]. Mekhilef et al. [25] studied various applications of solar technologies in the agricultural sector. They identified a number of advantages of solar irrigation systems when compared with conventional systems, including fuel cost savings, reduced noise and environmental pollution. According to Meah et al. [26], almost 25,000 tonnes of carbon dioxide emissions have been saved as a result of the solar PV water pumping systems installed by the University of Wyoming Motor Testing and Training Center between 1991 and 2008 when compared with coal-powered electricity generation. In a case study examining the applications of solar PV on rural development in Bangladesh, the author identified a number of advantages, such as no grid electricity or fuel costs, high durability, suitability in remote areas, and environmentally friendly electricity generation. According to the author, solar PV systems could contribute towards global poverty reduction and help meet other Millennium Development Goals, such as the reduction in hunger, disease, and environmental degradation [27].

The cost of PV modules decreased rapidly from 4 USD/W in 2008 to 0.8 USD/W in 2012 and have since stabilised. Further decreases in costs are expected as they become more widely deployed and as technology improves [15]. Total life cycle costs for water pumping systems over a 25-year period were calculated and found to be lowest for PV systems in comparison with grid-powered and diesel-driven systems. The authors concluded that solar PV systems are the most cost effective for water pumping in remote areas, despite having higher capital costs than diesel generators [26]. In a study on the use of solar PV pumps for drip irrigation systems in orchards in India, researchers found the systems to be economically viable for orchards in arid regions, with a benefit–cost ratio of around 2.6. Additionally, the authors expect further improvements in economic performance as the technology improves [28]. In a study on the use of solar energy in agri-processing in South Africa, solar PV systems in packhouses were determined to be economically viable [29].

The aim of this study was to determine the environmental mitigation potential of replacing grid-powered irrigation in South African maize production with photovoltaic irrigation systems using life cycle assessment (LCA). The following impact indicators were assessed: global warming potential, non-renewable fossil and nuclear energy use, freshwater and marine eutrophication, land use, particulate matter, acidification, and water scarcity.

This paper is based on a presentation held at the World Sustainability Forum in January 2017 [30], and on a contribution to the International Conference on Life Cycle Assessment of Food 2016 [31].

2. Materials and Methods

To define clean technology optimisation strategies, an LCA of South African maize was carried out according to ISO 14040 and 14044 standards [32,33]. The system boundaries included the value chain of maize production, including seedbed preparation, cultivation, and harvesting (Figure 1). The production and application of fertilisers and pesticides, as well as water for irrigation were considered in the cultivation phase. Additionally, land use, direct field emissions, the production and use of tractors and agricultural machinery, including diesel consumption, were taken into account. Transportation of maize to a storage corporation, and its storage in a silo for six months were also included. Further processing, such as milling, was not included.

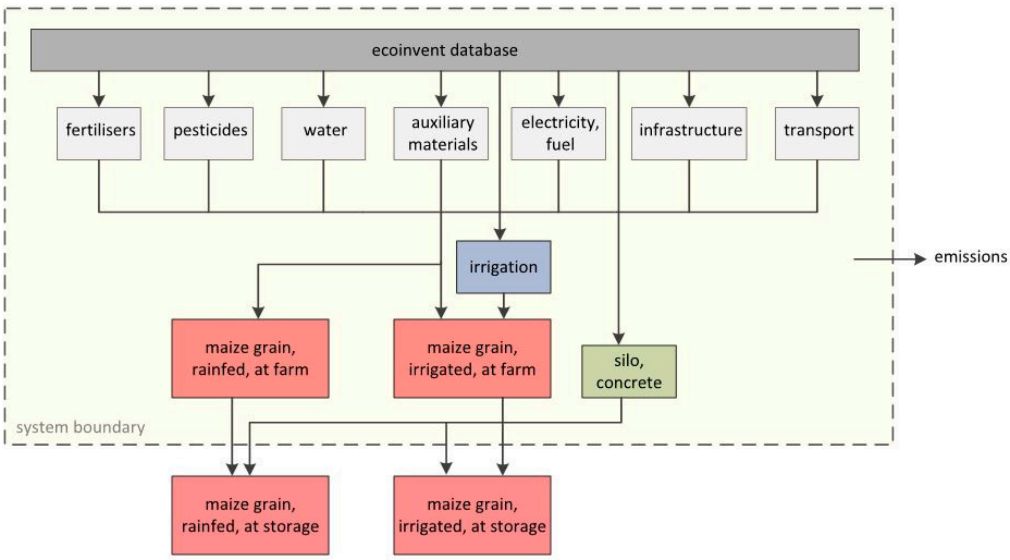

Figure 1. South African rainfed and irrigated maize production and the system boundaries used in this study.

The most relevant production data, including data on cultivation area, fertiliser and pesticide application, diesel consumption, and yield were obtained from planning models and maize production reports provided by Grain SA, the national grain producers' association, and from the Griekwaland Wes Korporatief (GWK) cost guide [34–38]. The planning models apply to cultivation in three maize production regions: the Eastern Highveld, North West, and Central and Northern Free State. Transport distances were obtained from an extension officer for South African Breweries Ltd., Johannesburg, South Africa [39], as well as by using online distance calculators for land [40] and sea [41] routes. Background data for the life cycle inventories were taken from the international ecoinvent v3.3 database using the system model "allocation, recycled content" [42].

The Grain SA planning models and the data obtained from them apply to the 2011/2012 production period [34–36]. Data referring to maize production, cultivation area, and maize yields are average values for the period 2006–2013 [37]. Data taken from the GWK cost guide refer to the production year 2014 [38]. The functional unit of the LCA was defined as one kilogram of maize at silo storage. A comparison was made between rainfed maize, maize produced using irrigation powered by grid electricity, and maize produced using PV irrigation systems.

Table 1 shows the impact indicators included in the life cycle impact assessment and the methods used to calculate the impacts.

Table 1. Impact indicators used to calculate the environmental impact of South African rainfed and irrigated maize.

Indicator	Method	Description
Climate change	IPCC [43], GWP 100a	The impact indicator climate change accounts for all greenhouse gas (GHG) emissions. The potential climatic effect of each greenhouse gas is compared with the climate impact of CO_2 and expressed in CO_2-equivalents.
Non-renewable energy (fossil and nuclear)	Cumulative energy demand [44]	Cumulative energy demand (CED) is a measure of energy use throughout the life cycle of a product, including both direct and indirect (grey) consumption of energy [44]. In this study, only fossil and nuclear energy resources were considered.
Freshwater and marine eutrophication	ILCD [45]	Aquatic eutrophication is the enrichment of nutrients in the aquatic environment. Because growth of phytoplankton depends on the availability of P and N, emissions of P or N can be converted into biomass [46]. Long-term emissions are excluded from the life cycle impact assessment.
Land use	Ecological Scarcity 2013	For the impact assessment of land use, biodiversity of different land types is considered. Specific eco-factors are available for 14 different biomes [47].
Particulate matter	ILCD [45]	Quantification of the impact of premature death or disability that particulates/respiratory inorganics have on the population, in comparison to $PM_{2.5}$. It includes the assessment of primary (PM_{10} and $PM_{2.5}$) and secondary PM (including creation of secondary PM due to SO_x, NO_x and NH_3 emissions) and CO [45].
Acidification	ILCD [48,49]	Accumulated Exceedance (AE), characterising the change in critical load exceedance of the sensitive area in terrestrial and main freshwater ecosystems, to which acidifying substances are deposited [48,49].
Water footprint	Water scarcity [50]	Water scarcity is based on the ratio of withdrawn to available water and is expressed as m^3 deprived to m^3 consumed water. The indicator is applied to the consumed water volume and assesses consumptive water use only.

3. Life Cycle Inventory

3.1. Inputs

Average production data for South African maize production taken from Grain SA [34–37] and GWK [38] can be seen in the inventory overview in Table 2.

Table 2. Average production data for rainfed and irrigated maize produced in South Africa for the years 2006–2014 [34–38].

	Unit	Maize, Rainfed	Maize, Irrigated
Yield	t ha^{-1}	3.77 †	8.13 †
Seeds	kg ha^{-1}	10.0	23.1
Fertilisers			
Lime	t ha^{-1}	0.9	1.0
NPK	kg ha^{-1}	85	282
Manure	t ha^{-1}	2.5	2.5
Pesticides			
Herbicides	kg ha^{-1}	0.5	0.0001
Insecticides/fungicides	L ha^{-1}	7.7	2.2
Irrigation			
Water	m^3 ha^{-1}	0	7000
Electricity	kWh ha^{-1}	0	1900
Diesel consumption	L ha^{-1}	71.9	79.7

† Moisture content of 13% at harvest.

A number of pesticides are applied during maize production and these were taken into account in the life cycle inventory (Table S1). Multi-nutrient fertilisers and cattle manure are also applied. Half of all farmers apply 10 t ha^{-1} cattle manure with an N-content of 1.1%, P-content of 0.4%, and K-content of 1.0% in alternate years (Table S2). No liquid slurry or compost are applied [51].

Tractors and trailers, imported from the USA, Canada, and Europe, are used for the transport of agricultural inputs and products. Outside South Africa, freight lorries are used for overland transport, and transoceanic freight ships are used for overseas transport. Freight lorries are also used for the majority of transport within South Africa (85.9%) [52], and transport datasets were modified according to country-specific conditions. Since the 1950s, fuel has been produced synthetically from coal in South Africa [53]. Synthetic diesel meets an estimated 16.9% of South Africa's diesel demand [54]. The diesel production mix was adjusted accordingly, and the life cycle inventory of synthetic diesel was taken from an LCA on synfuels [54]. Electric freight trains are used for the remaining 14.1% of inland transport [52]. The transport distances and the origin of inputs and equipment included in this study are shown in Table S3 in the SM.

In 2015/2016, 241,000 hectares of maize were irrigated [7]. Although yields are higher under irrigation, fuel and fertiliser use also increase. Centre pivot irrigation systems are the most commonly used irrigation systems in South Africa. A life cycle inventory was set up using country-specific electricity and water data (Table S4). Based on the Senter 360 model, a 60-hectare irrigation system includes a 6.5 kW electric motor, and a 75 kW pump [55]. To irrigate at a rate of 12 mm per day, the system uses 310 m^3 water per hour. Using these data, the specific electricity consumption of the irrigation system was calculated using the following equation:

$$\mathrm{ECP} = \frac{\mathrm{PD_P} + \mathrm{PD_M}}{\mathrm{WU}}$$

where ECP is the electricity consumption for pumping (kWh/m^3); PD_p is the power demand for the pump (kW); PD_M is the power demand for the motor (kW); and WU is water use (m^3/h).

There is significant variability in the quantity of water used for irrigation. Accordingly, an average of 7000 m^3 ha^{-1} a^{-1} was calculated based on data from Grain SA and GWK [34–36,38], and on personal communication with WD Hall [56] (Table S5).

South African maize is stored before further processing and/or exporting. Since grain maize is harvested at a moisture content of 13%, drying before storage is not necessary [57]. The majority (approximately 80%) is stored in concrete silos [58]. According to AFGRI [58], one of South Africa's largest grain storage companies, concrete silos with a storage capacity of 4500 t are roughly 15 m in diameter, with a height of around 35 m. Approximately 420 m^3 of concrete is needed for the construction of each silo [58]. The dimensions of the silo foundation were estimated to have a surface area of 400 m^2 and a thickness of 1 m, therefore requiring 400 m^3 of concrete for construction. Maize is stored in a silo for an average of six to seven months [58].

Photovoltaic electricity production for solar powered irrigation in South Africa was modelled based on the 570 kWp open ground multi-crystalline silicon power plant in the ecoinvent database v3.3 [42]. The photovoltaic yield was adjusted to the main maize production areas (Northwest and Free State). The city Welkom in Free State was used to estimate the photovoltaic yield, where an annual photovoltaic yield of 1760 kWh/kWp can be expected for optimal orientation according to the Photovoltaic Geographical Information System (PVGIS) of the Joint Research Council of the European Commission, assuming a performance ratio (PR) of 73.7% [59]. A 30-year lifetime of the photovoltaic modules was assumed, with a yield degradation of 0.7% per year. This corresponds to an average decrease in annual yield of 10.5%, resulting in an average annual yield of 1575 kWh/kWp, including degradation. These assumptions regarding lifetime and degradation correspond with the recommendations in the methodology guidelines for LCA of the IEA Photovoltaic Power Systems Program [60]. An area of 7.366 m^2/kWp is needed for a photovoltaic power plant with a nominal power of 1 kWp for this type of module with 13.5% efficiency [61]. With an average yield of 1575 kWh/kWp, this results in an annual yield of 214 kWh/m^2 of PV module.

3.2. Emissions

The N-Emission-Model by Meier et al. [62] was used to calculate the direct field emissions of ammonia (NH_3), dinitrogen monoxide (N_2O), and nitrate (NO_3) arising from the use of organic and mineral fertilisers (Tables S6–S8).

Ammonium contained in fertilisers and nitrogen contained in slurry and manure can be converted into ammonia and emitted into the air during fertiliser application. Ammonia contributes towards both acidification and eutrophication. Ammonia emissions from mineral fertiliser application were estimated to be 2% of the total N applied, in accordance with ecoinvent inventories [63], using emission factors from Asman [64].

Dinitrogen monoxide (N_2O) is produced as an intermediate during the denitrification process and as by-product of the nitrification process. Nitrogen emissions are positively correlated with increasing production intensity. N_2O is a greenhouse gas with an impact 298 times higher than that of CO_2 over 100 years [43]. N inputs from fertilisers, microbial fixation, nitrogen deposition, and management-induced turnover in the soil, as well as nitrogen removal in the products are considered in the model [62]. As maize is not leguminous, the N fixation rate is zero and it was assumed that no N immobilisation occurs due to the sandy texture of the soil in South Africa.

Crop cultivation leads to both short- and long-term nitrate emissions. Excess nitrogen applied during cultivation results in short-term emissions and long-term emissions emitted after the cultivation period derive from plant residues and mineralisation caused by mechanical impact [65]. The quantity of ammonia-N, the mass of N in above and below ground plant residues, and the fraction of N lost by leaching are taken into account in the model [62].

Nitrous oxide (NO_x) emissions also arise during denitrification. NO_x is associated with smog, acid rain, fine particle, and ground level ozone formation. Direct NO_x emissions from fertilisers and soil emissions can be derived from N_2O emissions as follows [63] (Table S9):

$$NO_x = 0.21 \times N_2O.$$

Due to leaching, run-off, and soil erosion, phosphate from fertilisers can enter water systems, where it can lead to eutrophication [66]. The emission model SALCA-P [67] was used to calculate phosphate emissions. Three kinds of phosphorous emissions were considered in this study (Section 2.5):

- Leaching of soluble phosphate to groundwater
- Run-off of soluble phosphate to surface water
- Erosion of particles containing phosphorous to surface water.

Phosphate leaching to groundwater was estimated using average leaching values, specific for each land use category, corrected according to P fertilisation, as shown here:

$$P_{gw} = P_{gwl} \times F_{gw}$$

where P_{gw} is the quantity of P leached to groundwater (kg ha^{-1} a^{-1}); P_{gwl} is the average quantity of P leached to groundwater for land use category (kg ha^{-1} a^{-1}); and F_{gw} is the correction factor for fertilisation by slurry (1 as no slurry in applied in South African maize production [51]).

Phosphate run-off to surface water was calculated using average run-off values, corrected according to P-fertilisation, using the following equation:

$$P_{ro} = P_{rol} \times F_{ro}$$

where P_{ro} is the quantity of P lost through run-off to rivers (kg ha^{-1} a^{-1}); P_{rol} is the average quantity of P lost through run-off for land use category (kg ha^{-1} a^{-1}); and F_{ro} is the correction factor for fertilisation with P.

The correction factor for P fertilisation was calculated as follows:

$$F_{ro} = 1 + \frac{0.2}{80} \times P_2O_{5min} + \frac{0.7}{80} \times P_2O_{5sl} + \frac{0.4}{80} P_2O_{5man}$$

where F_{ro} is the correction factor for fertilisation with P; P_2O_{min} is the quantity of P_2O_5 contained in mineral fertilisers (kg ha^{-1}); P_2O_{5sl} is the quantity of P_2O_5 contained in slurry or liquid sewage sludge (kg ha^{-1}); and P_2O_{man} is the quantity of P_2O_5 contained in solid manure (kg ha^{-1}). As slurry is not used in South African maize cultivation [51], P_2O_{5sl} is zero.

Phosphorous emissions to surface waters resulting from the erosion of particles containing phosphorous were calculated using the following equation:

$$P_{er} = S_{er} \times P_{cs} \times F_r \times F_{erw}$$

where P_{er} = quantity of P emitted through erosion to surface waters (kg P ha^{-1} a^{-1}); S_{er} is the quantity of soil eroded (kg ha^{-1} a^{-1}) (average value of 2200 kg ha^{-1} a^{-1} [68–70]); P_{cs} is the P content in the top soil (kg P/kg soil) (average value of 0.00095 kg P/kg soil [67]); F_r is the P enrichment factor (average value of 1.86 [71]); and F_{erw} is the fraction of the eroded soil that reaches the river (0.05, since surface waters between agricultural fields are rare and the distance to the next river or lake is greater than 100 m [67]).

Heavy metals identified as causing problems in agriculture are: Cadmium (Cd), Chromium (Cr), Copper (Cu), Nickel (Ni), Mercury (Hg), Lead (Pb), and Zinc (Zn) [72]. Heavy metal emissions were calculated using the SALCA-heavy metal model [73]. Three kinds of heavy metal emissions were considered in this study (Section 2.6):

- Leaching of heavy metals to groundwater
- Emissions of heavy metals to surface waters due to the erosion of soil particles
- Emissions of heavy metals to agricultural soil

A simplified method, with fixed leaching values, was used to calculate the heavy metal emissions to groundwater:

$$M_{leach\ i} = m_{leach\ i} \times A_i$$

where $M_{leach\ i}$ is the agriculturally related heavy metal i emission; $m_{leach\ i}$ is the average leaching of heavy metal i [74]; and A_i is the allocation factor for the share of agricultural inputs towards the total input for heavy metal i.

The allocation factors were calculated using the following formula:

$$A_i = M_{agro\ i} / \left(M_{agro\ i} + M_{deposition}\right)$$

where A_i is the allocation factor for the share of agricultural inputs towards the total input for heavy metal i; $M_{agro\ i}$ is the total input of heavy metal from agricultural production (fertilisers, seeds and pesticides) (mg ha^{-1} a^{-1}); and $M_{deposition}$ is the total input of heavy metal from atmospheric deposition (mg ha^{-1} a^{-1}).

Erosion can lead to heavy metal emissions into surface water. These emissions were calculated using the equation:

$$M_{erosion\ i} = c_{tot\ i} \times B \times a \times f_{erosion\ i} \times A_i$$

where $M_{erosion\ i}$ is the agriculturally related heavy metal emissions through erosion (kg ha^{-1} a^{-1}); $C_{tot\ i}$ is the total heavy metal content in the soil (kg kg^{-1}) [75]; B is the rate of soil erosion (kg ha^{-1} a^{-1}) (2200 kg ha^{-1} a^{-1} for South Africa [68–70]); A is the accumulation factor (1.86 for P according to Prasuhn [67]); $f_{erosion\ i}$ is the erosion factor considering the distance to river or lakes (0.05, since surface waters between agricultural fields are rare and the distance to the next river or lake is greater than 100 m [73]); and A_i is the allocation factor for the share of agricultural inputs towards the total input for heavy metal i.

The emissions of heavy metals to agricultural soil were calculated by multiplying the balance of heavy metal inputs (from fertilisers, pesticides, seeds, and deposition) and outputs (in exported biomass, leaching, and erosion) by the aforementioned allocation factor:

$$M_{soil\ i} = \left(\sum inputs_i - \sum outputs_i\right) \times A_i$$

where $M_{soil\ i}$ is the emission to agricultural soil (mg ha^{-1} a^{-1}); $inputs_i$ are the inputs into the soil (fertilisers, pesticides, seed and deposition) (mg ha^{-1} a^{-1}); $outputs_i$ are the outputs from the soil (exported biomass, leaching and erosion) (mg ha^{-1} a^{-1}); andA_i = allocation factor for the share of agricultural inputs towards the total input for heavy metal i.

Water scarcity was calculated by multiplying water consumption for irrigation by the water stress index (WSI), the ratio of local freshwater withdrawal to availability [76]. It was assumed that irrigation only takes place during the warmest and driest months of the year (from October to January). Due to a lack of more specific data regarding monthly irrigation rates, it was assumed that total annual water consumption for irrigation was equally distributed over these four months. Pfister and Baumann [77] calculated monthly WSI for all catchment areas around the world. Six catchment areas (Catchment Area 62875, Catchment Area 63044, Catchment Area 63209, Catchment Area 63671, Catchment Area 63992, and Catchment Area 64168) cover the main maize production areas: Free State, North West, and Mpumalanga (Table S19).

4. Results

The life cycle impact assessment revealed substantial differences between rainfed maize, maize produced under irrigation using grid electricity, and maize grown using photovoltaic electricity for irrigation. The environmental hotspots of South African rainfed maize were determined to be fertiliser production, direct field emissions, and the operation of field machinery. These were also determined to be environmental hotspots in the production of irrigated maize. Irrigation, however, was an additional hotspot, accounting for more than a third of the total GHG emissions from the production of South African maize produced using grid-powered irrigation, largely due to the associated electricity consumption. The majority of South Africa's grid electricity is supplied by hard coal power plants [42], which are associated with considerable GHG emissions.

Despite 116% higher yields under irrigated production, the GWP per kilogram of irrigated maize in South Africa was determined to be 64% higher than that of maize produced without irrigation (Figure 2). Irrigation is responsible for 36% of the total GHG emissions of maize when powered by South African grid electricity. In regards to GWP, replacing grid electricity for irrigation with electricity produced using photovoltaics leads to a reduction of 34% (a drop from 0.80 kg CO_2-eq. kg^{-1} to 0.53 kg CO_2-eq. kg^{-1}), as can be seen in Figure 2. Maize irrigated using PV electricity has a similar GWP to maize produced without irrigation (0.49 kg CO_2-eq. kg^{-1}).

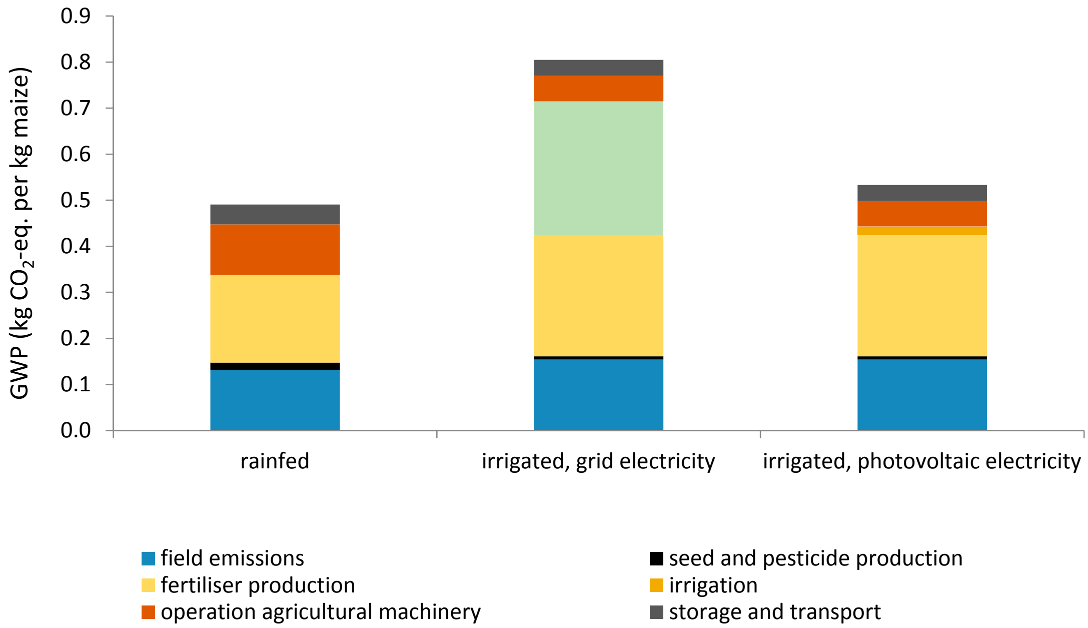

Figure 2. Global warming potential (GWP) (kg CO_2-eq.) associated with the production of 1 kg of: rainfed maize (**left**); maize produced under irrigation using South African grid electricity (**centre**); and under irrigation using electricity from photovoltaics (**right**).

Additionally, non-renewable fossil and nuclear energy demands are 48% and 59% lower with PV irrigation systems than with irrigation systems powered by grid electricity (Figure 3). Freshwater eutrophication, acidification, and particulate matter emissions are 54%, 21%, and 22% lower, respectively. However, replacing the electricity supply for irrigation has little impact on marine eutrophication and land use (Figure 3). When applying the ILCD impact assessment method, the extent to which marine eutrophication occurs is determined by the application of fertilisers and manure, as well as the emissions of N-containing compounds, such as nitrates and ammonium, into the air, soil, and water [46]. These inputs and emissions are determined by cultivation practices, such as the quantity and type of fertiliser applied, and therefore do not vary between grid-powered and PV-powered irrigated maize production. Land use associated with irrigated maize production is mainly due to the occupation of land for maize production and for the storage silo. As the yield is the same for both types of irrigated maize, these do not differ depending on the source of electricity for irrigation. Land use due to the photovoltaic system is negligible and therefore has little influence on the total.

The non-renewable nuclear energy demand is 8% higher for maize produced using PV irrigation systems in comparison with rainfed maize. Particulate matter and acidification are 9% and 25% higher, respectively. On the other hand, non-renewable fossil energy demands, freshwater eutrophication, and land use are 10%, 29%, and 53% lower, respectively. Marine eutrophication is similar for both rainfed maize and maize irrigated using South African grid electricity (Figure 3).

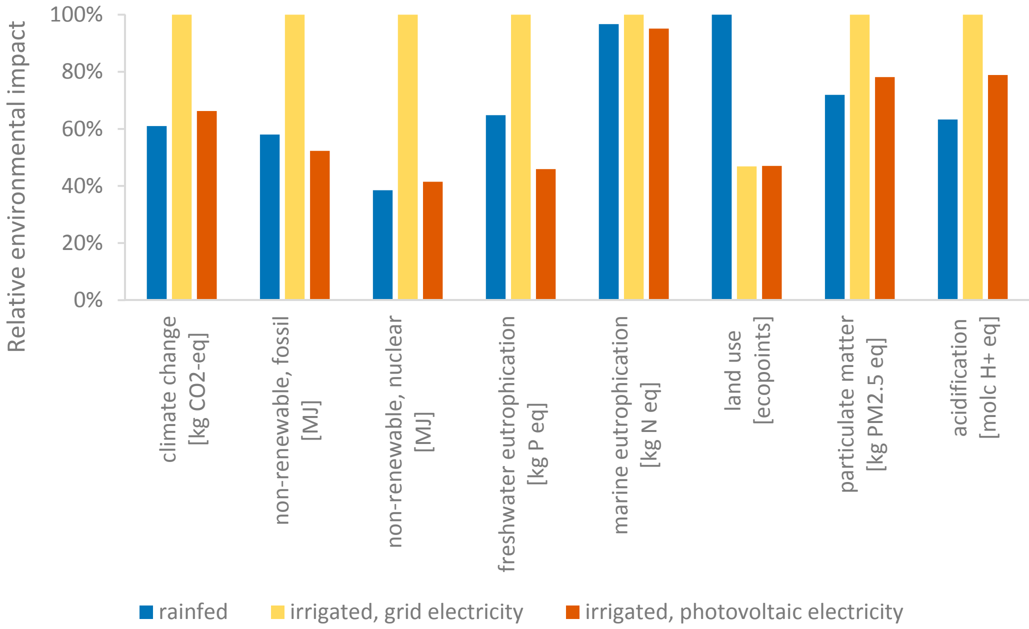

Figure 3. Relative environmental impact associated with the production of maize produced without irrigation (blue); with irrigation powered by grid electricity (yellow); and with photovoltaic irrigation systems (orange) in South Africa. The maize with the highest impact in each category is used as a reference at 100%.

Water stress induced by maize production in South Africa varies considerably between the different water catchment areas. Water scarcity during the irrigation period in South African maize production is, at 6976 m^3 ha^{-1} a^{-1} (Figure 4), highest in Catchment Area 1, which includes the northern part of North West and the northern part of Mpumalanga. In Catchment Area 5, which includes Free State, the southern part of North West, and the southern part of Mpumalanga, water scarcity is 5340 m^3 ha^{-1} a^{-1}. In comparison, water scarcity in the remaining catchment areas is low (Catchment Area 2: 523 m^3 ha^{-1} a^{-1}, Catchment Area 3: 133 m^3 ha^{-1} a^{-1}, Catchment Area 4: 96 m^3 ha^{-1} a^{-1}; Catchment Area 6: 179 m^3 ha^{-1} a^{-1}).

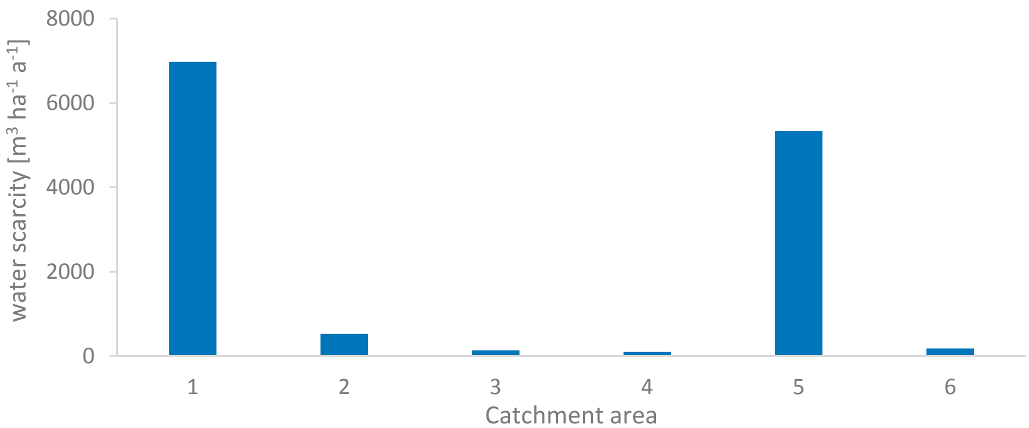

Figure 4. Water scarcity (m^3 ha^{-1} a^{-1}) of the six catchment areas in the main South African maize production areas Free State, North West, and Mpumalanga.

5. Discussion

The environmental impacts associated with South African maize produced using grid-powered electricity for irrigation are considerably higher for the majority of impact categories considered in this study in comparison with maize produced using PV irrigation systems. In regards to GHG emissions, as well as non-renewable energy use, particulate matter emissions, and acidification, the impacts of grid-powered irrigation can almost be eliminated using PV powered electricity. This is due to the composition of South African grid electricity, 88% of which is supplied by hard coal power plants. An additional 5% originates from nuclear power plants [42]. By eliminating the contributions of electricity with high environmental impacts, the overall environmental impact can be reduced considerably.

5.1. Comparison with Previous Studies

Although no previous studies have compared the environmental impacts of different electricity sources specifically for irrigation, other studies have shown a substantial difference in GWP between electricity generated using hard coal and PV. According to a meta-study of 167 case studies, GHG emissions were determined to be between 660 and 1050 kg CO_2-eq. per MWh of electricity produced using hard coal in comparison with emissions of between 13 and 190 kg CO_2-eq./MWh for electricity produced using solar photovoltaic systems [24]. These results are similar to other review studies, which determined electricity from hard coal to have a GWP of between 800–1200 kg CO_2-eq./MWh [22,23,78–82] and PV systems between 40 and 160 kg CO_2-eq./MWh [22,23,78–87].

Turconi et al. [24] compared NO_x and SO_2 emissions produced during electricity generation from various technologies. NO_x emissions ranged between 0.3–3.9 kg NO_x/MWH for hard coal and 0.15–0.40 kg NO_x/MWh for solar energy. The difference in SO_2 emissions is less pronounced: electricity production using hard coal results in SO_2 emissions of 0.03–6.7 kg SO_2/MWh in comparison with 0.12–0.29 kg SO_2/MWh for photovoltaics. In a comparative LCA of electricity generation options, researchers determined coal to have the highest environmental impacts by far for the majority of criteria studied: emissions of greenhouse gases, SO_2, NO_x, volatile organic compounds, particulates, and toxic metals; as well as land requirements when indirect factors were also taken into account [79].

Scharfy et al. [88] carried out a comparative multi-criteria decision analysis to rank clean technologies in agriculture in terms of sustainability, considering economic and social aspects as well as environmental impacts. Photovoltaic electricity achieved one of the highest sustainability scores, outperforming numerous other clean technologies.

5.2. Comparison with Other Countries

In comparison with rainfed maize, with a GWP of 0.49 kg CO_2-eq. per kilogram, the GWP of irrigated maize was determined to be 0.80 kg CO_2-eq. per kilogram. This is higher than that of irrigated maize produced in the US (0.54 kg CO_2-eq. kg^{-1}), in Switzerland (0.51 kg CO_2-eq. kg^{-1}), in Quebec, Canada (0.57 kg CO_2-eq. kg^{-1}), and ecoinvent's global production mix (0.60 kg CO_2-eq. kg^{-1}). Maize from Argentina, however, has a higher GWP than South African irrigated maize (1.24 kg CO_2-eq. kg^{-1}) [29]. In terms of inputs (seeds, fertilisers, pesticides, and irrigation water), as well as machine operation, field emissions, and transport, the system boundaries of the ecoinvent data sets are comparable with those applied in this study. However, in contrast to this study, storage in concrete silos was not taken into account. In South Africa, the yield is lower than in the USA, Switzerland, and Quebec and higher than in Argentina, which could, at least partially, account for the discrepancy in GWP between the different countries. A comparison of yields and GHG emissions of irrigated maize produced in various countries can be seen in Table 3.

Table 3. Comparison of the yield and global warming potential (GWP) of irrigated maize produced in different countries [42].

Country of Production	Yield (kg ha^{-1})	GWP (kg CO_2-eq. kg^{-1})
Argentina	7400	1.24
South Africa	8134	0.80
Canada	8900	0.57
Switzerland	9279	0.51
US	9315	0.54

5.3. Potential for South Africa

In 2015/2016, a total of 241,000 ha of maize were grown under irrigation in South Africa [7] (Table S20). Replacing all grid-powered irrigation systems with PV-driven systems could potentially reduce South Africa's greenhouse gas emissions by 536,000 t CO_2-eq. per year (Table 4).

Table 4. Data used to calculate the total mitigation potential of photovoltaic irrigation systems in South African maize production, based on data from 2015/2016 [7,34–36,89].

Irrigated production area 2015/2016 (1000 ha)	240.64
Irrigated maize yield (kg ha^{-1} a^{-1})	8134
GWP of maize irrigated using grid electricity (kg CO_2-eq. kg^{-1})	0.80
GHG emissions of South African irrigated maize production using grid electricity (t CO_2-eq. a^{-1})	1,575,364
Mitigation potential of PV irrigation	34%
Total mitigation potential for South Africa (t CO_2-eq.a^{-1})	535,642

In 2010, South Africa's GHG emissions (excluding Forestry and Other Land Use) amounted to 545 million tonnes CO_2-eq. [90]. Around 1.3 million hectares of land is irrigated in South Africa [9] and around 30% of total crop production occurs on this land [11]. Therefore, the potential GHG savings of introducing PV irrigation systems are significant. Assuming that the GHG reduction potential for other crops is similar to that of maize production on a per hectare basis, a total reduction of 2.9 million tonnes CO_2-eq. could be achieved if all irrigation were converted to PV driven systems. This amounts to just over 0.5% of the country's annual GHG emissions.

5.4. Assumptions, Uncertainties and Data Quality

Overall, the quality of the data was high. Up-to-date, detailed, and country-specific data were available for the majority of the most relevant parameters and the main maize production regions were taken into account.

However, a number of assumptions were made due to a lack of specific data. Transport distances from the farm to silo storage and the dimensions of the silo foundation were estimations. Moreover, neither seasonal nor annual variations were taken into account. Only three maize production regions were included in the study, although maize is also produced in other regions, albeit to a lesser extent. Only irrigation with centre pivot irrigation systems was included in the study. In regards to the PV system, no batteries or water storage tanks were considered. It was assumed that the electricity generated during periods when no irrigation occurs is utilised for other purposes. Therefore, any impacts associated with this electricity generation would be attributed to these other processes and not to maize production.

Soil erosion is a significant problem in South Africa, with more than 300 million tonnes of topsoil washed away every year [91]. However, due to a lack of specific data and impact assessment methods regarding the impact of South African maize production on soil erosion, it was not included in this study. Additionally, there was no allocation of products and only a single output, namely maize, was considered. However, maize stover can be used in bioenergy production or as animal feed or bedding and could therefore be considered a by-product of maize production. The cultivation of winter cover crops, which are usually planted after harvesting the cash crop and removed using herbicides prior to planting the cash crop for the subsequent growing season, was not considered in this study.

5.5. Potential Barriers to Implementation

Some studies identify land use requirements for PV energy generation as a possible barrier to implementation [14,79]. However, generation of the 1820 kWh of electricity per hectare per year (0.26 kWh/m^3 of electricity required for pumping, with irrigation of 7000 m^3/ha^{-1}/a^{-1} on average) required for the irrigation of South Africa's maize would require only 26 m^2 of solar panels, equivalent to a mere 0.26% of the cultivation area (Table S22). In 2015/2016, 241,000 hectares of land were used for irrigated maize production in South Africa [7], which would require a total of 627 ha of solar panels. Since these land requirements are negligible in comparison with the total area of production, land availability cannot be considered a limiting factor in the implementation of PV irrigation systems in South Africa.

In terms of renewable energies, the main barriers to implementation in South Africa in the past were economical. The competitive cost of renewables was particularly relevant: electricity prices were low due to abundant coal reserves, which made investment in renewable energies less attractive than in others regions with higher electricity prices [92]. However, this is no longer the case. The promotion of renewable energies is one of the South African government's strategic goals [93]. The Renewable Energy Independent Power Producer Procurement Programme (REIPPPP), with the objective of increasing electricity supply while reducing dependency on fossil fuels [94], has led to a decrease in average solar PV prices from 2.76 R/kWh in 2011 to 0.79 R/kWh in 2015 [95] and the tariffs projected for 2030 had already been reached by 2014 [96]. The programme was initially criticised due to the competitive advantage of coal-generated electricity at the time and in the first round of bids, the average price of electricity from renewables was around 3.5 times higher than that of coal-based power generation [97]. However, increasing costs of coal-based electricity generation, rapidly decreasing costs of solar PV energy generation, along with an increasingly competitive bidding process of the programme have changed this [96,97].

In only three years, solar PV (as well as wind-generated electricity) reached pricing parity with supply from new coal power stations in terms of levelised cost of electricity (LCOE) [98]. According to the Council for Scientific and Industrial Research (CSIR), the lifetime cost of new-build solar PV generated electricity in April 2016 was 0.62 R/kWh, compared with a new-build tariff of 1.03 R/kWh for electricity generated from coal [99]. Solar PV systems in South Africa packhouses were found to be economically viable, particularly for larger systems [29].

However, uptake of solar PV may be limited as the ability to connect such systems to the grid is not yet universal and because regulations concerning connection and the sale of excess electricity are not yet in place in all municipalities [29], which restrict the size of installations to ensure maximum self-consumption [95]. Negative perceptions towards solar PV, i.e., that it is expensive or unreliable, have been identified as further barriers to implementation [29]. Although capital cost is often considered a barrier to implementation, long-term cost saving potential, protection against fluctuating future fuel prices and innovative financing models may counteract these issues. Although a number of programmes established in South Africa to develop the solar energy sector have already led to significant progress, clear communication about these benefits is still necessary [29].

5.6. The Future of South African Irrigation

When comparing maize produced using PV irrigation systems with maize produced without irrigation, it is difficult to determine a clear recommendation. Some impacts (non-renewable nuclear energy demand, particulate matter, and acidification) are higher for maize produced using PV driven irrigation, whereas others are lower (non-renewable fossil energy demands, freshwater eutrophication, and land use). GWP and marine eutrophication are similar for both.

However, concern about water scarcity is growing worldwide, and this is especially true in South Africa. Water scarcity is particularly high in two of the catchment areas (Catchment Areas 1 and 5) within the maize production areas included in this study (Figure 4). Around 98% of all available water in the country is already allocated [100] and Davies and Day [101] predict that there will be no spare water in South Africa by 2020, providing the whole population is sufficiently supplied. According to Stats SA [102], there is likely to be a countrywide water deficit by 2025, with estimates ranging from 234 million m^3 per year to 2044 million m^3 per year. Agriculture is responsible for approximately 50% of South Africa's water use and water availability is one of the most significant factors limiting agricultural production [103]. Reductions in available water will make producing enough food in the future even more challenging.

Irrigation can allow crop production in areas where the climate is unsuitable and increase production in areas where water limits yields [104]. Expansion of irrigated areas may appear to be the logical solution to increase productivity, but this is not a viable course of action. Irrigation contributes to water over-extraction [100], as well as salinisation [105]. It can lead to the cultivation of crops in unsuitable regions, compounding the problem of unsustainable water use [100].

As irrigation in South Africa is likely to become even more widespread as a result of climate change, finding ways of minimising its environmental impacts is of utmost importance. While introducing PV irrigation systems can reduce a number of the environmental impacts associated with irrigated maize production in South Africa, other issues, such as water scarcity also need to be addressed. Water saving irrigation systems and limiting irrigation to areas with low water scarcity are possible approaches.

5.7. Alternative Means of Reducing the Environmental Impacts of Maize Production

Conservation agriculture (CA) is being encouraged globally to improve soil health and to sustain productivity. CA can slow surface water flow, reduce evaporation, and increase soil water holding capacity [106], which has the potential to increase production. CA on marginal lands can lead to substantial yield increases of around 50% when compared with conventional yields in Southern Africa [107]. One study found the yield of maize produced using CA in Eastern and Southern Africa to be 20–120% higher than for conventionally produced maize [108]. Some evidence suggests that CA results in even more significant improvement when rainfall is low [108], which could be particularly relevant in South Africa, due to the arid conditions. Increased yields can contribute towards lower environmental impacts as well as help improve food security and contribute towards poverty alleviation. Further benefits of CA include reduced erosion and compaction, and improved soil aggregation [109]. Maintaining a minimum of 30% soil surface cover by plant residues is considered essential in terms of soil and water conservation [106]. Leaving the maize stover on the field after the grain harvest has been shown to have positive effects on soil erosion, which is a significant problem in many areas in South Africa [110,111]. However, in semi-arid and arid regions of Africa, there may be a conflict of interests as alternative uses of crop residues, for example as fodder for livestock, may be given priority [106]. Although research and practical results suggest CA could be beneficial in South Africa, lack of communication about its benefits has resulted in relatively low adoption rates [112]. It is knowledge intensive and conversion from conventional farming practices is a major step for small-scale farmers in newly industrialised countries [108].

Efficient methods and scheduling can help reduce the impacts associated with irrigation [113]. A study carried out in Pongola (KwaZulu-Natal) comparing intuition-based irrigation with objective irrigation scheduling of sugarcane found that the objective method significantly decreased water use [114]. Additionally, clean technologies, such as wireless sensor irrigation networks (WSIN) may help lower the impacts of maize production. WSIN include soil moisture sensors, specialised software interfaces, and decision-supporting tools, which allow a more efficient and precise "water on demand" irrigation. Majsztrik et al. [115] showed a decline in average water consumption of approximately 50% compared with traditional irrigation in ornamental plant production in the USA. Furthermore, a reduction in fertiliser application, nutrient runoff, and greenhouse gas emissions could be attributed to the implementation of WSIN in horticulture. Further research is required to estimate the reduction potential of WSIN in the production of crops such as maize. Alternatively, drip irrigation and frequency converters for irrigation pumps may help reduce the environmental impact of irrigation. Advantages of drip irrigation include reduced water demands [116], a reduced risk of erosion [117], fewer plant diseases, less weed infestation, reduced energy consumption, and a reduction in eutrophication through well-directed irrigation and fertilisation [118]. Along with other applications, frequency converters can be used for irrigation pumps to reduce energy consumption. Trials on a South African farm have shown a 35% reduction in electricity use with the application of a frequency converter [119]. By applying a combination of these technologies and renewable energy, the potential for mitigating environmental impacts could be maximised.

6. Conclusions

The replacement of South African grid electricity with photovoltaic electricity in irrigation has been shown to be an effective means of reducing the environmental impact associated with irrigated maize production. The adoption of PV irrigation systems could potentially reduce the GHG emissions arising from South African maize production by 536,000 t CO_2-eq. per year. Additionally, non-renewable fossil and nuclear energy demands, freshwater eutrophication, acidification, and particulate matter emissions are lower than with irrigation systems powered by grid electricity. Depending on the impact indicator, up to 59% of the environmental impact can be eliminated by using irrigation powered by photovoltaic electricity as compared to systems running on grid electricity.

According to our calculations, land use is not a limiting factor for installing PV panels to generate solar energy for the large-scale irrigation of maize fields in South Africa. However, water scarcity is a significant problem in South Africa. Along with reducing environmental impacts, lowering agriculture's water consumption should be considered a priority.

Supplementary Materials: The following are available online at www.mdpi.com/2071-1050/9/10/1772/s1.

Acknowledgments: This research project was carried out within the framework of the Swiss–South African Joint Research Programme and was funded by the Swiss National Science Foundation and the South African National Research Foundation. The project "Applying Life Cycle Assessment for the mitigation of environmental impacts of South African agri-food products" was conducted in 2014–2017 in cooperation between Zurich University of Applied Sciences and University of Cape Town. This publication is a result of the project. The authors would like to thank Harro von Blottnitz from the University of Capetown for his collaboration and his review of this paper.

Author Contributions: Matthias Stucki and Deborah Scharfy conceived and designed the study; Sarah Wettstein analysed the data; and Karen Muir wrote the first draft of the paper. All authors contributed to the final version.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. FAO. Aquastat: Water Uses. Available online: http://www.fao.org/nr/water/aquastat/water_use/index.stm (accessed on 20 April 2015).
2. FAO. Chapter 2: Energy for Agriculture. Available online: http://www.fao.org/docrep/003/X8054E/x8054e05.htm (accessed on 30 April 2017).
3. World Bank World Development Indicators. Available online: http://wdi.worldbank.org/table/2.1 (accessed on 30 April 2017).
4. United Nations. *World Population Prospects: The 2015 Revision, Key Findings and Advance Tables*; Working Paper No. ESA/P/WP.241; United Nations, Department of Economic and Social Affairs: New York, NY, USA, 2015.
5. FAO. *How to Feed the World in 2050*; Food and Agriculture Organization of the United Nations (FAO): Rome, Italy, 2009.
6. United Nations. *World Population Prospects: The 2010 Revision*; United Nations, Department of Economic and Social Affairs, Population Devision: New York, NY, USA, 2011; Volume 1: Comprehensive Tables.

7. 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 13 April 2017).
8. GCIS. *South Africa Yearbook 2015/16*; Government Communication and Information System (GCIS), South Africa: Pretoria, South Africa, 2016.
9. GCIS. *South African Yearbook 2013/2014*; Government Communication and Information System (GCIS), Republic of South Africa: Pretoria, South Africa, 2014.
10. Cousins, B. Smallholder irrigation schemes, agrarian reform and accumulation from above and from below'in South Africa. *J. Agrar. Chang.* **2013**, *13*, 116–139. [CrossRef]
11. GCIS. *South African Yearbook 2008/09*; Government Communication and Information System (GCIS), Republic of South Africa: Pretoria, South Africa, 2009.
12. DAFF. *Maize Market Value Chain Profile 2014*; Department of Agriculture, Forestry and Fisheries (DAFF), Republic of South Africa: Pretoria, South Africa, 2014.
13. Frankl, P. *Technology Roadmap: Solar Photovoltaic Energy*; International Energy Agency (IEA): Paris, France, 2010.
14. Tsoutsos, T.; Frantzeskaki, N.; Gekas, V. Environmental impacts from the solar energy technologies. *Energy Policy* **2005**, *33*, 289–296. [CrossRef]
15. Van der Hoeven, M. *Technology Roadmap Solar Photovoltaic Energy—2014 Edition*; International Energy Agency (IEA): Paris, France, 2014.
16. IEA. *Snapshot of Global Photovoltaic Markets 2016*; International Energy Agency (IEA): Paris, France, 2017.
17. Ginley, D.S.; Cahen, D. (Eds.) *Fundementals of Materials for Energy and Environmental Sustainability*; Cambridge University Press: Cambridge, UK, 2011.
18. Green, M.A. *Third Generation Photovoltais*; Springer: New York, NY, USA, 2006.
19. Milichko, V.A.; Shalin, A.S.; Mukhin, I.S.; Kovrov, A.E.; Krasilin, A.A.; Vinogradov, A.V.; Belov, P.A.; Simovski, C.R. Solar photovoltaics: Current state and trends. *Phys. Uspekhi* **2016**, *59*, 727–772. [CrossRef]
20. Grant, T.; Beer, T. Life cycle assessment of greenhouse gas emissions from irrigated maize and their significance in the value chain. *Anim. Prod. Sci.* **2008**, *48*, 375–381. [CrossRef]
21. Renouf, M.A. LCA of Queensland cane sugar-lessons for the application of LCA to cropping systems in Australia. In Proceedings of the 5th Australian Conference on Life Cycle Assessment, 22–24 November 2006; Citeseer: Melbourne, Australia, 2006; pp. 22–24.
22. Cameco Corporation. Comparison of Lifecycle Greenhouse Gas Emissions of Various Electricity Generation Sources. Available online: https://www.cameco.com/uranium_101/static/pdf/Cameco_-_Corporation_Report_on_GHG_Emissions_nov_2010.pdf (accessed on 21 September 2017).
23. Dones, R.; Heck, R.; Hirschberg, S. Greenhouse gas emissions from energy systems, comparison and overview. *Encycl. Energy* **2004**, *3*, 77–95.
24. Turconi, R.; Boldrin, A.; Astrup, T. Life cycle assessment (LCA) of electricity generation technologies: Overview, comparability and limitations. *Renew. Sustain. Energy Rev.* **2013**, *28*, 555–565. [CrossRef]
25. Mekhilef, S.; Faramarzi, S.Z.; Saidur, R.; Salam, Z. The application of solar technologies for sustainable development of agricultural sector. *Renew. Sustain. Energy Rev.* **2013**, *18*, 583–594. [CrossRef]
26. Meah, K.; Fletcher, S.; Ula, S. Solar photovoltaic water pumping for remote locations. *Renew. Sustain. Energy Rev.* **2008**, *12*, 472–487. [CrossRef]
27. Ahammed, F.; Taufiq, D.A. Applications of solar PV on rural development in Bangladesh. *J. Rural Community Dev.* **2008**, *3*, 93–103.
28. Pande, P.C.; Singh, A.K.; Ansari, S.; Vyas, S.K.; Dave, B.K. Design development and testing of a solar PV pump based drip system for orchards. *Renew. Energy* **2003**, *28*, 385–396. [CrossRef]
29. Van Vuuren, P.F.J.; Pineo, C.B.; Basson, L. Solar energy in agri-processing. In Proceedings of the Southern African Solar Energy Conference 2016, Tellenbosch, Africa, 31 October–2 November 2016.
30. Scharfy, D.; Stucki, M.; Eymann, L.; Keller, R.; Wettstein, S.; von Blottnitz, H. Green Technologies for Food Production: The Mitigation Potential in South African Fruit, Maize and Dairy Value Chains. In Proceedings of the Conference of the World Sustainability Forum 2017, Cape Town, South Africa, 28 January 2017.
31. Wettstein, S.; Scharfy, D.; Berli, C.; von Blottnitz, H.; Stucki, M. South African maize production: Mitigating environmental impacts through solar powered irrigation. In Proceedings of the 10th International Conference on Life Cycle Assessment of Food, Dublin, Ireland, 19–21 October 2016.

32. ISO. *Environmental Management—Life Cycle Assessment—Requirements and Guidelines. ISO14040:2006*; International Organization of Standarization: Geneva, Switzerland, 2006.
33. ISO. *Environmental Management—Life Cycle Assessment—Requirements and Guidelines. ISO14044:2006*; International Organization of Standarization: Geneva, Switzerland, 2006.
34. Grain, S.A. *Operational Planning of White Maize Grain Production in the Production Year 2011/2012 in Eastern Highveld, South Africa*; Grain S.A.: Lynnwood Ridge, South Africa, 2014.
35. Grain, S.A. *Operational Planning of White Maize Grain Production in the Production Year 2011/2012 in Northwest, South Africa*; Grain S.A.: Lynnwood Ridge, South Africa, 2014.
36. Grain, S.A. *Operational Planning of White Maize Grain Production in the Production Year 2011/2012 in Central and Northern Free State, South Africa*; Grain S.A.: Lynnwood Ridge, South Africa, 2014.
37. Grain, S.A. *Maize production in South Africa from 2006–2013*; Grain S.A.: Lynnwood Ridge, South Africa, 2014.
38. Rechtus, S.; GWK Beperk, Kimberly, South Africa. Personal communication, 2016.
39. Coetzee, J.; South African Breweries, Johannesburg, South Africa. Personal communication, 2016.
40. DistanceFromTo. Distance Between Cities Places on Map. Available online: http://www.distancefromto.net (accessed on 15 April 2015).
41. SeaRates.com. Available online: http://www.searates.com/de/reference/portdistance (accessed on 15 April 2015).
42. Ecoinvent Centre. *Ecoinvent Data v3.3*; Swiss Centre for Life Cycle Inventories: Zürich, Switzerland, 2016.
43. IPCC. *Climate Change 2013: The physical Science Basis*; Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change; Cambridge University Press: Cambridge, UK, 2013.
44. Hischier, R.; Weidema, B.; Althaus, H.-J.; Bauer, C.; Doka, G.; Dones, R.; Frischknecht, R.; Hellweg, S.; Humbert, S.; Jungbluth, N. Implementation of life cycle impact assessment methods. *Final Rep. Ecoinvent V2* **2010**, *2*.
45. Rabl, A.; Spadaro, J.V. The RiskPoll Software. Available online: http://www.arirabl.com/software (accessed on 21 September 2017).
46. Goedkoop, M.; Heijungs, R.; Huijbregts, M.; De Schryver, A.; Struijs, J.; Van Zelm, R. ReCiPe 2008: A Life Cycle Impact Assessment Method Which Comprises Harmonised Category Indicators at the Midpoint and the Endpoint Level. Available online: http://www.leidenuniv.nl/cml/ssp/publications/recipe_characterisation.pdf (accessed on 21 September 2017).
47. Frischknecht, R.; Büsser Knöpfel, S. Swiss Eco-Factors 2013 According to the Ecological Scarcity Method. Available online: https://www.bafu.admin.ch/bafu/en/home/topics/economy-consumption/economy-and-consumption--publications/publications-economy-and-consumption/eco-factors-2015-scarcity.html (accessed on 21 September 2017).
48. Seppälä, J.; Posch, M.; Johansson, M.; Hettelingh, J.-P. Country-dependent Characterisation Factors for Acidification and Terrestrial Eutrophication Based on Accumulated Exceedance as an Impact Category Indicator (14 pp). *Int. J. Life Cycle Assess.* **2006**, *11*, 403–416. [CrossRef]
49. Posch, M.; Seppälä, J.; Hettelingh, J.-P.; Johansson, M.; Margni, M.; Jolliet, O. The role of atmospheric dispersion models and ecosystem sensitivity in the determination of characterisation factors for acidifying and eutrophying emissions in LCIA. *Int. J. Life Cycle Assess.* **2008**, *13*, 477–486. [CrossRef]
50. Pfister, S.; Baumann, J. Monthly characterization factors for water consumption and application to temporally explicit cereals inventory. In Proceedings of the LCA Food 2012: VII International Conference on Life Assessment in the Agri-Food Sector, Bari, Italy, 22–24 September 2010.
51. Coetzee, J.; South African Breweries, Johannesburg, South Africa. Personal communication, 2015.
52. Viljoen, N. *10th Annual State of Logistics Survey for South Africa 2013*; The Council for Scientific and Industrial Research (CSIR): Pretoria, South Africa, 2014.
53. Internationl Energy Agency Coal Research Ltd.; FuelConsult GmbH; Glówny Instytut Górnictwa; Tallinn University of Technology, S.P. E.V. E.O. P.S. Review of Worldwide Coal to Liquids. R, D&D Activities and the Need for Futher Initiatives within Europe. Available online: http://www.iea-coal.org.uk/documents/82184/7171/Review-of-worldwide-coal-to-liquids-R,-D&D-activities-and-the-need-for-further-initiatives-within-Europe (accessed on 21 September 2017).
54. Dick, J. *Simple Life Cycle Assessment of Sasol Synfuels Secunda (Unpublished)*; University of Cape Town: Cape Town, South Africa, 2012.

55. Marais, L.; Sentor 360, Klerksdorp, South Africa. Personal communication, 2015.
56. Hall, W.; Maize producer, Heidelberg, South Africa. Personal communication, 2015.
57. Du Plessis, J. *Maize Production*; Department of Agriculture, Forestry and Fisheries in cooperation with ARC-Grain Crops Institute: Pretoria, South Africa, 2003.
58. Vorster, L.; AFGRI, Centurion, South Africa. Personal communication, 2015.
59. JRC-EC PV Potential Estimation Utility. Available online: http://re.jrc.ec.europa.eu/pvgis/apps4/pvest.php?lang=en&map=africa (accessed on 25 April 2015).
60. Frischknecht, R.; Heath, G.; Raugei, M.; Sinha, P.; de Wild-Scholten, M. *Methodology Guidelines on Life Cycle Assessment of Photovoltaic Electricity*, 3rd ed.; National Renewable Energy Laboratory (NREL): Golden, CO, USA, 2016.
61. Jungbluth, N.; Stucki, M.; Flury, K.; Frischknecht, R.; Büsser, S. *Life Cycle Inventories of Photovoltaics*; ESU-Services Ltd.: Uster, Switzerland, 2012.
62. Meier, M.S.; Schader, C.; Berner, A.; Gattinger, A. Modelling N_2O emissions from organic fertilisers for LCA inventories. In Proceedings of the 8th International Conference on Life Cycle Assessment in the Agri-Food Sector, Saint-Malo, France, 1–4 October 2012.
63. Nemecek, T.; Kägi, T. *Life Cycle Inventories of Agriculture Production Systems*; ART: Zürich, Switzerland; Dübendorf, Switzerland, 2007.
64. Asman, W.A.H. *Ammonia Emission in Europe: Updated Emission and Emission Variations*; National Institute of Public Health and Environmental Protection: Bilthoven, Utrecht, The Netherlands, 1992.
65. Meier, M.S.; Jungbluth, N.; Stoessel, F.; Schader, C.; Stolze, M. Higher accuracy in N modeling makes a difference. In Proceedings of the 9th International Conference Life Cycle Assessment in the Agri-Food Sector, San Francisco, CA, USA, 8–10 October 2014; pp. 8–10.
66. Prasuhn, V.; Grünig, K. *Evaluation der Ökomassnahmen-Phosphorbelastung der Oberflächengewässer durch Bodenerosion*; Eidgenössische Forschungsanstalt für Agrarökologie und Landbau: Zürich-Reckenholz, Swizerland, 2001.
67. Prasuhn, V. *Erfassung der PO4-Austräge für die Ökobilanzierung. SALCA-Phosphor*; Agroscope FAL Reckenholz: Zurich, Switzerland, 2006.
68. 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: Canterbury, New Zealand, 2013; ISBN 978-953-51-1092-7.
69. 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.
70. UWC Erosion. Available online: http://www.botany.uwc.ac.za/envfacts/facts/erosion.htm (accessed on 28 April 2015).
71. Wilke, B.; Schaub, D. Phosphatanreicherung bei Bodenerosion. *Mitt. Dtsch. Bodenkndul. Gesellsch* **1996**, *79*, 435–438.
72. Kühnholz, O. *Schwermetalle in der Ökobilanz von landwirtschaftlichen Produktionssystemen*; Agroscope FAL Reckenholz: Zürich-Reckenholz, Switzerland, 2001.
73. Freiermuth, R. Modell zur Berechnung der Schwermetallflüsse in der landwirtschaftlichen Ökobilanz. Available online: https://www.agroscope.admin.ch/dam/agroscope/de/dokumente/themen/umwelt-ressourcen/produktionssysteme/salca-schwermetall.pdf.download.pdf/SALCA-Schwermetall.pdf (accessed on 21 September 2017).
74. 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*; FAT: Bern, Switzerland; Tänikon, Switzerland, 1997.
75. Keller, T.; Desaules, A. *NABO: Böden der Schweiz: Schadstoffgehalte und Orientierungswerte (1990–1996)*; Bundesamt für Umwelt, Wald und Landschaft: Bern, Switzerland, 2001.
76. Pfister, S.; Koehler, A.; Hellweg, S. Assessing the Environmental Impacts of Freshwater Consumption in LCA. *Environ. Sci. Technol.* **2009**, *43*, 4098–4104. [CrossRef] [PubMed]
77. Pfister, S.; Baumann, J. Monthly characterization factors for water consumption and application to temporally explicit cereals inventory. In Proceedings of the 8th International Conference on Life Cycle Assessment in the Agri-Food Sector (LCA Food 2012), Saint-Malo France, 2–4 October 2012; pp. 1–4.

78. Dones, R.; Heck, T.; Bauer, C.; Hirschberg, S.; Bickel, P.; Preiss, P. *Externalities of Energy: Extension of Accounting Framework and Policy Applications New Energy Technologies*; Paul Scherrer Institute: Villingen, Switzerland, 2005.
79. Gagnon, L.; Belanger, C.; Uchiyama, Y. Life-cycle assessment of electricity generation options: The status of research in year 2001. *Energy Policy* **2002**, *30*, 1267–1278. [CrossRef]
80. Hondo, H. Life cycle GHG emission analysis of power generation systems: Japanese case. *Energy* **2005**, *30*, 2042–2056. [CrossRef]
81. Spandero, J.V.; Langlois, L.; Hamilton, B. Greenhouse gas emissions of electricity generation chains—Assessing the difference. *IAEA Bull.* **2000**, *42*, 2.
82. Weisser, D. A guide to life-cycle greenhouse gas (GHG) emissions from electric supply technologies. *Energy* **2007**, *32*, 1543–1559. [CrossRef]
83. Bhat, I.K.; Prakash, R. LCA of renewable energy for electricity generation systems—A review. *Renew. Sustain. Energy Rev.* **2009**, 1067–1073. [CrossRef]
84. Cherubini, F.; Bird, N.D.; Cowie, A.; Jungmeier, G.; Schlamadinger, B.; Woess-Gallasch, S. Energy- and greenhouse gas-based LCA of biofuel and bioenergy systems: Key issues, ranges and recommendations. *Resour. Conserv. Recycl.* **2009**, *53*, 434–447. [CrossRef]
85. Evans, A.; Strezov, V.; Evans, T.J. Assessment of sustainability indicators for renewable energy technologies. *Renew. Sustain. Energy Rev.* **2009**, *13*, 1082–1088. [CrossRef]
86. Peng, J.; Lu, L.; Yang, H. Review on life cycle assessment of energy payback and greenhouse gas emission of solar photovoltaic systems. *Renew. Sustain. Energy Rev.* **2013**, *19*, 255–274. [CrossRef]
87. Sherwani, A.F.; Usmani, J.A. Varun Life cycle assessment of solar PV based electricity generation systems: A review. *Renew. Sustain. Energy Rev.* **2010**, *14*, 540–544. [CrossRef]
88. Scharfy, D.; Boccali, N.; Stucki, M. Clean technologies in agriculture—How to prioritise measures? *Sustainability* **2017**, *9*, 1303. [CrossRef]
89. DAFF. *Trends in the Agricultural Sector 2016*; Department of Agriculture, Forestry and Fisheries (DAFF), Republic of South Africa: Pretoria, South Africa, 2017.
90. DEA-RSA. *GHG Inventory for South Africa*; Department of Environmental Affairs (DEA), Republic of South Africa: Pretoria, South Africa, 2014.
91. Hoffmann, T.; Todd, S.; Ntshona, Z.; Turner, S. *Land Degradation in South Africa*; University of Cape Town: Cape Town, South Africa, 2014.
92. Pegels, A. Renewable energy in South Africa: Potentials, barriers and options for support. *Energy Policy* **2010**, *38*, 4945–4954. [CrossRef]
93. National Planning Commision. *National Development Plan 2030: Our Future-Make It Work*; National Planning Commision: Pretoria, South Africa, 2012.
94. DE-RSA. Perspectives on the REIPPPP and the Investment and Business Opportunities It Offers. Available online: http://www.energy.gov.za/files/WOESA/2015/northwest/Perspectives-on-the-REIPPPP-and-the-investment-and-business-opportunities-it-offers.pdf (accessed on 13 June 2017).
95. Betz, S.; Caneva, S.; Weiss, I.; Rowley, P. Photovoltaic energy competitiveness and risk assessment for the South African residential sector: PV energy competitiveness and risk assessment in South Africa. *Prog. Photovolt. Res. Appl.* **2016**, *24*, 1577–1591. [CrossRef]
96. Bisccḥof-Niemz, T.; Calitz, J.; Wright, J.G. Benefits of solar PV reserve provision in South Africa. In Proceedings of the 4th Southern African Solar Energy Conference, Stellenbosch, South Africa, 31 October–2 November 2016.
97. Walwyn, D.R.; Brent, A.C. Renewable energy gathers steam in South Africa. *Renew. Sustain. Energy Rev.* **2015**, *41*, 390–401. [CrossRef]
98. Sager, M. *Climate Change and Energy. Renewable Energy Vision 2030- South Africa*; WWF-SA: Cape Town, South Africa, 2014.
99. Bischof-Niemz, T. *Cost of New Power Generators in South Africa*; Comparative Analysis Based on Recent IPP Announcements 14.102016; CSIR: Pretoria, South Africa, 2016.
100. WWF Agriculture: The Greatest User of Water. Available online: http://wwf.panda.org/what_we_do/footprint/agriculture/impacts/water_use/ (accessed on 21 April 2015).
101. Davies, B.; Day, J. *Vanishing Waters*; University of Cape Town Press: Cape Town, South Africa, 1998.
102. Stats SA. *National Accounts: Water Management Areas in South Africa*; Stats SA: Pretoria, South Africa, 2010.

103. GCIS. *South African Yearbook 2011/12: Agriculture, Forestry and Fisheries*; Government Communication and Information System (GCIS), Republic of South Africa: Pretoria, South Africa, 2012.
104. Van Averbeke, W.; Denison, J.; Mnkeni, P. Smallholder irrigation schemes in South Africa: A review of knowledge generated by the Water Research Commission. *Water SA* **2011**, *37*. [CrossRef]
105. Van Rensburg, L.; De Clercq, W.; Barnard, J.; Du Preez, C. Salinity guidelines for irrigation: Case studies from Water Research Commission projects along the Lower Vaal, Riet, Berg and Breede Rivers. *Water SA* **2011**, *37*. [CrossRef]
106. Fowler, R.; Rockström, J. Conservation tillage for sustainable agriculture: An agrarian revolution gathers momentum in Africa. *Soil Tillage Res.* **2001**, *61*, 93–108. [CrossRef]
107. Erenstein, O.; Sayre, K.; Wall, P.; Hellin, J.; Dixon, J. Conservation Agriculture in Maize- and Wheat-Based Systems in the (Sub)tropics: Lessons from Adaptation Initiatives in South Asia, Mexico, and Southern Africa. *J. Sustain. Agric.* **2012**, *36*, 180–206. [CrossRef]
108. Rockström, J.; Kaumbutho, P.; Mwalley, J.; Nzabi, A.W.; Temesgen, M.; Mawenya, L.; Barron, J.; Mutua, J.; Damgaard-Larsen, S. Conservation farming strategies in East and Southern Africa: Yields and rain water productivity from on-farm action research. *Soil Tillage Res.* **2009**, *103*, 23–32. [CrossRef]
109. Hobbs, P.R. Conservation agriculture: What is it and why is it important for future sustainable food production? *J. Agric. Sci.* **2007**, *145*, 127. [CrossRef]
110. Smith, H.; Grain SA, Pretoria, South Africa. Personal communication, 2017.
111. Strauss, J.; Western Cape Department of Agriculture, Elsenburg, South Africa. Personal communication, 2017.
112. Derpsch, R.; Friedrich, T. Development and current status of no-till adoption in the world. In Proceedings of the CD 18th Triennial Conference of the International Soil Tillage Research Organisation (ISTRO), Izmir, Turkey, 15–19 June 2009.
113. Kotze, I.; Rose, M. *Farming Facts and Futures: Reconnecting South Africa's Food Systems to Its Ecosystems*; WWF-SA: Cape Town, South Africa, 2015.
114. Singels, A.; Smith, M.T. Provision of irrigation scheduling advice to small-scale sugercane growers using a web based crop model and cellular technology: A South African case study. *Irrig. Drain.* **2006**, *55*, 363–372. [CrossRef]
115. Majsztrik, J.C.; Price, E.W.; King, D.M. Environmental benefits of wireless sensor-based irrigation networks: Case-study projections and potential adoption rates. *HortTechnology* **2013**, *23*, 783–793.
116. Postel, S.; Polak, P.; Gonzales, F.; Keller, J. Drip Irrigation for Small Farmers: A New Initiative to Alleviate Hunger and Poverty. *Water Int.* **2001**, *26*, 3–13. [CrossRef]
117. FAO. Chapter 6. Drip Irrigation. Food and Agriculture Organization of the United Nations—Document Repository. Available online: http://www.fao.org/docrep/s8684e/s8684e07.htm#6.2 (accessed on 30 June 2015).
118. Hebeisen, T.; Ballmer, T. Potential der Tröpfchenbewässerung bei Kartoffeln. Available online: http://www.agroscope.admin.ch/veranstaltungen/00610/index.html?lang=de&download=NHzLpZeg7t,lnp6I0NTU042l2Z6ln1acy4Zn4Z2qZpnO2Yuq2Z6gpJCFeXx2gWym162epYbg2c_JjKbNoKSn6A%20 (accessed on 30 June 2015).
119. König, A. Multi Criteria Evaluation of Mitigation Solutions in Agriculture. Master-Tutorial: Applying Life Cycle Assessment for the Mitigation of Environmental Impacts of South African Agri-Food Products. Master's Thesis, Zurich University of Applied Sciences, Wädenswil, Switzerland, 2015.