Agronomic and environmental studies of potato (*Solanum tuberosum* L.) and analysis of its value chain in Zimbabwe

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Abstract

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Irish potato is food for more than a billion people worldwide. In Zimbabwe, Irish potato is becoming an important food crop. The government declared it a national strategic food security crop on 18 May 2012. This major policy pronouncement, qualified Irish potato for government initiated farmer support initiatives such as mechanisation and irrigation capacity building. The growing importance of potato as a food crop is prefaced on rising food insecurity in the country coupled with the impact of the radical land reform of 2000 on agricultural production. The land reform completely restructured commercial agriculture when about 96 % of the original 12.5 million ha of large-scale commercial farmland in 1980 was taken up for resettlement by 2010. Two resettlement models were used, the A1 and A2 resettlement models. The former resembles the communal area land allocation system while the later are self-contained small to medium scale farm units ranging about 35 to 300 ha. The newly resettled farmers have started growing potato adding to the already existing communal area and the few remaining large-scale commercial farmers. It is in this context that the potential of the new agrarian structure to sustainably increase Irish potato production was investigated. Increasing potato production on a sustainable basis will enable the crop to assert itself as a national strategic food security crop and help ease the food security challenges the country is grappling with. A grower survey was conducted on the cultural practices, input use, average yield, and infrastructure for potato production. The survey data was used to categorise the growers. Only growers with a minimum 5 years continuous potato growing experience were targeted making the data collected dependable. Grower resource footprints of land, water, biocides and nutrients were calculated based on the actual yield, Ya. Further, the Ya data collected were used to calculate the yield gap, YG, based on the yield of the best performing growers, Yh, simulated yield potential, Yp, and water-limited potential yield, Yw, of the respective agro-ecological areas. The LINTUL-POTATO model was used to estimate Yp, Yw and water need. This model simulates potential dry matter production based on radiation use efficiency of intercepted light by the potato crop. Another model, the Cool Farm Tool-Potato was used to further distinguish and appraise the production systems in terms of

yields, inputs and efficient use of energy as reflected in their CO_2 balances. The model calculates the contributions of various production operations to the total greenhouse gas (GHG) emission. Consequently, grower practices which contribute the most to the GHG emission were identified and generic mitigation measures for each production system were suggested. Realising the growing importance of sustainability issues in agricultural production and the scarcity of evaluation protocols in cropping systems, the study developed a framework that can be used to evaluate cropping systems. The framework was constructed using the potato-based cropping systems in the Eastern Highlands of Zimbabwe. Finally, instead of just focusing on the production related aspects only, the study also took into cognisance the need to understand the performance of the entire Irish potato sector in Zimbabwe. A value-chain analysis was therefore conducted to evaluate the performance the Irish potato sector in the country. Irish potato production in Zimbabwe is still low. Experts estimate annual production at nearly 120,000 t from around 6,000 ha. The large-scale commercial and the A2 resettlement are large-scale, high input and mechanised systems with an average potato area of 9 ha per planting. The communal area and A1 resettlement are smallholder low input systems with average potato area per planting of 0.8 ha and animal-drawn equipment is used. On resource use efficiencies, the actual tuber yield ranged from 8 – 35 t/ha across all systems representing a yield gap of over 77 %. Comparing with the simulated average potential yield, the mean actual yield observed ranged from 8 to 35 % of the simulated potential yield, translating to a yield gap of 65 to 92 %. Hence there is a large potential to increase potato production in these environments. The nutrient use efficiencies range were: 97 to 162 g potato g^{-1} N, 93–105 g potato g^{-1} P_2O_5 and 97–123 g potato g^{-1} K_2O. This was anticipated because of the high synthetic fertiliser use and the low actual yields reported. The biocide use efficiencies ranged from 0.5 to 0.9 kg potato g^{-1} active ingredient (a.i.) fungicide, and 8 to 15 kg potato g^{-1} a.i. insecticide. Regarding water use, the average water use efficiency based on irrigation water and rainfall, ranged from 2 to 6 g potato l^{-1}, while the simulated potential water use efficiency from irrigation and precipitation ranged from 9 to 17 g potato l^{-1}. The large gap observed between actual and potential water use efficiency shows the scope to improve crop management practices to increase actual yield while lowering irrigation water. On the CO_2 balance of the systems, a high carbon footprint was reported with an average of 251 kg CO_2 eq./t potato. The least average carbon footprint was 216 kg CO_2 eq./t potato for the communal area, while the A2 resettlement system had the highest of 286 kg CO_2 eq./t potato. The high carbon footprint was anticipated as a reflection

of the systems' inefficiencies in terms of low yields and high input use. Focussing on the performance of the entire Irish potato sector, value chain analysis showed considerable levels of value-addition and gross profit of at least 13 % at each linkage. While the sector enjoys government policy support, major factors impacting on the value-chain performance relate to high potato production costs, low yields, and lack of farmer training. On the proposed framework on cropping sustainability, the indicator thresholds serve to monitor farmer progress as they improve their practices towards the desired direction of sustainability. This study demonstrated that there is tremendous potential to increase potato output and help ease the food insecurity challenges the country currently faces.

Keywords: Irish potato, food security, stakeholder analysis, sustainability indicators, Cool Farm Tool-Potato, yield gap, resource use efficiency, LINTUL-POTATO model, Zimbabwe.

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Chapter 1

General introduction

O. Svubure

1. Zimbabwe: geographical location, climate and general land use

Zimbabwe is located in southern Africa (Fig. 1). It is placed wholly within the tropics extending from latitudes 15°37'S to 22°24'S and from longitudes 25°14'E to 33°04'E. Altitude ranges between 162 m and 2592 m above mean sea level (amsl). About 80 % of the country is higher than 600 m amsl and less than 5 % is above 1500 m amsl. An extensive high inland plateau which is some 650 km long by 80 km wide bisects the country in the southwest to northeast direction and lies between 1,200 and 1,675 m amsl. Its northward extension drops into the Zambezi valley bordering Zambia and likewise southwards it dips into the Limpopo valley bordering South Africa. This central plateau known as the Highveld forms a watershed between the Zambezi and the Limpopo River systems. Other rivers and streams flow southeast into the Limpopo River and northwest into the Zambezi River. The Highveld extends eastwards of the country leading to the north-south mountain spine peaking to an altitude of 2,592 m amsl on Mount Inyangani. The Mt. Inyangani summit is the country's highest point. This eastern border of the country is known as the Eastern Highlands. On either side of the Highveld is the Middleveld, a plateau with an altitude ranging from about 600 to 1,200 m amsl. The remaining low lying areas below 600 m amsl constitute the Lowveld, relatively flat plains in the Zambezi and Limpopo basins.

The climate of Zimbabwe derives its characteristics from its position in the tropics and its topography. Although the country is completely within the tropics, much of the Highveld and Eastern Highlands have subtropical to temperate climate conditions respectively because of the high average elevation. There are distinct seasons in Zimbabwe. These are: (1) summer, a period from mid-November to March characterised by hot and wet conditions; (2) winter, a cold dry period from April to July; and (3) spring, a hot and dry season from August to mid-November. There is a marked temporal and spatial variation in rainfall in the country. Reliability of rainfall increases from south to north following the intertropical convergence zone (ITCZ) which is associated with deep convective clouds, showers and thunderstorm rainfall. Rainfall reliability also increases from west to east following high altitude which causes orographic effects resulting in rainfall. Air temperatures are closely related to altitude. Mean annual temperature ranging from about 25 °C in the Lowveld in spring to less than 15 °C in winter above 1800 m amsl in the Eastern Highlands. Frost may occur at high altitudes especially in June and July. Local topography, however, is the main determinant of frost risk with low lying areas that retain cold night air being particularly susceptible. Zimbabwe is divided into five agro-ecological regions (Fig. 1), known as natural regions (NR) mainly according to the rainfall regime, soil quality and vegetation (Vincent and Thomas, 1960). The Eastern Highlands also known as the Nyanga Eastern Highlands wholly lies in NR 1, while the Highveld is located in NR 2a, 2b and in parts of NR 3.

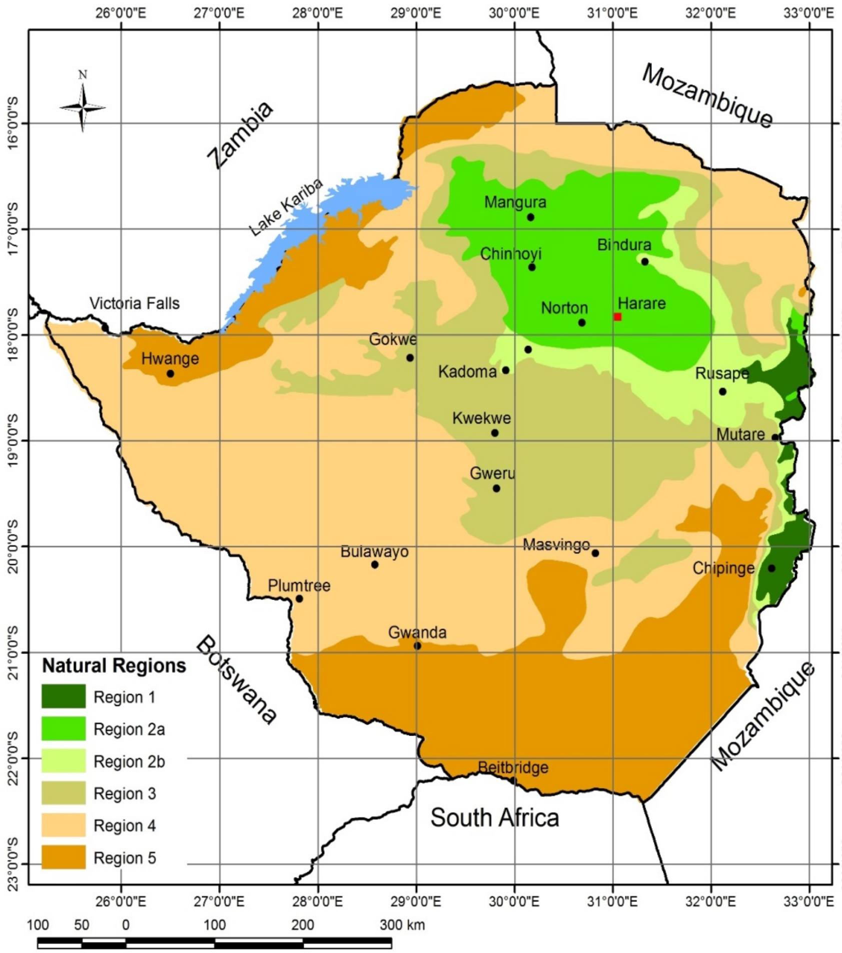

Fig. 1. Natural Regions of Zimbabwe
(adapted from Vincent and Thomas, 1960)

Table 1 describes the natural regions and their farming systems. NR 1 lies in the eastern part of the country. It is a specialized and diversified farming region with high altitude and steep slopes. Crops commonly grown here include coffee and tea, deciduous fruits (e.g., apple) and horticultural crops, such as potato, peas and other vegetables. Initial potato seed bulking is done here as well as intensive ware potato production. Located in the middle of the northern part of the country are NR 2a and 2b. These regions are suitable for intensive cropping and livestock production. They account for 75–80 % of the area planted to crops in the country. The major crops are maize, flue-cured tobacco, soybean, sorghum and potato. Rainfall is fairly reliable and is received in the summer season from November through March/April. Ware potato production and further bulking of seed potato are mainly carried out in this region at elevations of 1,200 to 1,800 m amsl (Joyce, 1982b). Another region, NR 3 lies in the middle altitude areas of the country. Livestock farming is the major activity. Due to unreliable starts of the rainy season, mid-season dry spells and high temperatures, supplementary irrigation plays a major role in cropping in this region. Natural region 4 and 5 cover the lowland areas in both the north and the south of the country. Both regions are considered too dry for successful cropping without supplementary irrigation.

Zimbabwe has a total surface area of about 390,000 km^2 of which nearly 387,000 km^2 is land area. Currently, agricultural land, which includes all arable land, land under permanent crops, and under permanent pastures, occupies about 40 % of the land area. The arable and forest area constitutes about 10 and 40 % of the land area, respectively. Table 2 shows the general land use in Zimbabwe and the trend in the last two decades. Zimbabwe's economy relies heavily on the agriculture sector. According to 2013 estimates, agriculture contributed about 20 % to the country gross domestic product (Zimbabwe Economy, 2015). The major crops grown in Zimbabwe are: maize, cotton, soybean, wheat, tobacco and horticultural crops. Maize is the country's staple crop and accounts for nearly half of the cropped area. Tobacco is the top agricultural export earner. Table 3 shows the production of the main food crops in Zimbabwe.

2. The 2000 radical land reform in Zimbabwe

The Fast Track Land Reform Programme (FTLRP) initiated in 2000, completely restructured commercial agriculture in Zimbabwe. A large proportion of the large-scale commercial farms were subdivided into smaller units and allocated to new farmers under two resettlement models, the A1 and A2 resettlement models. The A1 resettlement model is based on the communal area land allocation system where the beneficiary household is allocated about 6 hectares of arable land and grazing land is communal.

Table 1. Description of the Natural Regions of Zimbabwe

Natural Region	Area × 1000 (ha)	Percent of total land area (%)	Annual rainfall (mm) and temperature conditions	Farming system
1	700	2	Greater than 1000. Rainfall received in all months of the year; relatively low temperatures	Suitable for dairy, beef farming, forestry, tea, coffee, maize, potato and vegetable production
2a	4,100	10	700–1050. Rainfall confined to summer. Probability of rainfall > 500 mm (between October and April) is > 90 %. Length of summer growing period is 140–170 days	Suitable for intensive farming, based on maize, soybean, tobacco, potato and livestock
2b	1,760	5	650–900. Rainfall confined to summer. Probability of rainfall > 500 mm (between October and April) is 80–90 %. Length of summer growing period is 120–150 days	Suitable for intensive and semi-intensive farming, based on maize, soybean, tobacco, potato and livestock
3	7,290	18	500–800. Relatively high temperatures and infrequent heavy rainfall. Subject to seasonal droughts and severe mid-season dry spells	Semi-intensive farming region. Suitable for livestock production together with production of fodder crops and cash crops such as cotton under good farm management
4	14,780	38	450–650. Subject to frequent seasonal droughts and severe dry spells during the rainy season	Semi-extensive region. Suitable for farm systems based on livestock and drought tolerant fodder crops
5	10,440	27	<450. Very erratic rainfall	Extensive farming region. Suitable for extensive cattle ranching. Forestry, wildlife and tourism

(**Source**: Vincent and Thomas, 1961)

On the other hand, in the A2 resettlement model, beneficiary households were allocated self-contained small to medium scale farm units for cropping, grazing, residential and woodlots use. Unit sizes under normal circumstances ranged from about 35 ha in the high rainfall regions through 300 ha in the drier parts of the country (MLRR, 2009). Later in the land reform process, larger A2 farms, similar to the large-scale farms of the past, were also created (Moyo, 2011). By 2009, a total of 6,214 farmland properties covering about 11 million ha were acquired and allocated to 144,755 households under the A1 resettlement model and 22,896 households under the A2 resettlement model (MLRR, 2009). Fewer than 400 individually owned white farms remained by 2009, from about 4,500 in 1999 (MLRR, 2009).

In summary, the new agrarian landscape in the country is now comprised of the already existing communal area farming systems, the new resettlement models, and the greatly reduced large scale commercial farming system. The responsibility to meet the ever increasing demand for agricultural products for food, feed and fuel for a growing population of the country and also for the export market now rests squarely on the shoulders of the new

Table 2. Land use in Zimbabwe

Land use	**Area (km^2)**			
	1990	**2000**	**2007**	**2012**
Total surface area	390,760	390,760	390,760	390,760
Land area	386,850	386,850	386,850	386,850
Agricultural land	130,100	150,600	154,500	155,625
Arable land	28,900	35,800	40,000	40,000
Permanent cropland	1,000	1,100	1,200	1,200
Forest area	222,340	188,940	169,140	156,240

Source: World Bank, 2014.

Table 3. Cultivated area and production of main food crops in Zimbabwe

Crop/year	**2011**		**2012**		**2013**	
	Area (ha)	**Production (t)**	**Area (ha)**	**Production (t)**	**Area (ha)**	**Production (t)**
Maize	1,603,000	1,452,000	960,000	968,000	900,000	799,000
Wheat	12,000	23,000	11,000	20,000	10,000	25,000
Potato	3,195	53,691	3,200	55,000	3,500	58,000
Soybean	56,000	80,000	60,000	90,000	60,000	90,000

Source: FAOSTAT, 2013.

agrarian structure.

3. Potato production in Zimbabwe and its increasing importance as a food crop

The history of potato production in contemporary Zimbabwe can be traced back to the early 1900s. For example, records show that the potato tuber moth, *Phthorimaea operculella* (Zell.), was already acknowledged as the most troublesome pest of the 1903/04 cropping season (Mitchell, 1904). A disease which was similarly problematic back then was black scab caused by the fungus *Synchytrium endobioticum*. The government responded by issuing a gazette, Government Notice No. 309 of 1909, which outlined regulations affecting the importation of potatoes in order to prevent further introductions of black scab into the country (Jack, 1909).

Variety trials began in 1911 (Bell, 1927). Up to the late 1920s, practically one variety, Up-to-date, was grown and every year considerable quantities of seed were imported to meet demand (Bell, 1927). Farmers also had to retain the first and second harvests as seed for further plantings (Bell, 1927). Potato production was low and only European growers produced potato. For example, in the 1924/25 cropping season, a total of about 1,200 hectares were planted and yield was low because a large proportion of growers grew potato to meet requirements on the farm, hence grew the crop without the best of treatments (Bell, 1927). A breeding programme was initiated in 1956 to cater for the country's requirements for high-quality seed of adapted varieties. The breeding activities are mainly done in the Eastern Highlands at Nyanga Experiment Station located at elevations above 1800 m amsl. Since the 1960s, only the national breeding programme has been authorized to import potatoes under rigid quarantine procedures, and then only for breeding and evaluation purposes (Joyce, 1982a). Zimbabwe's emphasis on breeding and seed production is motivated largely from the need to avoid the introduction of pests through imported seed potatoes that might threaten tobacco production (Joyce, 1982b). Tobacco is a very important crop for export and has been the country's single largest foreign currency earner. Hence anything that can potentially harm tobacco production in the country, the government urgently takes corrective action. In 1975, the International Potato Center (CIP) started collaborating with Zimbabwe and one of the arrangements was availing true potato seed to the country’s breeding programme (Joyce, 1982a). The national breeding programme has been very successful. Since its inception, it has worked with over four hundred potential varieties, seventy of which have been evaluated in variety trials, and twelve of which were distributed to commercial seed potato producers (Joyce, 1988). Average potato yields improved from about 9 t/ha in the early 1960s to over 15 t/ha in the 1980s, attributed primarily to the success of the national breeding programme (Joyce, 1988). Potato production gradually rose in the 1990s to about 36,000 t in 1990 and increased further to over 40,000 t in 2000 due to constant increases in both cropped area and yield (FAOSTAT, 2013). In 2013, production reached a peak of 58,000 tonnes from a cropping area of 3,500 ha. Faced with growing food insecurity since the 2000 land reform and coupled with a perceived increase in both potato production and consumption, the government of Zimbabwe decided to deliberately support potato production in the country. On 18 May 2012, the government declared Irish potato a national strategic food security crop (The Herald, 2012). Before this day, only the staple maize crop had the national strategic food security crop status. This upgrading implied that potato is now included in the government initiated inputs, mechanisation and irrigation development support programmes to boost farmer production capacity. Unlike maize which is confined to summer (November through March) production, potato could be grown year round thereby perfectly complementing maize production. Supplemental irrigation would be required in the dry winter season.

4. Problem statement

Irish potato is set to become an important crop in Zimbabwe riding on the major policy boost it has received from the government. However, potato production in Zimbabwe is generally regarded as a high input crop. For example, the general synthetic fertiliser supplies recommended by extension are 120, 123, and 149–199 kg/ha of N, P, and K, respectively, for an average fresh tuber yield of 30 t/ha (FAO, 2006; Manzira, 2011). Therefore, the question of efficient use of resources used as inputs in potato production such as land and synthetic fertilisers becomes central. Also by extension, the question of sustainability of potato production in Zimbabwe becomes an issue. It is now more than a decade after the radical land reform and the country is still beset with rising food insecurity. The circumstances are now appropriate to interrogate the potential of the new agrarian structure to increase the production of Irish potato in Zimbabwe. Increasing potato production on a sustainable basis will enable the crop to indeed assert itself as a national strategic food security crop, and will help ease the food security challenges the country is grappling with.

5. Objectives of the study

The overall objective of the study was therefore to assess the potential to sustainably increase Irish potato production in Zimbabwe and help ease the food security challenges of the country. This overall objective was disaggregated into 5 sub-objectives and for further clarity, each sub-objective was in turn disaggregated into several specific objectives.

5.1 Sub-objective 1: to assess the potato production systems in Zimbabwe.

Over a decade after the landmark agrarian reform, it was appropriate to study the productive capacity of potato production systems that emerged from the land reform programme initiated in 2000 and in a way to evaluate the impact of the Fast Track Land Reform Programme (FTLRP) on the crop. It became even more necessary now following the declaration of potato as strategic national food security just like maize, the staple crop (The Herald, 2012). Specifically the following issues were addressed: (i) the planet earth resource base endowment available to the different production systems or grower categories; (ii) input use rate in each production system; (iii) infrastructure for potato production present; (iv) the agro-ecological conditions in the major growing environments; and (v) identification of constraints and possible solutions.

5.2 Sub-objective 2: to assess the yield gap and resource footprints of the Irish potato production systems.

The estimate of the amount of food production increase on already existing croplands depends on the difference between the current actual yields and the yield potential of the crop in the given agro-ecological environment, called the yield gap (Van Ittersum *et al*., 2013). While the actual yield (Ya) can be regarded as the average crop yield obtained by the grower in recent years, the crop yield potential in the grower's agro-ecological environment can be defined in several ways. It can be the yield of the best performing growers, Yh, or the simulated maximum (potential) yield potential, Yp, or the simulated water-limited potential yield, Yw of the agro-ecological environment. The yield gap, YG, is the difference between Ya and Yh, Yp or Yw. The yield gap therefore, is a measure of unexploited food production potential of an agro-ecological area. Therefore, the potential to increase potato production in the country was explored through use of the yield gap concept. Realising the need to increase potato output with less input of land, water, nutrient or biocide, the study also investigated the efficiency of use of these resources. The specific objectives developed included: (i) to determine the potential, water-limited and actual field yields of potato in the major potato growing regions identified and to analyse the yield gap; (ii) to establish the resource footprints (e.g., land, water, mineral fertilisers, and biocides) for potato production in the different production systems; and (iii) to offer recommendations to improve production.

5.3 Sub-objective 3: to assess the CO_2 balances of the Irish potato production systems.

Agriculture contributes significantly to the world greenhouse gas (GHG) emissions. Farmers need to fine-tune agricultural practices to balance the trade-off between increasing productivity in order to feed the growing global population and lowering GHG emissions to mitigate climate change and its impact on agriculture. Major emission sources in cropping include manufacture and use of synthetic fertilisers and biocides, fossil fuel combustion in tractor use, soil-related emissions, and other practices. In potato production in Zimbabwe, agricultural extension services recommend high fertiliser applications which may not always be efficiently used by the crop (FAO, 2006; Manzira, 2011). Besides, potato is normally grown under full or supplemental irrigation often using underground water sources, thereby incurring huge pumping energy and the associated carbon costs. It is therefore important to know the major sources of GHG emission in potato production in Zimbabwe and to quantify it in order to determine potential, ‘climate smart’ mitigation approaches. Moreover, such knowledge of the emission sources and their respective estimates will allow for benchmarking, where growers can compare their scores or performance against other growers at the local, regional, and national levels. Benchmarking uses the variation among growers on selected performance indicators as leverage or incentive to stimulate inter-farm competition and therefore continuously improve indicator performance (De Snoo, 2006). In this study, the carbon footprint of the different Irish potato production systems in Zimbabwe was assessed. The specific objectives addressed were: (i) to distinguish the potato production systems that appeared after the land reform in terms of yields, inputs and efficient use of energy as reflected in CO_2 balances; (ii) to identify practices which contribute the most to the greenhouse gas (GHG) emission and derive from them generic means to make these systems more efficient; and (iii) to suggest possible mitigation measures to growers of the distinct potato production systems.

5.4 Sub-objective 4: to analyse the Irish potato value chain in post land reform Zimbabwe.

Rather than focussing on the production aspects only, the study also considered the question of the performance of the entire Irish potato sector in the country, a sector not well understood before this moment. An analysis of the potato value chain in the country will provide an insight on where, how, and why value is created and added along the chain. The analysis will therefore lead to an understanding of why the value chain assumes a certain structure, and how it could be leveraged for change to enhance development. For example, the major factors impacting on the value-chain performance will be isolated and possible corrective measures suggested. The specific objectives of this study were therefore: (i) to identify and map the main actors in the value chain and the relationship between them; (ii) to describe the activities performed by each actor; (iii) to determine the value chain performance; (iv) to identify the constraints and opportunities within each actor segment; and (v) to suggest strategies to enhance the competitiveness and profitability of the Irish potato industry in Zimbabwe.

5.5 Sub-objective 5: to develop a framework for evaluating sustainability of Irish potato cropping systems in Zimbabwe.

While the demand for agricultural products for food, feed and fuel continue to rise, concerns on sustainability are equally increasing. Protocols to assess the sustainability of agricultural systems become indispensable as part of the toolkit to move agricultural systems toward the desired direction of sustainability. However, protocols to evaluate the sustainability of agricultural systems are scarce especially in the context of developing countries. The question arises of what framework to use to evaluate and communicate the sustainability of cropping systems? The specific objectives addressed in this study were: (i) to define a framework to assess the sustainability of cropping systems in Zimbabwe; and (ii) to gain experience of the framework outworking, through conducting a practical application on the potato-based cropping systems that resulted from Zimbabwe's land reform.

6. Approach of the study

A combination of concepts and methods were used to explore the potential to sustainably increase Irish potato production in Zimbabwe and help ease the food security challenges of the country. Fig. 2 presents a schematic illustration of the methods the study drew upon, the sources of information used and the resultant output. The case study approach was used to understand and characterise the potato production systems in Zimbabwe. Following a desk study to identify stakeholders already interfacing with growers to gain insight on the different potato growers, a detailed survey was subsequently conducted on grower practices in potato cultivation. Data was collected on aspects that included land preparation, planting, fertilisation, biocide use, irrigation, harvesting and grading practices. In addition, data was also collected on gross farm and cropping land sizes, potato planting area, technology use levels, seed rates, labour, average gross potato yield in the past 5 years, planting and harvesting dates. Only growers with a minimum of 5 continuous years of potato growing experience were targeted. Such growers had an established routine practice and a relatively stable input use rate and yield making the data collected dependable. The grower survey data was used to address the first objective (Section 5.1), by characterising the potato production systems that appeared from the land reform programme of 2000. The characterisation of potato production systems in Zimbabwe is presented in *Chapter 2*.

In addressing the second objective (Section 5.2), the grower survey data was used in combination with the concept of the yield gap analysis, resource use efficiency, and the application of modelling to explore the measure of unexploited potato production potential in the major potato growing areas of Zimbabwe. The survey data was also used to calculate the resource footprints of land, water, biocides and nutrients based on the actual potato yields (Ya). As already defined in Section 5.2, the actual potato yield (Ya) is the average yield obtained by the grower in recent years applying their normal practices. Further, the actual yield, Ya data collected were used to calculate the yield gap (YG), being the difference between Ya and yield of the best performing growers (Yh), the simulated maximum (potential) yield potential (Yp), or the simulated water-limited potential yield (Yw) of the agro-ecological environment. For a particular crop cultivar, Yp represents the maximum attainable yield achieved when the crop is grown under non-limiting conditions of water and nutrient supply, with biotic stress effectively controlled. In rainfed systems, Yw of a particular crop cultivar is the maximum yield attainable and is only limited by plant available water.

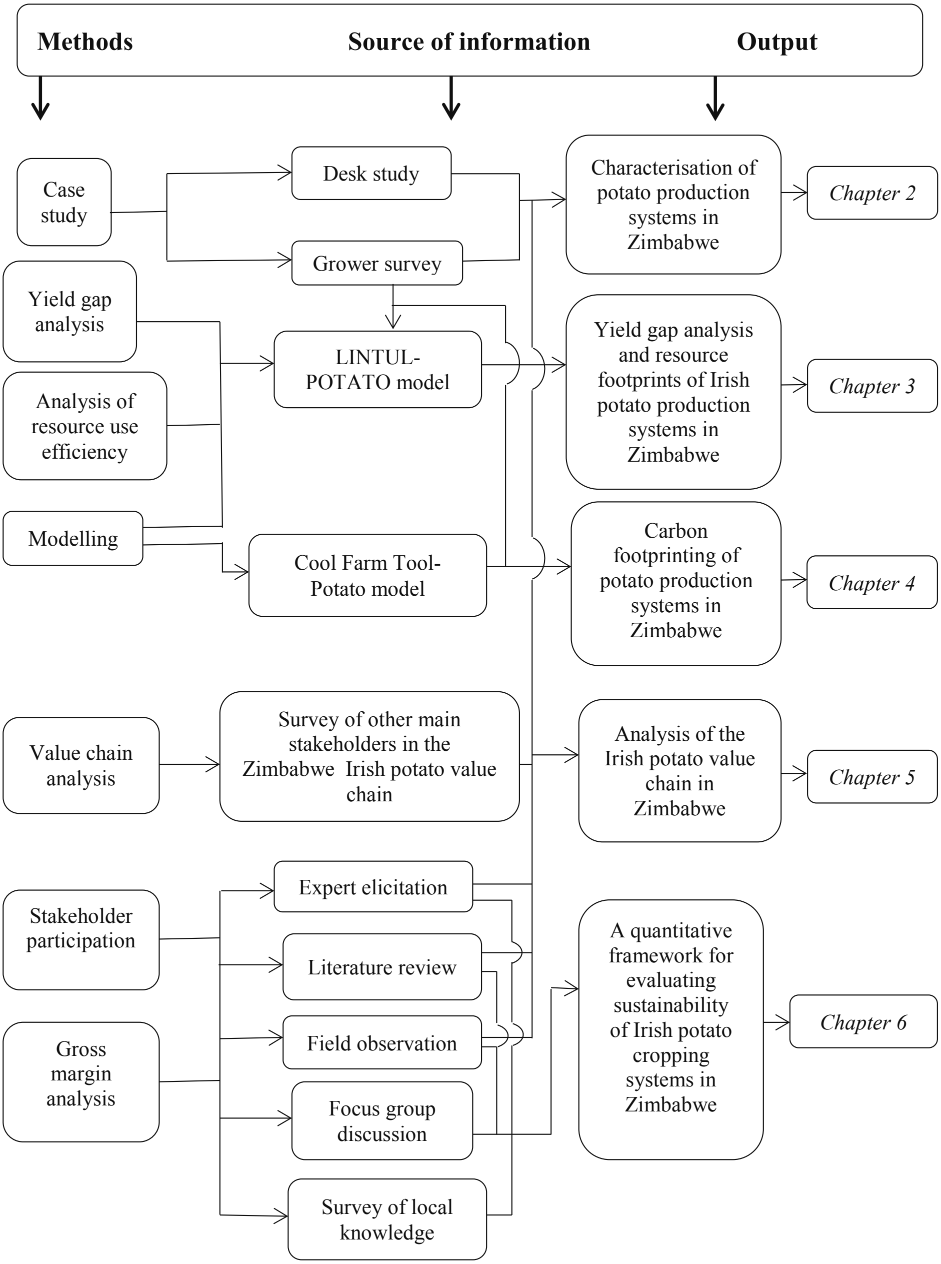

Fig. 2. The study approach scheme illustrating the methods, sources of information and output

The LINTUL-POTATO model as described by Kooman and Haverkort (1995), was used to simulate the potential dry matter production (Yp and Yw) of potato for the different agro-ecological regions in Zimbabwe. Model input data included long term meteorological data such as daily minimum and maximum temperatures, incoming solar radiation, rainfall, and reference evapotranspiration. Also grower soil and resource management input data for the model included soil texture, rooting depth, planting depth, percent irrigation, date of planting and harvest. In addition, the survey data was also used to understand the general Irish potato agronomic practices in Zimbabwe. The output of this study is presented in *Chapter 3* of this thesis.

In addressing the third objective (Section 5.3), the grower survey data was used in combination with the application of modelling to understand the impact of the potato production practices on greenhouse gas (GHG) emission by the different potato production systems in Zimbabwe. The 'Cool Farm Tool-Potato' (CFT-Potato) model as described by Hillier *et al*. (2011) was used to estimate the GHG emissions of the different Irish potato production systems in Zimbabwe and to identify practices that contribute the most to the GHG emissions. The CFT-Potato model integrates several globally-determined empirical models and uses them to calculate GHG emissions as CO_2 equivalents (Hillier *et al*., 2011; Haverkort and Hillier, 2011). The input data for the CFT-Potato model was obtained from the grower survey such as the inputs and cultural practices growers employ in potato production. Soil samples were also collected mainly for texture, pH, and organic matter determination as additional input data to the CFT-Potato model. The output of this study is discussed in *Chapter 4* of this thesis.

The value chain analysis concept was used in combination with several methods that included a desk study, formal surveys, expert elicitation, field observations and local knowledge in order to gain an understanding of the performance of the potato value chain in Zimbabwe (Section 5.4). Value chain concepts have featured prominently in development since the mid-1990s primarily to design and implement interventions (Gelli *et al*., 2015). Taylor (2005) viewed value chain analysis as a diagnostic tool, defined as a "multi-dimensional assessment of the performance of value chains, including the analysis of product flows, information flows and the management and control of the value chain". The desk study was followed by formal surveys to collect quantitative data on identified stakeholders in the Irish potato industry in Zimbabwe. In addition, expert elicitation, field observations and local knowledge in order to gain an understanding of the performance of the potato value chain. The gross margin analysis concept was useful to get a rapid appraisal of the financial performance of each identified group of actors along the value chain. The output of this study is discussed in *Chapter 5* of this thesis.

The approach of literature review and expert opinion was employed to propose a framework for evaluating sustainability of Irish potato cropping systems in Zimbabwe, and address the fifth objective of this thesis. Drawing from such concepts as integrated frameworks to aid decision-making in sustainability assessment processes (Paracchini *et al*., 2011; Reed and Dougill, 2002; Reidsma *et al*., 2011; Purushothaman *et al*., 2012; König *et al*., 2012); expert-assisted participatory approach (Vaidya and Mayer, 2014), and the concept of indicators as assessment tools (Breckenridge *et al*., 1995; Mascarenhasa *et al*., 2014), the framework to evaluate cropping sustainability in Zimbabwe presented in this thesis was constructed. The proposed framework is discussed in *Chapter 6* of this thesis.

7. Expected outcomes of the study

Achieving the objectives outlined in this thesis will:

(a) contribute to a better understanding of the new agrarian structure in Zimbabwe that emerged from the radical land reform at the turn of the new millennium,
(b) provide a measure of unexploited potato production capacity that can help address problems of food insecurity in the country,
(c) evaluate the impact of resource/input use, and contribute to identify resources currently limiting potato yield and offer suggestions to narrow the gap,
(d) contribute to a better understanding of the main actors in the potato value chain in Zimbabwe, and
(e) provide a framework for evaluating sustainability of cropping systems for future use not only on potato but other crops and regions.

8. Thesis outline

This thesis consists of a general introduction (*Chapter 1*), followed by five research papers addressing the five research objectives already outline in Section 1.5 (*Chapters 2 to 6*), and lastly a general discussion chapter (*Chapter 7*). *Chapter 2* characterises the potato production systems currently present in Zimbabwe. *Chapter 3* focuses on the yield gap and the resource footprints of potato and the efficiency of potato production in the different production systems of Zimbabwe. *Chapter 4* further distinguish the potato production systems in Zimbabwe in terms of yields, inputs and efficient use of energy as reflected in CO_2 balances. Practices that contribute the most to the GHG are identified and possible mitigation measures to make these systems more efficient are suggested. Using the value chain analysis tool, *Chapter 5* presents an evaluation of the potato industry in order to increase our understanding of the performance of the Irish potato sector in the country. *Chapter 6* focuses on the proposed framework for evaluating sustainability of cropping systems in Zimbabwe. A practical application of the framework is provided through the example of Irish potato-based cropping systems in the Eastern Highlands of Zimbabwe. *Chapter 7* provides the general discussion. This chapter summarises the main findings of the study and explores their implications to the Irish potato sector in Zimbabwe. Suggestions of new directions for further research are outlined.

Chapter 2

Comparative analysis of Irish potato production systems in Zimbabwe after the 2000 landmark Agrarian Reform

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Submitted to Potato Research

Abstract

Irish potato production in Zimbabwe can be traced back to the early 1900s. Large-scale commercial farmers dominated production. Potato is the most important horticultural crop and has since been declared a strategic national food security crop. In 2000, the Fast Track Land Reform Programme, completely restructured commercial agriculture and potato farming. A product of the agrarian reforms, the A2 and A1 resettlement growers, started growing potato. The A1 resettlement model has individually owned cropping land and shared grazing, while A2 resettlement comprise of self-contained farm units. A survey was conducted to characterise potato growers, mainly to understand the current potato production systems and assess the impact of the landmark reform programme on potato farming. Four production systems: large-scale commercial, communal area, A2 resettlement and A1 resettlement were identified, and two main growing agro-ecological regions, the Highveld and Eastern Nyanga Highlands. In 1961–2013, significant positive trend for annual planted area, average yield and total production were observed. In terms of yield, Zimbabwe is fourth in southern Africa with average yield of 17 t/ha in the 2009–2013 period. Large-scale commercial and A2 resettlement systems are well-mechanized and growers owned large land holdings ranging 165–1600 ha and 31–390 ha respectively, and average potato area was 11 and 8 ha, respectively. Communal area and A1 resettlement growers owned 3 and 4 ha cropping area respectively, with average potato areas of 1.1 and 0.4 ha respectively. Input use was significantly different among the production systems. High synthetic fertiliser and biocides use was observed.

Key words: Irish potato, production systems, agro-ecological zone, input application rate, farm characterisation, Zimbabwe

1. Introduction

Irish potato cultivation in contemporary Zimbabwe became well established by the early 1900s (Joyce, 1982a). For example, the potato tuber moth, *Phthorimaea operculella* (Zell.), was recorded and acknowledged as the most troublesome pest of the 1903/04 cropping season (Jack, 1904). Also Government Notice No. 309 of 1909 outlined regulations affecting the importation of potato in order to prevent the introduction of "Black scab" into the country (Jack, 1909). Up to the late 1920s, practically only one variety, Up-to-date, was grown and every year considerable quantities of seed were imported and the first and second harvests were retained for further plantings (Timson, 1927). Production was low and only European growers produced potato. In the 1924/25 cropping season, a total of about 1,200 hectares were planted and yield was low because a large proportion of growers grew potato to meet requirements on the farm, hence they grew the crop without the best of cultural practices (Bell, 1927). In 1956, the government started a potato breeding programme and demarcated the potato Quarantine area and the breeding station at Nyanga Experiment Station (Joyce, 1982b). The Quarantine area is responsible for the initial seed potato multiplication. In the 1960s, the national breeding programme was authorized to import potato only for breeding and evaluation purposes (Joyce, 1982b). Rigid quarantine rules were mandatory in the importation procedures, mainly to protect tobacco production from potential introduction of pests through imported seed potato (Joyce, 1982b). Tobacco was a very significant export crop for the country. In 1975, the International Potato Center (CIP) started supplying true seed to the national breeding program (Joyce 1982a). Over 12 cultivars were released since the inception of the national breeding programme making a tremendous impact on potato production in the country (Joyce, 1988). Joyce (1988) reports average yields of 15 t/ha in the 1980s up from 9 t/ha in 1960s, attributed primarily to the success of the breeding program. However, the potato breeding programme has stopped since the turn of the millennium mainly due to the socio-economic and political problems the country is grappling with.

Total crop output assumed a steady increase trajectory in the 1990s rising to over 40,000 tonnes in 2000 due to constant increases in both cropped area and yield (FAOSTAT, 2013). The large-scale commercial farming sector dominated potato production then. This farming sector was highly developed, with some of the best infrastructure and farming skills on a comparative basis with most of Africa. Together with smallholder agriculture then, the large-scale farmers provided Zimbabwe with the foundation for food security and selfsufficiency that was the envy of a continent dominated by civil wars, poverty and famine. Some of the large commercial farmers of Zimbabwe were 3rd or 4th generations of staying and working the land, acquiring farming experience and skills across the different enterprises (field crops, livestock and horticulture crops including potato) providing Zimbabwe with one of the most developed human resources in Africa (Rukuni and Eicher, 1994).

The Fast Track Land Reform Programme (FTLRP) that was initiated in 2000 was a radical commission by the government, that completely restructured commercial agriculture in Zimbabwe and along with it the potato farming systems. A large proportion of the large-scale commercial farms were subdivided into smaller units and allocated to new farmers under the A1 and A2 Resettlement models. The A1 resettlement model resembles the communal area land allocation system and the beneficiary household was allocated about 6 ha of arable land and communal grazing land. In the A2 resettlement model, beneficiary households were allocated self-contained, small to medium scale farm units for cropping, grazing, residential and woodlots use. Unit sizes under normal circumstances ranged from about 35 ha in the high rainfall regions through 300 ha in the drier parts of the country. Later in the land reform process, larger A2 farms, similar to the large-scale farms of the past, have also been created (Moyo, 2011). By 2009, 6,214 farmland properties covering nearly 11 million ha were acquired and allocated to 144,755 households under the A1 resettlement model and to 22,896 households under the A2 resettlement model (MLRR, 2009). Fewer than 400 individually owned white farms remained by 2009, from about 4,500 in 1999 (MLRR, 2009).

Over a decade after the landmark agrarian reform, it is pertinent to evaluate the productive capacity of the potato land. It becomes even more compelling now because potato is now a declared strategic national food security just like maize, the staple crop (The Herald, 2012). The potato production systems in the different growing environments in Zimbabwe need to be analysed especially in the context of the seemingly yet to be finalised agrarian reform programme. There is a dearth of information on the impact of the land reform on potato production systems in Zimbabwe. Hence the purpose of this study was to establish and analyse the potato production systems in Zimbabwe and in a way to assess the impact of the FTLRP on production of the crop. Specifically the following issues were considered: (i) the natural resource base endowment available to the different production systems or grower categories; (ii) input use in the various agro-ecological environments and production systems; (iii) infrastructure for potato production present; and (v) identification of constraints and possible solutions. An analysis of these important issues will elicit further research questions on the potato industry in the country. For example, the question of resource footprints of land, water, biocide and mineral fertiliser used in potato production by the identified production systems and agro-ecological zones in the country?

2. Materials and methods

2.1 Study area and sampling

A comprehensive grower survey was carried out in the period 2011 through 2014. In order to identify the regions currently active in potato production in Zimbabwe, besides literature, the initial port of call were stakeholders already interfacing with growers. These were among others, the potato seed houses, the government extension agency, research institutions, government seed services regulatory authority, and farmer organizations. Figure 1 shows the major potato growing areas in Zimbabwe visited in the grower surveys and the soil sampling sites.

2.2 Farmer selection and data collection

Data was collected on practically all the grower practices in potato production. The sample in each area were growers with a minimum of 5 continuous years of potato growing experience. Such growers had an established routine practice and a relatively stable input use rate and yield making the data collected dependable. In many regions, growers with this experience especially among the recently resettled A1 and A2 farmers were not common. Advance appointments with the government extension agency, Agritex (Agricultural, Technical and Extension Services) in each area were made and the selected growers were visited for the data collection exercise. Growers selected represented a broad spectrum of gross farm and cropping land sizes, technology use levels and water resources. The growers sampled included three large-scale commercial growers and four A2 resettlement growers from the Quarantine area located in the Nyanga Eastern Highlands agro-ecological zone. This area is an isolated zone created by a statutory instrument (Joyce, 1982b). It is responsible for the initial potato seed multiplications and only 21 out of the 27 growers in the area are active (Ackerman, personal communication, 2012).

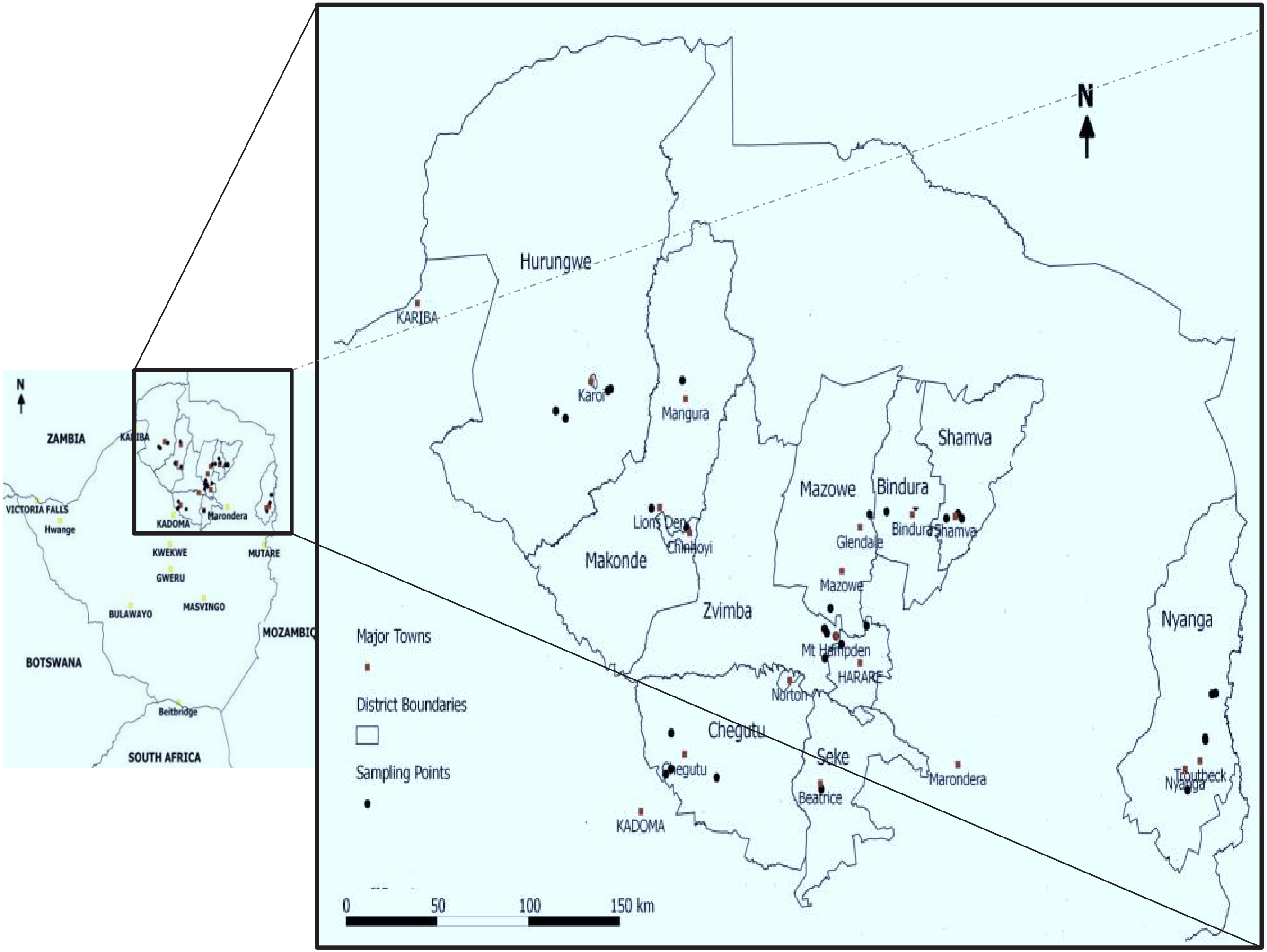

Fig. 1. Map of Zimbabwe indicating the major Irish potato growing districts and the grower survey and soil sampling points

A further 18 communal area, 5 A1 resettlement, 5 A2 resettlement and one of the four remaining large scale commercial growers, all outside the Quarantine area completed the Nyanga Eastern Highlands sample. Statistics on potato grower numbers is variable. Officials from the department of Agritex in Nyanga estimate about 1,500 communal area and less than 100 A1 resettlement growers. A total of 11 large scale commercial and 14 A2 resettlement growers were interviewed in the extensive Highveld agro-ecological zone. According to Agritex officials, the Highveld has fewer than 50 large scale commercial growers and about 100 A2 resettlement growers, while a few A1 resettlement and communal area growers are beginning to show interest in potato growing. Table 1 gives an overview of the number of growers interviewed per agro-ecological zone and per production system.

Table 2 summarizes the questions asked in the interviews. The growers and/or their respective operations managers could easily respond to the questions regarding land property sizes, water resources, water application rates and irrigation frequencies. For the other questions on yield, fertiliser, labour and biocide application rates, the growers referred to their records. Some growers kept these and also rainfall records spanning more than 10 years which could be a testimony to the training role of Agritex. For especially fungicide and pesticide type, dose and frequency of applications, the grower's responses were checked against the labels on the chemical packaging from the respective agro-chemical companies.

Soil samples were taken for analyses, mainly pH, texture and NPK. The samples were taken from the fallow potato fields in which the grower wanted to plant the next potato crop. The analysis results could help understand the textural class growers preferred for potato growing and the general soil fertility management by the growers. Data on input application rates were used to analyse the variation across agro-ecological environments and production systems of the grower. Mineral fertiliser application rates were also compared against those used by growers in the neighbouring countries. The input use data were also used together with the farm features and infrastructure for potato production present to characterise the potato production systems in Zimbabwe. Long term meteorological data were purchased from the Meteorological Services Department (MSD) and they were used to characterise the agro-ecological conditions of the main growing areas. Data on area, output and yield were obtained from various sources such as from literature, FAO and the Central Statistics Office, CSO (now ZIMSTAT). The data were used to discuss the development trajectory of the Zimbabwe potato crop in recent years. Factors constraining production were identified both from literature and the grower interviews.

Table 1. Number of growers per production system interviewed in the Highveld and Eastern Nyanga Highlands agro-ecological zones of Zimbabwe, in the period 2011–2014.

Agro-ecological zone	**Sampling area**	**Production system**			
		Large-scale commercial	A2 resettlement	A1 resettlement	Communal area
Eastern Nyanga Highlands	Nyanga Quarantine Area	3	4	0	0
	Nyanga district*	1	5	5	18
Highveld	Harare	5	2	0	0
	Bindura	2	5	0	0
	Chegutu	2	2	0	0
	Chinhoyi	1	2	0	0
	Karoi	1	3	0	0

*Excluding the Quarantine area

Table 2. Summary of the grower survey.

Grower name, farm name and location

Farm characteristics

- Land holding/farm type/ownership
- Gross area of the farm
- Arable land area
- Potato area per planting
- Average rotation length in years
- Range and average yield obtained in the past 5 years

Potato production practice

- Planting and harvest date
- Cultivar(s) grown
- Amount of seed used
- Plant spacing applied

Fertiliser

- Fertiliser type, dose/rate of application and formulation
- NPK composition

Biocides (fungicides, insecticides, herbicides and nematicides)

- Type, active ingredient percent, dose and number of applications

Irrigation infrastructure present

- System type (centre pivot, semi-portable, drip or surface)
- Irrigated area
- Irrigation water source (surface/underground and distance to field edge)
- Total irrigation water applied per growing season

Farm implements present

- Tractor(s)
- Tractor/ox-drawn implements (e.g. plow, ridger, potato digger...)

Labour

- Average number of workers per hectare potato

Energy

- Hydro-electricity, diesel/petrol generators

Potato grading equipment

Potato washing equipment

2.3 Data analysis

Data were subjected to analysis of variance (ANOVA) using the GenStat 16th edition statistical package (VSN International, 2011). All the mean values of the input use rates in the different production systems identified under the different agro-ecological regions were tested for significant differences using the F-test at 5 % level. The mean values of the input use rates were separated using the least significance difference (LSD) test at 5 % level where the F-test showed significant effects.

3. Results and discussion

3.1 Annual potato area, output and yield in Zimbabwe

Since the beginning of potato farming in the early 1900s, the area increased 4-fold from about 600 ha in 1926 to over 2,400 ha in 1961 (Bell, 1927; FAOSTAT, 2013). The trend of annual average yield, planted area and total annual production was positive for the period 1961 to 2013 though with notable annual variation (Fig. 2). Total crop production increased steadily to over 40,000 tonnes in 1989 due to constant increases in both cropped area and yield (Figs 2B and 2C). For annual planted area, average yield and total production, the positive trend was significant (Fig. 2). In 2013, production reached a peak of 58,000 tonnes from a cropping area of 3,500 ha, both records being the highest ever reached. The country aims to plant 30,000 ha potato annually (Ackerman, personal communication, 2013; The Herald, 2011). This target is based on market potential projections sufficient to absorb more plantings and the assertion by the seed houses that they have the potential to produce enough seed for this area (The Herald, 2011). In 2010, the government banned the importation of potato mainly to protect local growers (Dube, 2013). However smuggling of potato from South Africa into the south-western parts of the country is still being reported (Chimoio, 2013). The current potato grower base of the country is however, limited to a few remaining white large scale commercial and A2 resettlement farmers. Only Nyanga district, a traditional potato growing area has in addition A1resettlement and communal area growers.

At the regional level, Zimbabwe is in eighth position out of 10 selected countries in southern Africa in terms of the average annual potato area planted in the period 2009–2013 (Fig. 3c; FAOSTAT, 2013). In terms of yield, Zimbabwe is fourth out of these 10 regional countries with an average annual yield of 17 tonnes per hectare in the 2009–2013 period (Fig. 3a; FAOSTAT, 2013). This may imply that for a sustained growth in potato production, the country should focus on increasing the grower base especially among the smallholder sector. Concurrently, there is room to increase potato yield through improving resource use efficiencies, particularly synthetic fertilisers. In addition, improving water management, pest and disease control, and use of high yielding cultivars may improve production efficiency. Probably profitability of the potato enterprise may increase from the current state.

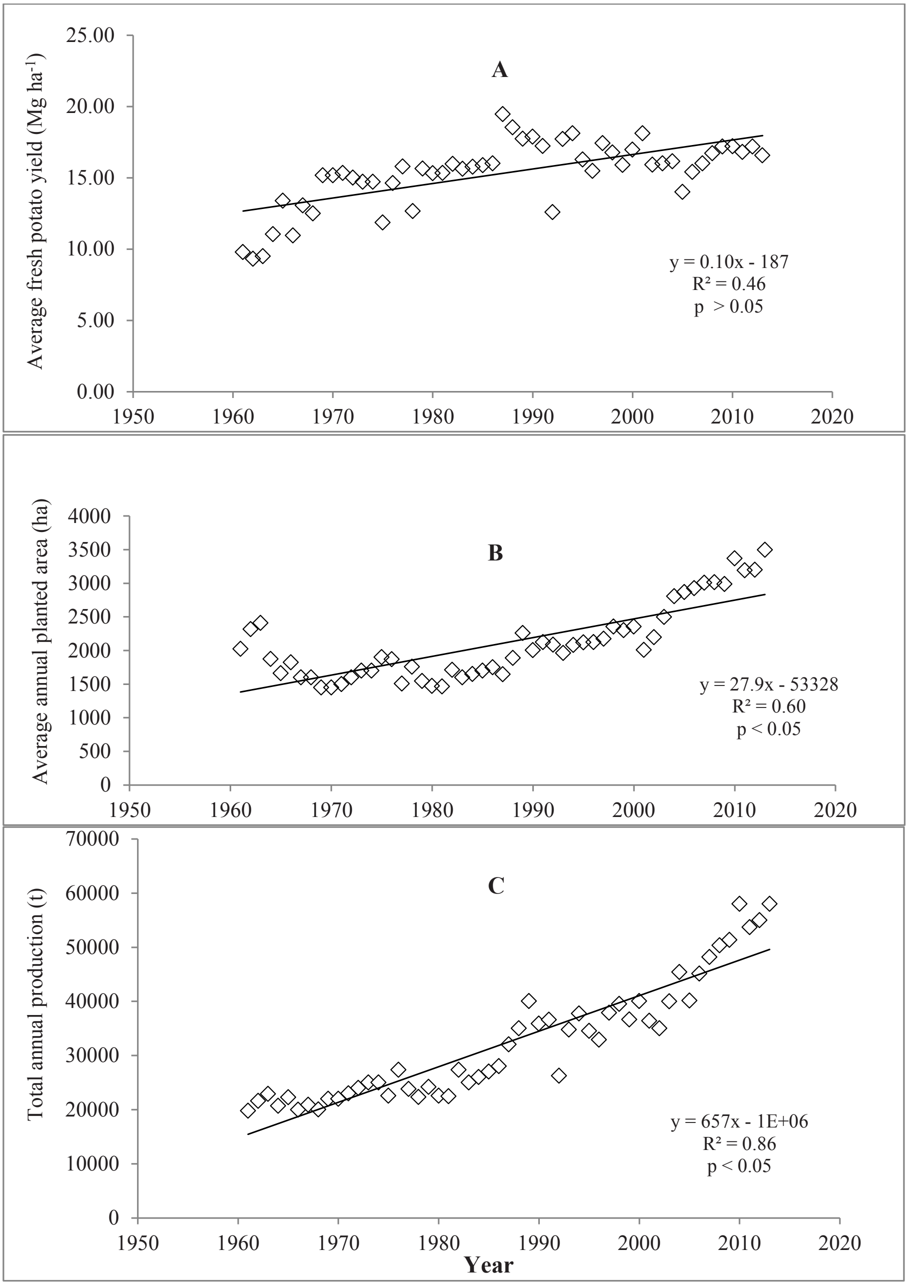

Fig. 2. Development trend of fresh tuber yield (A), area planted (B) and total fresh tuber production (C) of Irish potato during the period 1961 to 2013 in Zimbabwe (CSO, 1993, 1996, 1999, 2001, 2002; FAOSTAT, 2013).

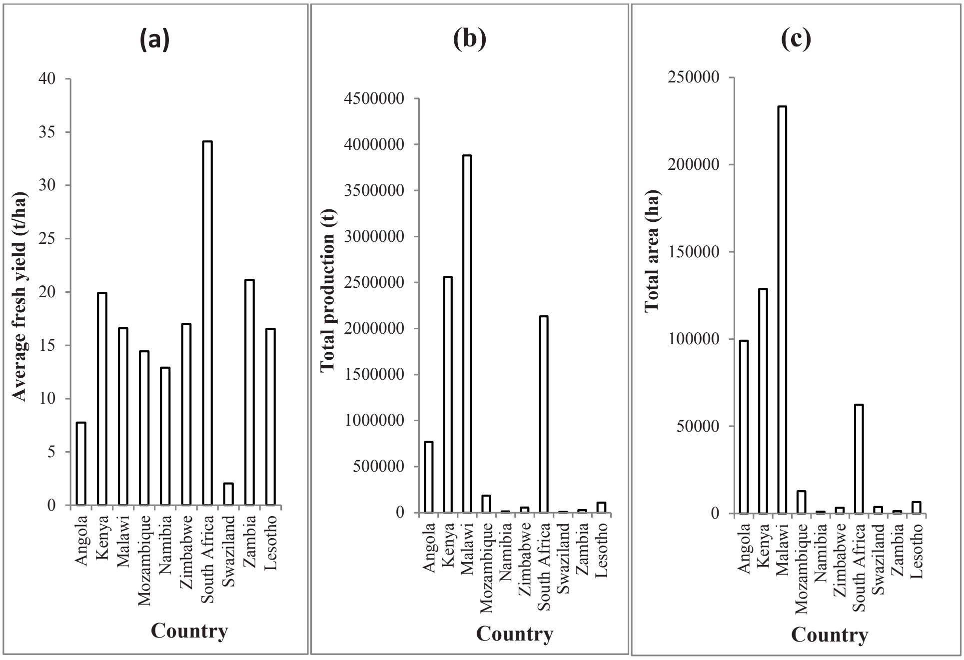

Fig. 3. Average yield (a), total production (b) and total area (c) of fresh potato tuber as annual averages of the period 2009–2013 of selected countries in southern Africa (FAOSTAT, 2013).

Smallholder growers sampled cited high costs of potato production especially seed and fertiliser as a constraining factor. An article by a local daily newspaper quoted beneficiaries of the land reform programme producing potato expressing concern over high costs of production (The Herald, 2011). This, the growers say, was making it difficult for resource-poor but interested growers to break into the sector (The Herald, 2011). Commercial potato farming in Zimbabwe is capital intensive. Computations of the variable costs of potato production estimate at least 7,000 USD per hectare with seed contributing more than 36 percent of the total variable costs. Interest to produce potato is huge but is restricted by the high production costs coupled by the more than decade long economic malaise from which the country has yet to emerge (The Herald, 2011; Manzira, personal communication, 2013). Hence recent calls to encourage smallholder farmers to take up potato production were made (USAID, 2013).

3.2 Potato production systems in Zimbabwe: production zones

Two production/agro-ecological zones were distinguished: (i) the Nyanga Eastern Highlands at elevations above 1,800 m amsl (above mean sea level) and (ii) the Highveld region at altitudes of 1,200 to 1,800 m amsl. The Eastern Highlands agro-ecological zone in Nyanga district hosts the government breeding activities at the Nyanga Experiment Station and the initial seed multiplication in the Quarantine area. Multiplication of seed potato is in two stages. First, foundation seed undergoes three multiplications to produce grade AA1 seed through AA3 seed. This is done in a designated quarantine area in Nyanga district at altitudes above 1,800m amsl. One crop is produced each year under rain-fed conditions with plantings usually in November at the onset of spring rains. Growers here receive virus-free seed tubers from the government breeding programme and carry out three multiplications, foundation seed through class AA3 (Joyce, 1982b). This area must be completely free of other solanaceous plants. The seed potato is rain-fed because of the risk of Bacterial wilt from the soil-borne bacterium *Ralstonia solanacearum* from irrigation water sediments. This is basically the reason growers here do not have irrigation systems (Ackerman, personal communication, 2012). Class AA3 seed then leaves the quarantine area and goes to the Highveld for further multiplication into class A1 through A3 and all of A1, A2 and A3 class seed is used for ware potato production. Outside the Quarantine area in the Eastern Highlands, ware potato production activities are carried out by large scale commercial, communal area, A1 and A2 resettlement growers. Generally the soils range from sand to sandy clay, with clay content ranging from 6 to 52 % (Tables S1 and S2 in Supplementary material). Lowest mean monthly minimum temperatures recorded was 5.2 °C in July and highest long term mean monthly maximum temperature of 23.2 °C in November (Table S3). The Eastern Highlands receives rainfall throughout the year. Long term mean monthly rainfall of about 114 mm is recorded and it ranges from about 14 mm in August to about 340 mm in January (Table S3). In terms of rainfall and temperature regimes, the Eastern Highlands provides the best agro-ecological environment for potato production in Zimbabwe. For example, the cool temperatures, dry soils, and isolation from viruses allow Double A seed to remain in the ground up to July after maturing in March without any loss of yield or quality (Joyce, 1982b). Following harvest, the tubers are stored in well ventilated sheds without refrigeration. The rising temperatures in August and September enables the tubers to break dormancy and such tubers are well-sprouted and in excellent condition for planting in November (Joyce, 1982b). In the Eastern Highlands, ware potato production is year round, hence the potato spends little time in storage.

The Highveld agro-ecological zone is much wider in areal extent and includes the Harare, Bindura, Chegutu, Chinhoyi and the Karoi regions (Fig. 1). There is also a wide variation in the predominant weather (Table S1) and soil conditions (Tables S4, S5 and S6). Lowest mean monthly minimum temperatures recorded was 7.1 °C in July and highest long term mean monthly maximum temperature of 31.7 °C in October (Tables S4, S5 and S6). Soils are generally clay loams. Long term average annual rainfall ranges from about 800 mm in the Chinhoyi region to about 830 mm in the Harare region. In the Highveld areas, besides the summer crop of November through March/April, two additional crops are grown under irrigation in early and late winter. The first irrigated crop is planted from as early as the end of January commencing growth with the last rains and is irrigated from April or May until harvest in June/July (Timson, 1946; Joyce, 1982a). Planting of the second irrigated crop takes place in the middle of the dry season in June/July but can be delayed until early August in frost prone areas (Timson, 1946). Harvest of the second crop is in November/December and is often hindered by wet conditions due to the onset of the rainy season (Joyce, 1982a).

3.3 Potato production systems in Zimbabwe: land characteristics

A total of four potato production systems were identified in the major potato growing areas of Zimbabwe (Tables 3 and 4). These were the large-scale commercial, communal area, A1 and A2 resettlement production systems. The large scale commercial holdings had average gross land size ranging from 165 to 1,600 ha and varied with the area and the agro-ecological zones (Tables 3 and 4). Cropping area in the large scale commercial production systems ranged from 17 to 900 ha and the average potato area per planting was 11 ha and ranged from 3 to 25 ha. Due to the large holdings available, the large scale commercial growers could all practice a minimum of 3 years potato rotation against a general recommendation of a minimum of 4 years.

In the A2 resettlement production system, growers sampled had gross land size ranging from 31 to 390 ha and the cropping area ranged from 16 to 313 ha. The average potato area per planting was 8 ha and ranged from 1 to 23 ha, and a minimum 3 year potato rotation was practised.

The A1 resettlement and communal area production systems were only identified in the Eastern Highlands Nyanga agro-ecological zone. Cropping area averaged 4 and 3 ha in the A1 resettlement and communal area production systems respectively; whereas the average potato area per planting was 0.4 and 1.1 ha respectively. Both production systems practised 1-year potato rotation probably due to the limitations of cropping land available. The Quarantine area is comprised of the large scale commercial and A2 resettlement production systems only. Growers sampled here had gross land sizes ranging from 147 to 347 ha and the cropping area ranged from 82 to 111 ha. Potato area per planting ranged from 17 to 25 ha and growers practised a minimum 3-year rotation system (Table 4).

3.4 Potato production systems in Zimbabwe: mechanisation and irrigation characteristics

All the growers sampled from the large scale commercial and A2 resettlement production systems had irrigation facilities used for the early and late winter potato crop (Table 2). Karoi region was the exception with 33 % of the A2 resettlement growers interviewed without irrigation facilities. The irrigated area ranged from 8 to 180 ha and both pivot and semi-portable irrigation systems were available. All the irrigating growers have grid hydro-electricity energy for the irrigation systems and some had standby diesel generators for use during power outages. Similarly all the sampled growers in the large scale commercial and A2 resettlement production systems owned at least one tractor and equipment for land preparation, planting, spraying and potato harvesting. None though had potato washing equipment but 60 percent of the growers sampled from the large scale commercial sector had cold room facilities. This high level of mechanised potato production creates an impression particularly among smallholder farmers that these are a prerequisite before the crop can be produced. In the Eastern Highlands Nyanga district, similarly all the large scale commercial and A2 growers interviewed had irrigation systems drawing water from surface water sources (Table 4). The irrigated area ranged from 0.4 to 22 ha (Table 4). In the A1 resettlement and communal area production systems, 89 and 94 % had irrigation facilities, respectively. Both production systems had semi-portable irrigation designs and all were gravity fed giving the growers a huge saving on irrigation energy costs. In terms of mechanisation, all the large scale commercial growers in Nyanga owned at least one tractor and equipment for land preparation, planting, spraying, harvesting and potato grading. The rest of the growers in the communal area, A1 and some A2 resettlement production systems also had animal-drawn equipment for potato production.

Table 3. Farm characteristics, farm equipment and irrigation resources inventory of Irish potato growers in the Highveld agro-ecological zone of Zimbabwe, based on interviews in the period 2011–2014.

Characteristic	**Harare**		**Bindura**		**Chegutu**		**Chinhoyi**		**Karoi**	
	LSC	A2	LSC	A2	LSC	A2	LSC	A2	LSC	A2
Farm characteristics										
Land holding/type (% of growers sampled)	29	71	29	71	50	50	40	60	50	50
Farm total size (ha)	190	31	1600	236	221	305	500	390	400	149
Cropping area (ha)	131	23	900	172	95	74	105	313	280	108
Potato planting area per planting (ha)	15	3	7	7	3	1	10	23	10	4
Rotation length (years)	3	3	4	3	3	2	2	3	3	4
Irrigation characteristics										
Irrigation facilities present (% of growers sampled)	100	100	100	100	100	100	100	100	100	67
Total area irrigated (ha)	101	8	180	113	15	59	18	33	10	27
Centre pivot systems (% of growers sampled)	20	0	50	0	0	50	0	100	100	0
Semi-portable systems (% of growers sampled)	80	100	100	100	100	100	100	33	100	100
Hydro-electricity energy (% of growers sampled)	100	100	100	100	100	100	100	100	100	100
Diesel irrigation energy (% of growers sampled)	10	0	50	0	50	0	50	33	100	100
Surface irrigation water (% of growers sampled)	0	0	100	60	0	50	0	33	100	100
Ground irrigation water (% of growers sampled)	100	100	0	40	100	50	100	67	0	0
Equipment Ownership (% of growers sampled)										
Cold room facilities	60	0	0	0	0	0	0	0	0	0

Note: LSC = Large Scale Commercial, A2 = A2 Resettlement. All sampled growers owned at least one tractor and equipment for potato production. Some growers owned both pivots and semi-portable irrigation systems. Stand-by generators (diesel driven) were used during power outages.

Table 4. Farm characteristics, farm equipment and irrigation resources inventory of Irish potato growers in Eastern Nyanga Highlands agro-ecological zone of Zimbabwe, based on interviews in the period 2011 – 2014.

Characteristic	**Nyanga district (excl. Quarantine area)**				**Quarantine area**	
	LSC	A2	A1	CA	LSC	A2
Farm characteristics						
Land holding/farm type [% of growers sampled]	11	14	25	50	29	71
Farm total size [ha]	165	59	4	3	347	147
Cropping area [ha]	17	16	4	3	111	82
Potato planting area per planting [ha]	7.5	3.3	0.4	1.1	25	17
Rotation length [years]	4	2	1	1	4	3
Irrigation characteristics						
Growers with irrigation facilities [% of growers sampled]	100	100	89	94	0	0
Total area irrigated [ha]	22	5.9	0.4	1.2	0	0
Centre pivot irrigation system [% of growers sampled]	0	0	0	0	0	0
Semi-portable of irrigation system [% of growers sampled]	100	100	100	100	0	0
Hydro-electricity energy source [% of growers sampled]	100	20	0	0	0	0
Diesel energy source [% of growers sampled]	0	40	0	0	0	0
Gravity [% of growers sampled]	0	40	100	100	0	0
Surface irrigation water source [% of growers sampled]	100	100	100	100	0	0
Under-ground irrigation water source [% of growers sampled]	0	0	0	0	0	0
Machinery/Implements Owned [% of growers sampled]						
Tractors	100	40	0	0	100	100
Potato grading equipment	100	0	0	0	100	100
Cold room facilities	33	0	0	0	0	0

Note: LSC = Large scale commercial, A2 = A2 resettlement, A1 = A1 resettlement, CA = Communal area; all the sampled growers owned equipment for land preparation, planting, spraying and potato harvesting. None had potato washing equipment.

Growers applied varying amounts of irrigation water across the different production systems (Table 5). The irrigation water quantities applied per ha were significantly different ($p < 0.001$) among the production systems (Table 5). Lowest average irrigation water use (213 mm) was reported in the A1 resettlement production system, all located in the Nyanga Eastern Highlands. The humid and high rainfall conditions experienced there (Table S3) decrease the need for supplemental irrigation. However the high average irrigation application amount observed (736 mm) in the communal area system, all located in the Nyanga Eastern Highlands was unexpected. This was explained by the fact that the majority of the communal area growers' irrigation systems are gravity-fed, hence the tendency to over-irrigate. This practice of over-irrigating is common where adequate irrigation water is easily available or the energy cost is minimal. For example, in Chile, Haverkort *et al*. (2014) reported that growers applied twice the amount of the calculated water need.

The majority of A2 resettlement and large scale commercial growers were located in the Highveld agro-ecological zone and their average supplementary irrigation water use was 465 and 549 mm/ha respectively (Table 5). The Highveld region experiences a tropical climatic pattern, with a distinct summer rainfall and dry winter season (Tables S4, S5 and S6). Hence, supplementary irrigation becomes necessary for the winter potato crop. As already alluded to, the first irrigated (early winter) crop is normally planted in January, commencing growth with the last summer rains and is irrigated from April until harvest in June/July (Timson, 1946; Joyce, 1982a). Planting of the second irrigated (late winter) crop takes place in the middle of the dry season in June/July and the crop is harvested in November/December. The onset of the rainy season in November/December reduces the need for supplementary irrigation.

3.5 Potato production systems in Zimbabwe: general input application rates

3.5.1 Fertiliser application rates

All of the N, P and K nutrient levels used were significantly different ($p < 0.05$) across all production systems (Table 5). The average mineral fertiliser application rate among all the sampled growers was 154 kg N/ha, 91 kg P/ha and 155 kg K/ha which is generally above the general recommended NPK rates in other neighbouring countries. For example, the general recommended rates in Kenya were 90 kg N/ha and 101 kg P/ha (Kaguongo *et al*., 2008); in

South Africa 170 kg N/ha, 70 kg P/ha, and 100 kg K/ha (FAO, 2005) and in Ethiopia 110 kg N/ha, 18 kg P/ha, and 83 kg K/ha) (Haile and Mamo, 2013). Both the large scale commercial and A2 resettlement production systems used higher nutrient application rates than the smallholder A1 resettlement and communal area systems (Table 5). General synthetic fertiliser recommendations for an average potato yield of 30 t/ha in Zimbabwe is 120, 123, and 149 – 199 kg/ha of N, P, and K, respectively (FAO, 2006; Manzira, 2011). The large scale commercial and A2 resettlement systems had a tendency to apply rates exceeding the general recommendations. Probably this caters for micro-climate and soil differences or is an insurance in the absence of soil analysis, since more than 95 % of the sampled growers did not have soil tests to determine pH and inherent soil fertility levels.

In the large scale commercial production system, no significant relationships were observed between actual potato yield and the NPK nutrient application rates (Fig. 4, 5 and 6). This probably suggests that generally the nutrient use levels in the large scale commercial production system has approached a ceiling as determined by the yield potential of the cultivars grown. From this relationship (Fig. 4 to 6), it is most likely that fertiliser application rate is probably one of the least likely causes of low potato yields in the large scale commercial production system. Actually, there is a real danger of over-fertilisation in the large scale commercial production system and the potential for losses into the environment. Recently, studies on wheat production in many regions of China have observed over-application of fertilisers which led to increases in both residual nutrients and the potential for losses into the environment (Chuan *et al*., 2013). Growers in the large scale commercial production systems need to focus on other limiting crop management aspects to improve fertiliser use efficiency of potato and thereby increase yield while reducing the fertiliser application rates. Lassaletta *et al*. (2014) demonstrated that it is possible to move the fertiliser-yield relationship to a more efficient level through shifting yield upwards. Such management interventions includes, better nutrient management, micro-nutrient amendments, high-yielding cultivars, water management, pest and disease management (Conant *et al*., 2013; Sutton *et al*., 2013). Growers in Zimbabwe are still using old cultivars of the 1980s and early 1990s due to the slowing down of the national breeding programme (Mazarire, personal communication, 2014). Significant positive relationships were observed between actual potato yield and the nutrient application rate in the communal area, A2 resettlement and A1 resettlement production systems (Fig. 4 to 6). Notably, the gradients of the nutrient use-yield relationship in the communal area production system were the largest compared to other production systems (Fig. 4 to 6). The least gradient was observed in the nutrient use-yield relationship of the large scale commercial production system (Fig. 4 to 6). Hence, this indicates that the highest yield response to nutrient use was in the communal area production system and that the least response was in the large scale commercial production system. This implies that yield benefits can be realised in the communal area systems through increasing nutrient use, especially, potassium, K_2O. However, the option of increasing nutrient use is untenable in the short to medium term in Zimbabwe. The cost of synthetic fertilisers is high, and the harsh macro-economic conditions currently obtaining in the country worsens the situation particularly of resource-constrained smallholder production systems. The remaining option of other cultural practices already alluded to needs to be explored.

3.5.2 Biocide application rates

Fungicides are by far the most frequently used biocide in potato production across all the production systems in Zimbabwe (Table 5). Early blight (*Alternaria solani*), because of the favourable climatic conditions for it, is more common and problematic than late blight (*Phytophthora infestans*) and other fungi (Manzira, 2011). Both fungicide and insecticide use was significantly different ($p < 0.001$) among the production systems (Table 5). The large scale commercial and A2 resettlement production systems used higher biocide application rates than the smallholder (A1 resettlement and communal area) systems. In the former production systems, the growers were better-resourced and tended to afford the recommended routine preventive and curative fungicide sprays. As anticipated, significant positive yield-biocide use relationships were observed (Fig. 7). The gradients of the biocide use-yield relationship in the communal area production system were the largest compared to other production systems, whilst the least gradient was observed in the biocide use-yield relationship of the large scale commercial production system (Fig. 7). Therefore, this indicates that the highest yield response to biocide use was in the communal area production system and that the least response was in the large scale commercial production system. This implies that biocide use in the large scale commercial system was approaching maximum levels. The highest yield response observed in the communal area system probably suggests that biocide use is important to increase yield in this sector. Knowledge of Integrated Pest Management (IPM) was completely absent among all the growers sampled. Hence there is opportunity for potato growers in Zimbabwe to learn and apply IPM techniques and lower

Table 5. Mean values of input application rates used in fresh Irish potato growing by the different production systems in the major potato farming areas of Zimbabwe, 2011-2014.

Production system	Yield [Mg/ha]	Biocides [g a.i./ha]			Nutrients [kg/ha]			Irrigation water [mm/ha]	Seed [kg/ha]
		Fungicides	Insecticides	Herbicides	N	P_2O_5	K_2O		
Large-scale commercial	28^{a}	34060^{b}	2553^{a}	2093	181^{a}	284^{a}	301^{a}	549^{b}	2269^{a}
A2 resettlement	23^{b}	38684^{a}	1454^{b}	2033	197^{a}	270^{a}	218^{a}	465^{b}	2199^{a}
A1 resettlement	8^{d}	18320^{d}	1015^{d}	na	94^{c}	91^{c}	90^{c}	213^{c}	990^{c}
Communal area	17^{c}	28048^{c}	1215^{c}	1960	143^{b}	185^{b}	137^{b}	736^{a}	1573^{b}
F pr.	*	**	**	ns	*	*	**	**	**
LSD	5	3664	185	70	26	50	35	107	309
CV (%)	36	17	18	4	24	33	27	27	25

Key: a.i. = active ingredient, na = not applicable, * denotes significant difference at $p < 0.05$, ** denotes significance at $p < .001$, ns denotes non-significance at $p < 0.05$, mean values in the same column followed by the same letter are not significantly different

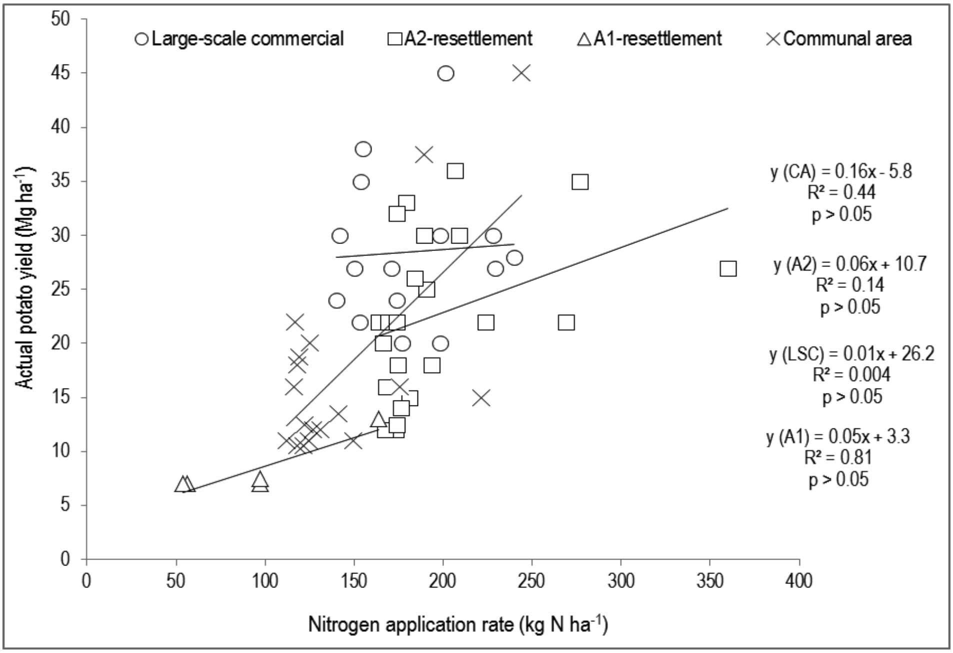

Fig. 4. Relationship between nitrogen (N) application rate and actual potato yield in the different potato production systems in Zimbabwe.

biocides use while maintaining or even increasing yields. According to Kromann *et al.* (2014), potato IPM for disease management involves integrating the use of resistant cultivars, fungicides and grower training. In order for farmers to adopt new technologies, it is important for them to understand the economic, ecological and practical benefits of the technology (Kromann *et al.*, 2014). Farmer training in Zimbabwe is the principal role of the government extension agency, Agritex.

Herbicide application rates were not significantly different ($p < 0.05$) among the production systems (Table 5). Generally growers followed the manufacturer recommendations for herbicide use hence the tendency to use similar dosages. The most commonly used herbicides were Metolochlor and Metribuzine. Similarly, nematicide use was not significantly different ($p < 0.05$) among the production systems (data not shown) because growers mostly applied them in accordance with manufacturer instructions.

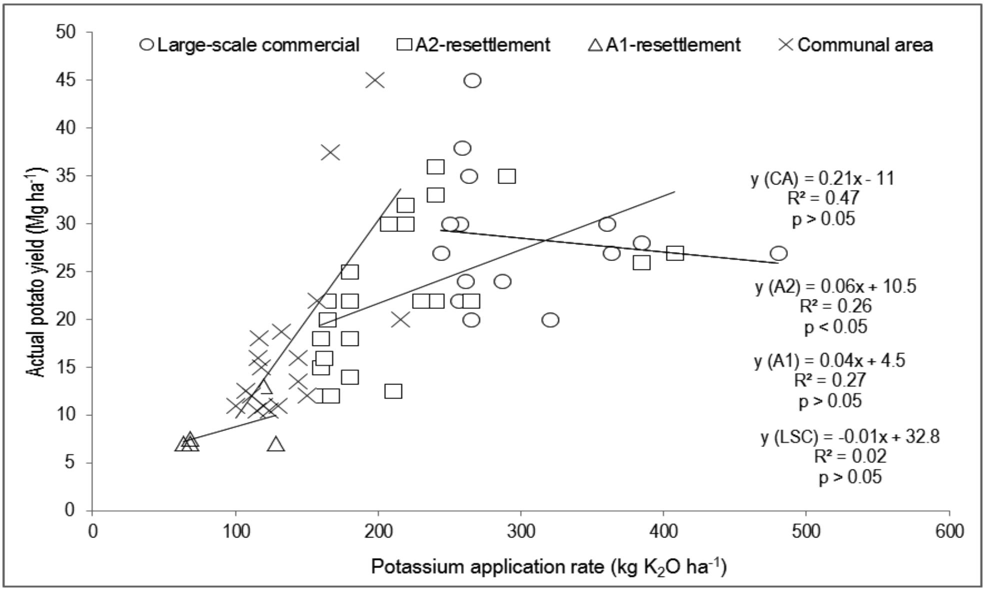

Fig. 5. Relationship between potassium (K_2O) application rate and actual potato yield in the different potato production systems in Zimbabwe.

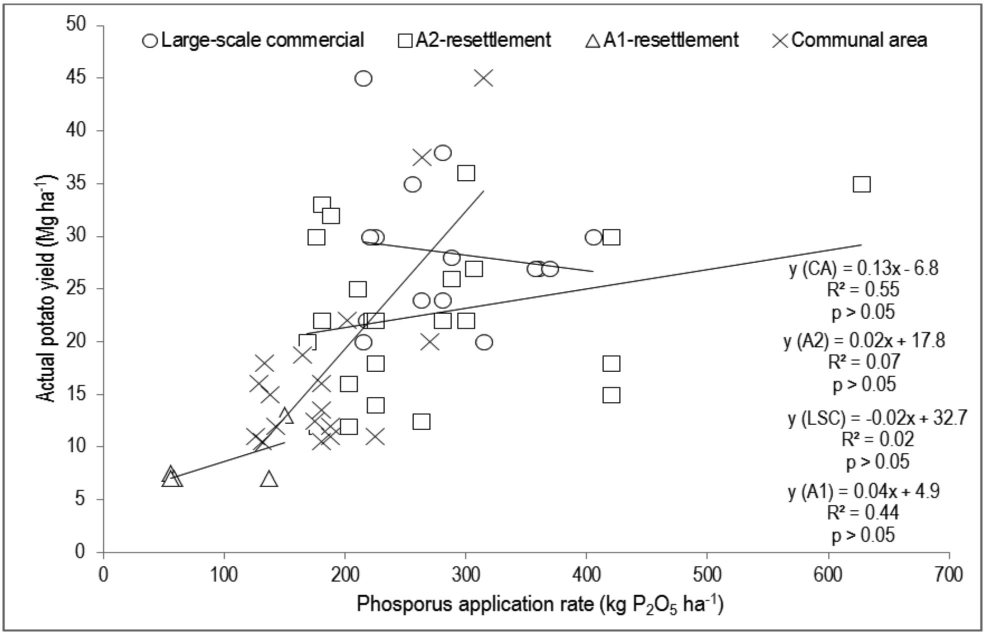

Fig. 6. Relationship between phosphorus (P_2O_5) application rate and actual potato yield in the different potato production systems in Zimbabwe.

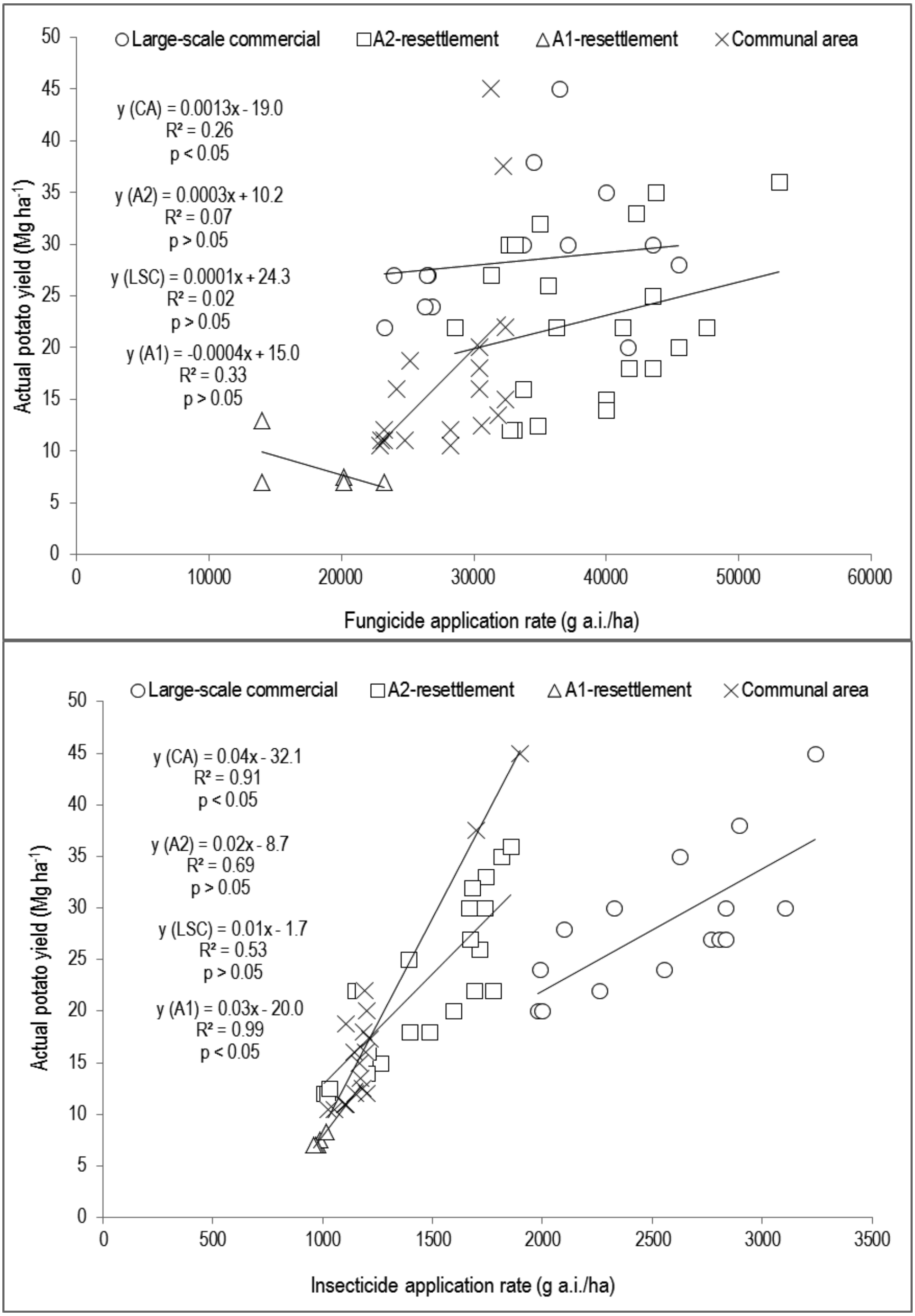

Fig. 7. Biocide use relationships with actual potato yield in the different potato production systems in Zimbabwe.

3.5.3 Seed rate

The seed rate was significantly different (p <.001) among the production systems (Table 5). It ranged from an average of 990 to 2269 kg/ha in the A1 resettlement and large scale commercial production systems, respectively (Table 5). However, the general seeding rate reported was 2.0 to 2.5 t/ha for ware potato and 2.5 to 3.3 t/ha for seed potato production (Manzira, 2011). Less weight of seed was used with small to medium size tubers. In Zimbabwe, small size seed is in the 25 to 37.5 mm diameter range, whereas medium size seed falls in the 37.5 to 50 mm range. Growers preferred the small to medium size seed to reduce seed costs.

3.5.4 Potato production systems in Zimbabwe: cultivar preferences

Tables 6 and 7 show the potato cultivar preferences among growers in the Eastern Highlands and Highveld areas of Zimbabwe, respectively. Growers were asked on the cultivars they prefer to grow and it was possible for one grower to mention more than one cultivar. Amethyst, a locally bred variety, was the most preferred and it occupied the largest area followed by BP1, originally from South Africa. Both cultivars are very old and were grown since the early 1980s (Joyce, 1988). The choice of the two cultivars was attributable to good yield and tolerance to late blight (*Phytophthora infestans*). Amethyst is a late maturing cultivar (17–19 weeks after planting) and has a high level of tolerance to late blight. BP1 is the earliest commercial variety on the market maturing in 14–15 weeks after planting and is moderately tolerant to late blight. Under good management, the two cultivars have been reported to yield in excess of 30 t/ha (Manzira, 2011). Other cultivars being grown include Montclare, Jasper and KY20, all locally bred. Mondial, recently registered in 2012, is a Dutch cultivar that was introduced from South Africa and is also steadily gaining popularity, especially in the Eastern Highlands. The local potato breeding programme stopped since the turn of the millennium, mainly due to financial constraints and a high breeder staff turnover in government service. Variety trials are still being conducted, although with imported generation zero material of some varieties. The country is not self-sufficient in terms of seed supply. More than 30 % of the seed requirement is imported annually from neighbouring South Africa in order to meet the steadily increasing grower needs (Manzira, personal communication, 2013).

Table 6. Irish potato cultivar preferences in the Eastern Nyanga Highlands farming area of Zimbabwe obtained from grower surveys conducted in the period 2011–2014.

Characteristic/production system	**Large scale commercial**	**A2 resettlement**	**A1 resettlement**	**Communal area**
Cultivar grown [% of growers sampled]				
BP1	100	90	60	60
Amethyst	100	75	60	60
Montclare	20	20	50	50
Jasper	20	20	50	50
Mondial	20	10	20	20
KY20	10	10	10	10

Note: Some growers grew more than one cultivar

Table 7. Irish potato cultivar preferences in the Highveld potato farming areas of Zimbabwe obtained from grower surveys conducted in the period 2011 – 2014

Characteristic/ agro-ecological zone	**Harare**		**Bindura**		**Chegutu**		**Chinhoyi**		**Karoi**		**Nyanga Quarantine**	
	LSC	A2	LSC	A2	LSC	A2	LSC	A2	LSC	A2	LSC	A2
Cultivar preferences (% of growers sampled)												
BP1	20	100	100	100	100	100	50	50	100	67	33	50
Amethyst	20	0	100	100	100	100	100	100	100	67	33	100
Mnandi	40	0	0	0	0	0	50	50	0	0	0	0
Mondial	20	0	0	0	0	0	0	0	0	0	0	0
Jasper	0	0	0	0	0	0	0	0	0	33	0	25
Montclare	0	0	0	0	0	0	0	0	0	0	33	50
KY20	0	0	0	0	0	0	0	0	0	0	33	25

Key: LSC = Large Scale Commercial, A2 = A2 Resettlement; some growers grew more than one cultivar.

4. Conclusions and recommendations

The case of the Irish potato production system in Zimbabwe showed a steady increasing trajectory of area, yield and total production of the crop in an era of uncertainties following the landmark agrarian reforms initiated in 2000. Several inferences can be made from this study. These include seed shortages and the very depressed seed breeding activities needed to answer grower problems such as low yield, low pest and diseases tolerance that is reflected in the rather high biocide application rates. High synthetic fertiliser use rates were observed in the rather high biocide application rates. High synthetic fertiliser use rates were observed in the large-scale and A2 resettlement systems. It is important therefore to move the fertiliser-yield relationship to a more efficient level through appropriate interventions to shift yield upwards and improve nutrient-use efficiency. Such management interventions includes, better nutrient management, micro-nutrient amendments, high-yielding cultivars, water management, pest and disease management. Compared to the staple maize crop, potato production costs were on the high side, especially seed and fertiliser costs and this may be a deterrent to smallholder growers to grow the crop. Smallholder potato growers (A1 and communal area production systems) are limited to the Eastern Nyanga Highlands and there is a need to create appropriate awareness among smallholder growers in the Highveld agro-ecological zone to grow the crop under rain-fed conditions. A positive development is that the A2 resettlement production system is slowly merging into the large scale commercial system in terms of input application rates, level of mechanisation and irrigation infrastructure and potato yield.

This case study of Irish potato production system in Zimbabwe can be adopted as a model to study and analyse potato production systems in the region and in other countries. It can also be readily adopted to study and analyse other crop production systems besides Irish potato in the country and beyond.

5. Compliance with Ethical Standards

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This manuscript has not been submitted to any other journal for simultaneous consideration, and neither has it been published previously in part nor in full.

Conflict of Interest: The authors declare that they have no conflict of interest.

Supplementary material. Soil characterisation of the major Irish potato growing environments in Zimbabwe.

Table S1. Soil characteristics of Irish potato growers in the major potato farming areas of Zimbabwe, interviewed in the period 2011 – 2014.

Characteristic/ agro-ecological zone	**Harare**		**Bindura**		**Chegutu**		**Chinhoyi**		**Karoi**		**Nyanga Quarantine**	
	LSC	**A2**	**LSC**	**A2**	**LSC**	**A2**	**LSC**	**A2**	**LSC**	**A2**	**LSC**	**A2**
Fine sand (0.25-0.02 mm) (%0	31	33	31	33	27.5	29.8	43.0	27.3	39.5	41.3	39.7	31.5
Medium sand (0.25-0.5 mm) (%)	9	7	13	7	16.0	14.8	9.0	12.3	20.8	23.0	18.3	20.5
Coarse sand (0.5-2.0 mm) (%)	4	3	5	3	10.0	8.0	2.0	4.3	21.3	5.7	12.7	16.9
Silt (0.02-0.002 mm) (%)	26	22	21	22	17.5	19.0	17.0	24.0	9.5	17.7	15.0	15.0
Clay (< 0.002 mm) (%)	30	36	31	36	29.0	28.4	29.0	32.0	9.0	12.3	14.7	16.2
Organic matter content (%)	2.9	0.8	0.9	0.7	0.4	1.3	1.3	2.4	1.1	0.8	6.5	5.0
pH (in 0.01M $CaCl_2$)	5.4	4.9	4.9	6.0	6.1	5.72	5.6	5.9	5.5	6.1	4.5	4.5
Mineral N (initial) (ppm)	32.5	6.5	12.5	16.6	25.5	16.2	10.0	21.3	15.3	19.3	9.0	27.7
Mineral N (after incubation) (ppm)	49.0	33.5	32.5	30.8	45.5	35.8	21.0	51.7	34.8	29.0	47.5	53.0
Available P (resin extract) (ppm P_2O_5)	138.5	14.5	53.0	44.8	56.5	35.8	13.0	20.3	43.8	19.0	31.5	5.5
Exchangeable K (mg eq./100 g soil)	1.0	0.3	0.3	0.5	7.9	4.1	0.1	1.0	1.2	3.0	0.10	0.16
Exchangeable Ca (mg eq./100 g soil)	5.8	4.8	9.6	8.2	6.4	10.2	1.7	2.5	1.6	2.2	1.3	1.7
Exchangeable Mg (mg eq./100 g soil)	1.7	1.7	5.5	4.3	2.1	2.9	1.2	1.9	1.1	1.5	0.6	0.7

Key: LSC = Large Scale Commercial; A2 = A2 Resettlement; eq. = equivalent.

Table S2. Soil characteristics of Irish potato growers in the Nyanga (excluding the Nyanga Quarantine Area) farming area Interviewed in the period 2011-2014, Zimbabwe.

Characteristic	**Large Scale Commercial**		**A2-Resettlement**		**A1-Resettlement**		**Communal Area**	
	average	**range**	**average**	**range**	**average**	**range**	**average**	**range**
Fine sand (0.25-0.02 mm) [%]	43.0	29.1 – 47.8	27.8	19.0 - 33.0	25.4	21.0 - 32.0	34.2	12.0 - 63.0
Medium sand (0.25-0.5 mm) [%]	23.2	26.6 – 34.5	31.3	27.0 - 39.0	28.2	11.0 - 38.0	10.7	2.0 - 32.0
Coarse sand (0.5-2.0 mm) [%]	9.1	6.5 – 18.7	14.5	8.0 - 19.0	25.0	16.0 - 38.0	9.2	1.0 - 22.0
Silt (0.02-0.002 mm) [%]	4.0	3.0 – 12.4	10.0	6.0 - 16.0	6.9	3.0 - 14.0	17.5	3.0 - 39.0
Clay (< 0.002 mm) [%]	20.0	18.2 – 23.4	18.5	14.0 - 21.0	14.3	8.0 - 38.0	28.4	6.0 - 52.0
Organic matter content [%]	2.43	2.01 – 3.90	1.6	1.2 - 2.2	1.2	0.5 - 4.2	3.1	0.3 - 7.8
pH (in 0.01M $CaCl_2$)	5.2	4.8 – 5.5	4.5	4.4 - 4.8	4.8	4.1 - 5.8	4.3	4.1 - 5.0
Mineral N (initial) [ppm]	10.0	2.4 – 36.5	9.5	3.0 - 23.0	12.9	5.0 - 33.0	20.6	3.0 - 69.0
Mineral N (after incubation) [ppm]	33.0	17.6 – 87.2	34.0	19.0 - 52.0	34.6	22.0 - 62.0	53.0	17.0 - 111.0
Available P (resin extract) [ppm P_2O_5]	14.0	3.3 – 71.8	9.0	3.0 - 19.0	15.7	2.0 - 61.0	11.5	1.0 - 47.0
Exchangeable K (mg equivalents per 100 g soil)	0.64	0.40 – 2.11	0.13	0.08 - 0.19	0.3	0.1 - 1.5	0.3	0.1 - 1.9
Exchangeable Ca (mg equivalents per 100 g soil)	2.03	0.83 – 2.61	1.6	1.1 - 2.3	1.3	0.4 - 2.1	1.5	0.4 - 4.8
Exchangeable Mg (mg equivalents per 100 g soil)	1.12	0.55 – 1.88	0.6	0.4 - 0.9	0.7	0.3 - 1.2	0.7	0.3 - 2.5

Table S3. Climatic characteristics in the Nyanga Irish potato farming area of Zimbabwe, average over 1985 – 2010.

Month	**Mean monthly precipitation [mm/month]**	**Mean monthly maximum temperature [$^{\circ}$C]**	**Mean monthly minimum temperature [$^{\circ}$C]**	**Mean monthly radiation [MJ $m^{-2}d^{-1}$]**	**Mean monthly evaporation [mm/d]**
January	339.9	22.4	13.1	20.2	3.8
February	243.3	22.1	12.9	20.4	3.7
March	162.3	22.1	12.4	19.7	3.7
April	70.9	21.0	10.3	18.2	3.5
May	23.9	19.7	7.6	16.3	3.2
June	24.5	17.8	5.6	15.0	2.8
July	23.1	17.1	5.2	15.5	3.1
August	14.8	19.6	6.3	18.5	4.0
September	21.1	22.4	8.9	21.6	5.5
October	66.9	22.9	10.8	22.8	5.7
November	125.7	23.2	12.1	22.8	4.9
December	250.0	22.4	12.6	20.2	3.8

Source: Meteorological Services Department, MSD, Zimbabwe, Nyanga Experiment Station weather station, 18^{o}13'S, 32^{o}44'N

Table S4. Climatic characteristics in the Chinhoyi Irish potato farming area of Zimbabwe, average over 1985 – 2010.

Month	**Mean monthly precipitation [mm/month]**	**Mean monthly maximum temperature [°C]**	**Mean monthly minimum temperature [°C]**	**Mean monthly radiation [MJ $m^{-2}d^{-1}$]**	**Mean monthly evaporation [mm/d]**
January	191.8	28.0	17.4	21	5.1
February	174.7	28.0	17.0	21	5.2
March	114.8	28.1	16.0	21	5.1
April	24.9	27.9	13.9	20	5.2
May	16.1	26.5	11.2	18	5.0
June	1.9	24.4	8.6	17	4.5
July	0.6	24.1	8.3	18	4.7
August	2.3	26.6	9.7	20	5.8
September	2.9	29.9	13.3	23	7.3
October	33.5	31.7	16.1	24	8.0
November	74.9	30.7	17.0	23	7.0
December	166.8	28.4	17.2	21	5.6

Source: Meteorological Services Department, MSD, Zimbabwe, Chinhoyi weather station 17°23'S, 30°23'N

Table S5. Climatic characteristics in the Karoi Irish potato farming area of Zimbabwe, average over 1985 – 2010.

Month	**Mean monthly precipitation [mm/month]**	**Mean monthly maximum temperature [°C]**	**Mean monthly minimum temperature [°C]**	**Mean monthly radiation [MJ $m^{-2}d^{-1}$]**	**Mean monthly evaporation [mm/d]**
January	199.8	26.2	15.7	19.5	7.9
February	183.5	26.2	15.3	19.4	7.9
March	116.6	26.5	14.9	19.1	7.8
April	33.0	26.3	12.4	19.7	8.0
May	8.2	24.8	10.0	17.5	7.2
June	3.1	22.9	8.3	16.0	6.5
July	0.3	22.7	7.5	16.5	6.7
August	0.2	25.2	9.0	20.1	8.2
September	1.4	28.4	11.9	22.5	9.2
October	20.3	29.8	14.1	23.7	9.7
November	86.4	29.0	16.3	22.6	9.2
December	167.0	26.8	15.1	20.0	8.2

Source: Meteorological Services Department, MSD, Zimbabwe, Karoi weather station 16°49'S, 29°51'N

Table S6. Climatic characteristics in the Harare (including Bindura and Chegutu) Irish potato farming area of Zimbabwe, average over 1985 – 2010.

Month	**Mean monthly precipitation [mm/month]**	**Mean monthly maximum temperature [°C]**	**Mean monthly minimum temperature [°C]**	**Mean monthly radiation [MJ $m^{-2}d^{-1}$]**	**Mean monthly evaporation [mm/d]**
January	218.4	27.0	16.4	20	5.0
February	130.2	26.8	16.0	20	4.9
March	120.4	26.9	15.2	20	4.9
April	32.2	26.1	12.6	20	4.7
May	14.7	24.6	9.7	18	4.2
June	3.2	22.4	7.4	17	3.8
July	0.8	22.2	7.1	17	4.1
August	2.4	24.7	9.1	20	5.3
September	2.7	27.9	12.5	23	7.1
October	30.0	29.4	15.0	24	7.7
November	85.8	28.9	16.1	22	6.9
December	189.0	27.4	16.3	20	5.3

Source: Meteorological Services Department, MSD, Zimbabwe, Belvedere weather Station 17°49'S, 31°02'N.

Chapter 3

Yield gap analysis and resource footprints of Irish potato production systems in Zimbabwe

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Abstract

Irish potato is the third most important carbohydrate food crop in Zimbabwe after maize and wheat. In 2012, the Government of Zimbabwe declared it a strategic national food security crop. In this study, we examine the country's potential for increasing Irish potato yield and help ease the nation's food security challenges. The magnitude of food production increase on already existing croplands depends on the difference between the current actual yields and the potential yield of the crop in the given agro-ecological environment, also called the yield gap. We used three already well-understood types of yield gap: (1) the gap between actual farmer yields, Ya, and the maximum (potential) yield, Yp, achieved when a crop is grown under conditions of non-limiting water and nutrient supply with biotic stress effectively controlled; (2) the gap between Ya and the water-limited yield, Yw, which is the maximum yield attainable under rainfed systems; and (3) the gap between Ya, and the highest yield, Yh, achieved by the best farmers in an agro-ecological area. A grower survey was conducted on the different potato production systems in the country in order to establish the actual yields and input application rates used in potato production. The actual potato yields were used to calculate efficiencies of natural and synthetic resources use. Potential and water-limited yields, and planting times of potato were established for the different agro-ecological regions using the LINTUL-POTATO model, a model based on interception and utilisation of incoming solar radiation. The mean actual yield observed ranged from 8 to 35 % of the potential yield, translating to a yield gap of 65 to 92 %, hence there is a huge potential to increase production. Simulated potential water use efficiency based on evapotranspiration range was 19-27 g potato l^{-1} against the actual water use efficiency of 2-6 g potato l^{-1} based on irrigation and rainfall. The current high fertiliser application rates and low actual yields we report, suggest inefficient fertiliser use in potato production in Zimbabwe. The average actual fungicide and insecticide use efficiencies were 0.7 and 13 kg potato g^{-1} active ingredient, respectively, across all production systems. All sampled growers lacked knowledge on integrated pest management, a concept which could possibly improve the biocide use efficiency through lowering biocide application rates while maintaining or even improving yields. Our analysis suggests that there is opportunity to improve water, nutrients and biocides resource use efficiencies and increase potato actual yields in Zimbabwe.

Key words: Irish potato, Actual yields, Yield gap, Resource use efficiency, Simulated potential and water-limited yields, LINTUL-POTATO model, Zimbabwe.

1. Introduction

Agriculture is currently grappling with the challenge to increase food production by 70–100 % in order to meet the food needs of a rising global population expected to reach over 9 billion people by 2050 (Bruinsma, 2009; Dubois, 2011). Options to raise food production include improving output from the current croplands, expanding existing croplands or simultaneously implementing both approaches. Expanding cropping area as an option would be accompanied with the negative impacts of increased greenhouse gas (GHG) emissions and soil resources degradation (Sanchez, 2002; IPCC, 2007; Sasson, 2012). Estimates of land available for cropland expansion in Sub-Saharan Africa are contested (Young, 2000; Lambin *et al*., 2013; Chamberlin *et al*., 2014). However, converting these potentially available croplands to cultivation could entail losing the inherent biodiversity under them. Some of these biomes could be of high social, economic and ecological value (Licker *et al*., 2010). Improving yield on current croplands would imply application of high levels of inputs such as synthetic fertilisers, practices that might negatively impact soil and water quality, climate change and biodiversity (Foley *et al*., 2005). However, the pursuit of increasing yield on current croplands without ecologically destructive agricultural practices can be realised through the approach of *sustainable intensification* or *ecological intensification* (Garnett *et al*., 2013; Struik and Kuyper, 2014). This approach views intensification as a transitional process from agricultural practices generally accepted as unsustainable to those regarded as environmentally sustainable (Struik and Kuyper, 2014).

The magnitude of food production increase on already existing croplands through sustainable intensification depends on the difference between the current actual yields and the yield potential of the crop in the given agro-ecological environment. This is the basis of the yield gap concept (Van Ittersum *et al*., 2013). There are different ways to calculate the yield gap depending on the definitions of the yield potential and the actual yield. The yield potential, Yp, of a particular crop cultivar is the maximum attainable yield achieved when the crop is grown under non-limiting conditions of water and nutrient supply, with biotic stress effectively controlled (Evans, 1993; Van Ittersum and Rabbinge, 1997). In irrigated systems, Yp is determined by the amount of incident solar radiation, temperature, CO_2 concentration and plant density during the growing season (Cassman *et al*., 2003), assuming good health of propagules. Another important yield assessment is the water-limited yield, Yw, which is equivalent to water-limited potential yield and is the maximum yield attainable in rainfed systems (Van Wart *et al*., 2013). Hence, Yw is limited by plant available water, which is mainly determined by rainfall, soil texture, topography, soil surface cover and the plant rooting pattern. The highest actual yield (Yh) locally attained in a given agro-ecological area is another important benchmark. Yh has been defined by Tittonell and Giller (2013) as the water and nutrient-limited yield that can be measured in the most productive fields of resource-endowed farmers in a community. Crop simulation models are frequently used to calculate robust estimates of Yp or Yw, characteristic of the prevailing climatic and soil conditions in the selected agro-ecological region. Surveying good growers can provide estimates of Yh for a particular agro-ecological region of interest. Average actual yield, Ya, is the crop yield actually achieved by farmers in a given agro-ecological region; the crop being grown under the general management practices commonly used in the region (Cassman *et al*., 2003). The yield gap, YG, is therefore the difference between Yp, Yw, or Yh and Ya. The formula (1 – Ya/Yp), (1 – Ya/Yw) or (1 – Ya/Yh) is used to provide a relative value of the YG. YG can be a useful measure to assess the efficiency of land use for crop production. Besides identifying regions where YG is widest (hence greatest opportunities to improve crop yield), a yield gap analysis can also be used to identify soil and management measures to close the gap (Van Ittersum *et al*., 2013). Additionally, yield gap analysis can be used to direct research priorities and as a benchmark to assess impact of input use, development initiatives or assess any future situation affecting land productivity (Van Ittersum *et al*., 2013).

The Fast Track Land Reform Program (FTLRP) in Zimbabwe at the turn of the millennium resulted in a new agrarian landscape with nearly 168,000 households resettled on approximately 11 million ha of former commercial farmland by 2009 (MLRR, 2009). Two resettlement models were used, the A1 resettlement model that resembles the communal area land allocation system and the A2 resettlement model that results in self-contained, small to medium scale farm units (MLRR, 2009). The new farmers are of diverse resource means with the majority being resource-constrained, which translates into similarly diverse farm management strategies with a bearing on yield and resource use efficiency.

Irish potato (*Solanum tuberosum* L.) is the most important horticultural crop in Zimbabwe, and the third most important carbohydrate food source after maize and wheat (The Herald, 2011). Some of the A1 and A2 resettlement model beneficiaries have started potato production adding to the already existing communal area potato farmers and the few remaining large scale commercial farmers. Growth projections target an annual potato crop of about 30,000 ha in the short to medium term (The Herald, 2011; Ackerman, personal communication, 2013). Currently about 3,500 ha of the crop is planted annually (FAOSTAT, 2013). Acknowledging the increased interest in potato production and consumption, the Government of Zimbabwe declared Irish potato a national strategic food security crop on 18 May 2012 (The Herald, 2012). Before this day, only the staple maize crop had the national strategic food security crop status. The new agrarian landscape and the national strategic food security status of Irish potato present a perfect scenario to investigate the scope of increasing potato production in Zimbabwe under the current cropping systems with available land and water resources. Yield gap analysis for potato in Zimbabwe can provide a measure of unexploited food production capacity that can help address problems of food insecurity. Such an analysis will help identify regions in the country best placed to increase potato production, to evaluate the impact of resource/input use, to identify resources currently limiting Ya and to discuss suggestions to narrow the gap.

The specific objectives of this study were: (1) to determine the potential, water-limited and actual field yields of potato in the major potato growing zones of Zimbabwe and to analyse the yield gap; (2) to establish the resource footprints (e.g., land, water, mineral fertilisers, and biocides) for potato production in the different production systems and agro-ecological zones; and (3) to offer recommendations to improve production.

2. Materials and methods

2.1 Grower survey

A grower survey was conducted in the traditional potato growing Highveld and Eastern Highlands regions of Zimbabwe in the period 2011 through 2014. The government agricultural extension agency, Agritex (Agricultural, Technical and Extension Services), selected growers to be visited for the field data collection exercise. Both irrigating and rain-fed potato farms were sampled. A minimum of 5 years continuous potato farming experience was required making the data collected dependable.

The sample included three large-scale commercial growers and four A2 resettlement growers from the Quarantine area located in the Nyanga Eastern Highlands agro-ecological zone. The Quarantine area is an isolated zone created by a statutory instrument (Joyce, 1982a). It is responsible for the initial potato seed multiplications and only 21 out of the 27 growers in the area are active (Ackerman, personal communication, 2012). A further 18 communal area (CA), 5 A1 resettlement and one of the four remaining large scale commercial growers, all outside the Quarantine area completed the Nyanga Eastern Highlands sample. The department of Agritex officials in Nyanga estimated about 1,500 communal area and less than 100 A1 resettlement growers. A total of 11 large scale commercial and 14 A2 resettlement growers were interviewed in the extensive Highveld agro-ecological zone. According to Agritex officials, the Highveld has less than 50 large scale commercial growers and about 100 experienced A2 resettlement growers, while a few A1 resettlement and communal area growers are beginning to show interest in potato growing. Data collected included gross farm and cropping land sizes, potato planting area, planting and harvesting dates, technology use levels, mineral fertiliser and biocides application rates, seed, labour, irrigation water use and the average gross potato yield (Ya) achieved. The data collected were used to calculate the resource footprints of land, water, biocides and nutrients based on the actual yields (Ya). Further, Ya data collected were used to calculate the YG based on the simulated Yp and Yw. In addition, the data was also used to understand the general Irish potato agronomic practices in Zimbabwe.

2.2 Computation of resource footprints

The concept of resource use efficiency (RUE) is important in the evaluation of crop production systems. The resources include land, water, biocides and nutrients. Management and environmental factors interact in influencing RUE in cropping systems (Fixen *et al.*, 2015). The partial factor productivity (PFP) measure as defined by Dobermann (2007) is a simple production efficiency expression, calculated in units of crop yield per unit of factor applied. It is calculated as PFP = Y/F, where Y is the yield of the harvested portion of a crop with factor applied, and F is the amount of factor applied (Dobermann, 2007; Fixen *et al.*, 2015). The PFP answers the question: how productive is a cropping system in relation to a specific amount of input applied (Dobermann, 2007; Fixen *et al.*, 2015)? The PFP is easily computed for any farm where the grower keeps records of inputs used such as fertilisers, biocides and water, and the respective yields. The grower survey data collected in the study were used to calculate the resource footprints of land, water, biocides and nutrients as PFP based on the actual yields (Ya). However, there are other RUE measurements and equations/expressions in use, but these indices require data that are not often readily available at farm level (Dobermann, 2007; Fixen *et al*., 2015).

2.3 Determination of the potential and water-limited yield potential

The potential dry matter production of potato for the different agro-ecological regions in Zimbabwe was calculated in this study using the LINTUL-POTATO model as described by Kooman and Haverkort (1995). The model simulation of potato dry matter is based on incident Photosynthetically Active Radiation, PAR (400–700 nm spectral range), a fraction of PAR intercepted by the crop and a radiation use efficiency, RUE (Spitters, 1990) to convert the intercepted light into dry matter. Calibration and validation of the model has been done for diverse cropping situations around the world (Kooman and Haverkort, 1995; Caldiz and Struik, 1999; Molahlehi *et al.*, 2013). In addition, the model was validated for the Zimbabwe case using observed crop growth parameters that included the number of days from planting to 50 % and 100 % emergence, days between emergence and 100 % ground cover, and days between 100 % ground cover and 95 % defoliation. These collected datasets were compared with output from the LINTUL-POTATO model simulations. Phenological development of the crop is driven by accumulated temperature. Under relatively high temperature conditions, the crop emerges early followed by rapid initial leaf growth and consequently increased solar radiation interception leading to rapid crop maturation and a reduced crop growth duration and yield. Simulations of radiation interception started at 50 % emergence through senescence, simulating shoot growth, foliar expansion, biomass accumulation and tuber growth on a daily basis. The meteorological data required by the model as input includes daily minimum and maximum temperatures, incoming solar radiation, rainfall, and reference evapotranspiration. Long term meteorological data were purchased from the Meteorological Services Department (MSD). Grower soil and resource management input data for the model included soil texture, rooting depth, planting depth, percent irrigation, date of planting and harvest. A growing period of 126 days was used to represent Amethyst, the most popular cultivar in Zimbabwe which matures in 17 to 19 weeks after planting. A planting depth of 15 cm was used as this is the common planting depth generally recommended for potato in Zimbabwe. The accumulated degree days from planting (with a base temperature of 2 °C) determines the time to crop emergence, leaf area development and the time of crop termination (Franke *et al*., 2011). The leaf area index (LAI) increases exponentially from crop emergence until a leaf area index of 0.75 is achieved. Thereafter, its development depends on temperature and water availability until a full crop cover is reached (LAI >3). Daily biomass growth is calculated using the crop's LAI, light interception (using an extinction coefficient of 1 (Spitters and Schapendonk, 1990)) and the RUE (1.25 g dry matter MJ^{-1} of intercepted photosynthetically active radiation, PAR, spectral range 400–700 nm). In the model, photosynthesis capacity is reduced when the average day temperature falls below 16 °C or when the maximum temperature exceeds 30 °C and is completely halted at temperatures below 2 °C and above 35 °C (Kooman and Haverkort, 1995). The harvest index for all cropping situations was set at 0.75 (Kooman and Haverkort, 1995), and simulated yields are presented as tuber fresh matter, assuming a dry matter concentration of 19 % to allow comparisons with the actual yield, Ya, reported by the growers. Daily evapotranspiration (ET) for potato was calculated from the Penman-Monteith grass reference evapotranspiration (ETo) (Smith *et al*., 1997) multiplied by a crop specific coefficient (Kc) according to the procedure recommended by Allen *et al.* (1996). The input parameters to calculate the daily ETo values were the daily maximum and minimum temperatures, relative humidity, wind speed, solar radiation, and precipitation. Plant available water (PAW) in the soil was supplied from irrigation and precipitation. The retention of PAW depended on the water holding capacity of the soil determining drainage, the rooting zone of the crop (up to 0.5 m) and evapotranspiration from the soil and the crop. The actual transpiration by the crop, and thereby the water-limited photosynthesis rate, equalled the potential evapotranspiration by the crop multiplied by a drought stress factor, which was a function of the plant available water in the soil (Franke *et al*., 2011).

The LINTUL-POTATO model was used to simulate potential and water limited yield of potato in the selected potato growing environments in Zimbabwe. Scenarios were simulated with 26 years of agro-meteorological data for the period 1985 to 2010 collected from weather stations located in the sampled zones. The effect of different planting dates on crop performance (Yp and Yw) was assessed by simulating planting on the 15th day of each month in the period 1985–2010, to determine the best planting month. Soil samples were taken from the fallow potato fields which the grower wanted to plant the next potato crop and were analysed for pH, texture, and NPK. The general irrigation intervals used for potato in Zimbabwe on light textured soils is 3–4 and 5–7 days during hot and cool months respectively applying a gross irrigation of 30 mm (Barnes, 1979). For hot and cool months the irrigation intervals range was 5–6 and 10–12 days, respectively, applying 40–45 mm for medium textured soils, and for heavy textured soils, the interval ranges from 6–7 and 12–14 days for hot and cool months, respectively, applying 50–55 mm (Barnes, 1979). With increasing reports of climate change in the last decade, probably these irrigation regimes need revision; however, the sampled growers confirmed that they still follow this irrigation practice. In the model, irrigation was skipped for 1 day if it rained more than the scheduled amount of irrigation, and for 2 days if it rained more than twice the scheduled amount. The effective irrigation was assumed to equal 80 % of the applied irrigation amount to account for application losses.

2.4 Data analysis

Data were subjected to analysis of variance (ANOVA) using the GenStat 16th edition statistical package. Mean values of the resource footprints of the different production systems identified under the different agro-ecological regions were tested for significant differences using the F-test at 5 %. The mean values of the resource footprints were separated using the least significance difference (LSD) test at 5 % where the F-test showed significant effects. Correlations were also done to find the relationship between the different variables (Gomez and Gomez, 1984). Further analysis of the relationship between the fresh potato yield in the different production systems and the corresponding nutrient/biocide application rate were done using Spearman Rank Correlation tests and associated t statistics.

3. Results and discussion

3.1 Agro-ecologies and general agronomic practices of Irish potato production in Zimbabwe

The main potato growing areas in the country are the Highveld region, a more or less gently undulating plateau at altitudes above 1,200 m amsl (above mean sea level), and the Eastern Highlands at higher elevations greater than 1,800 m amsl. The Highveld covers about 25 % of the country's total area of about 390,000 km^2. This region experiences a highly variable climatic pattern but is generally characterized by mild winters from May to September and hot summers from November to March. Precipitation mostly occurs in the summer months and averages around 750 to 900 mm. For example, Harare area located in the Highveld at 1480 m amsl experiences average winter and summer temperatures ranges of 6–8 and 15–26 °C, respectively. Harare also receives an average of 8 sunshine hours per day, and an annual average precipitation of 800 mm. The Highveld region is suitable for intensive farming systems based on crops and livestock production. The Eastern Highlands on the other hand comprises less than 5 % of the total country area. The high elevation gives it a characteristic microclimate and vegetation. This region receives the country's heaviest precipitation of more than 1,000 mm per annum. It has a more prolonged rainy season than the rest of the country lasting from October into April, with some precipitation in all months of the year. Average mean temperature ranges from about 11 °C in July to 18 °C in October. The comparatively low temperatures make the rainfall more effective, enabling the region to practise specialised and diversified farming with forestry, tea and coffee plantations, horticultural crops, and intensive livestock production. In both the Eastern Highlands and the Highveld regions, irrigated potato is generally grown throughout the year. However, the following growing seasons are common: summer (November through March/April), early winter (February through May/June) and a late winter crop planted in June/July or early August in frost-prone areas and harvested in November/December. Most soils are suitable for potato production, but medium textured loamy soils are frequently used. Deep ploughing (600 mm depth) is done followed by secondary tillage with a disc harrow to achieve a fine tilth seed bed. Furrows spaced 90–120 cm are opened. Basal fertiliser is banded in the furrows opened. The general fertiliser recommendation for potato production in Zimbabwe is 120, 123 and 149–199 kg/ha of N, P and K, respectively for a fresh tuber yield of about 30 t/ha. A nematicide is also sprayed along the furrows. About 2 tonnes per hectare of seed potato is required and the seed tuber size ranges from about 35 to 55 mm in diameter. The seed tubers are pre-sprouted (3–5 sprouts per tuber) to achieve quick and uniform emergence. Besides, sprouting also increases the main stem density and consequently the crop yield. Sprouting is done by storing the tubers under diffuse light conditions and sometimes a sprout stimulant can be applied. During planting, the tubers are mechanically or manually placed in the rows, 20 cm to 30 cm apart, depending on the seed tuber size and soil fertility. The seed tubers can be planted 7–10 cm deep under irrigation farming and can be slightly deeper (up to 15 cm) under rain-fed conditions. The furrows are then immediately covered manually with soil to achieve a flat surface. When plants are about 25 cm tall, about 70 kg N per hectare top-dressing is applied followed by the first ridging which is also done to control weeds. The second ridging is done three weeks later and is usually accompanied with about 150 kg/ha sulphate of potash (50 % K_2O) dressing. Problem pests include the potato tuber moth (*Phthorimaea operculella*), aphid (*Macrosiphum euphorbiae*), cutworm (*Agrotis spp.*), leaf miner (*Liriomyza spp.*), red spider mite (*Tetranychus spp*.) and the potato leafhopper (*Empoasca fabae*). Spraying for these and other pests begins shortly after emergence and is repeated weekly until the haulms are cut. Baboons (*Papio ursinus*) are a serious threat to potato production in Zimbabwe and where they occur, daytime guards have to be posted at considerable expense. Late blight (*Phytophthora infestans*) is a serious disease problem particularly during the summer ware crop in the Highveld. It is generally controlled by regular preventive and curative fungicide applications. The crop will be ready for harvesting when 95 % of the leaves have died off. Early cultivars mature in 14–16 weeks and late cultivars in 17–19 weeks. In seed potato production, the haulms are destroyed prematurely to minimise the proportion of oversized tubers, though this can also be achieved through closer in-row spacing at planting. In some cases haulms are destroyed for early harvesting or when there is risk of severe late blight attack.

Unlike in most developing countries, seed and ware potato storage in Zimbabwe is extraordinarily trouble-free. With year round production, both seed and ware potato spend little time in storage. In the designated quarantine area in the Eastern Highlands, harvesting of 'AA' seed potato can be spread out from March through July without noticeable yield or quality loss because of the dry soils, cool temperatures, and isolation from viruses (Joyce, 1988). The harvested tubers are stored in well ventilated sheds without refrigeration, and break dormancy with the rising temperatures in August and September. In the quarantine area, foundation seed undergoes three multiplications to produce grade AA1 through AA3 seed. Grade AA3 seed leaves the quarantine area for further multiplications mainly in the Highveld to produce grade A1 through A3 seed potato, all of which are used for ware potato production. Hence good quality seed potato is available for all plantings, that is in early winter (February), late winter (June to early August), summer (November/December) and any plantings in-between.

3.2 Land footprint: actual and potential potato yields

Significant differences ($p < 0.05$) in mean actual yields were observed among the production systems (Table 1). Tuber yield ranged from 8 t/ha in the A1 resettlement to 35 t/ha in the Large-scale commercial production systems, both in the Nyanga agro-ecological area (Fig. 1a). The A1 resettlement production system was the most technically inefficient system and used the lowest level of input for potato growing in the country (Fig. 2). Hence low yields were obtained. On the other hand, the large-scale commercial system was technically more efficient and high levels of inputs were applied in potato production achieving the highest yields in the country (Fig. 2). Assuming 35 t/ha as the locally attainable yield, defined, according to Tittonell and Giller (2013), as the water and nutrient-limited yield that can be measured in the most productive fields of resource endowed farmers in a community, a yield gap of over 77 % was observed, reflecting a huge potential to increase food production. High yields above 45 t/ha were reported by individual large-scale commercial growers in the Highveld areas of Harare and Bindura, further widening the already existing yield gap (Manzira, personal communication, 2013). The large-scale commercial production system has been the traditional potato growing system since the early 20th century in the country (Joyce, 1982b), hence it is older and more experienced than the recent A1 and A2 resettlement production systems. Besides, the large-scale commercial production system is well mechanised and has improved crop management practices over the years. This probably explains the higher actual yields reported by the large-scale production system than the other production systems (Fig. 1a). However the large-scale commercial production system is now small as only a few growers remained following the recent agrarian reforms in the country (MLRR, 2009). The communal area production system in Nyanga district had an average yield of 17 t/ha which is more than twice the yield level achieved in the A1 resettlement production system (Table 1). Potato is the staple food crop in Nyanga district and has a long history of cultivation by communal area growers, consequently gaining experience and improved management practices of the crop than the recent A1 resettlement growers.

Simulations of potato dry matter using the LINTUL-POTATO model for potential yield have been used before, for example in Argentina (Caldiz and Struik, 1999; Caldiz *et al*., 2001), South Africa (Franke *et al*., 2011; Haverkort *et al*., 2013), Lesotho (Molahlehi *et al.,* 2013), and in Chile (Haverkort *et al*., 2014), the South African and Lesotho examples being in the region close to the Zimbabwe case study. Readily observable crop growth parameters, such as days between planting and 50 % and 100 % emergence, days between emergence and 100 % ground cover, and days between 100 % ground cover and 95 % defoliation were satisfactorily comparable to the LINTUL-POTATO model output. Using the potato variety Amethyst, the simulated days between planting and emergence ranged from 11–16 days, 28–43 days between emergence and 100 % ground cover and 68–82 days between 100 % ground cover and harvest. The LINTUL-POTATO model simulations showed that the average potential yield ranged from 88.4 t/ha in the Chinhoyi and Karoi areas of the Highveld to 95.8

Table 1. Mean values of resource use efficiencies in fresh Irish potato farming in the different agro-ecological zones and production systems of Zimbabwe, 2011-2014.

Production system	**Yield** [Mg/ha]	**Biocide Use Efficiency** (kg potato/g a.i. biocide)				**Nutrient Use Efficiency** (g potato/g nutrient)			**WUE_i** (g potato/l water)
		Fungicide	**Insecticide**	**Herbicide**	**Nematicide**	**N**	**P_2O_5**	**K_2O**	
Large-scale commercial	28^a	0.9^a	11.1^b	13.7	11^a	162^a	105	99	5.7^a
A2-resettlement	23^b	0.6^b	15.4^a	11.4	9^b	116^b	93	106	4.8^b
A1-resettlement	8^d	0.5^b	8.1^c	na	3^d	97^b	104	97	4.6^b
Communal area	17^c	0.6^b	13.7^a	9.0	7^c	120^b	93	123	2.5^c
F pr.	0.004	0.008	<.001	0.313	0.004	0.01	0.714	0.177	0.002
	*	*	**	ns	*	*	ns	ns	*
LSD	4.9	0.2	2.1	3.9	1.9	26	24	23	1.1
CV (%)	36	36	24	38	36	32	38	32	36

Key: WUEi = water use efficiency (irrigation), a.i. = active ingredient, na = not applicable, * denotes significant difference at $p < 0.05$, ** denotes significance at $p < .001$, ns denotes non-significance at $p < 0.05$, mean values in the same column followed by the same letter are not significantly different t/ha in the Nyanga Eastern Highlands (Fig. 1a). This is mainly explained by the cool temperatures in the Nyanga Eastern Highlands leading to a long growing period and slow maturation process. Consequently, the cool temperatures experienced over the entire growing season in the Eastern Highlands allow for slow maturation leading to higher simulated potential yield (Fig. 3). Whereas in the warmer Highveld, rapid maturation tends to be favoured leading to lower simulated potential yield compared to the Eastern Highlands (Fig. 3). Using the long term weather data from 1985 to 2010, the mean monthly average temperatures ranged from 11 °C to 18 °C in the Eastern Highlands, whereas in the warmer Highveld they ranged from 16 to 24 °C (Fig. 3). The month of planting had a strong impact on the simulated potential and water-limited yields in all the agro-ecological growing environments studied (Fig. 4). In the Highveld, the June through September plantings tended to have suppressed simulated potential yields because of the warmer temperatures in the subsequent September through December growing months (Figs 4b, c and d). In practice, the late winter crop which is grown under irrigation coincides with the depressed simulated potential yields as it is normally planted in June or delayed to early August in frost prone areas. However, the late winter crop is still convenient for growers because it is harvested in November and December, capitalising on the good festive season market. The highest simulated potential yields in the Highveld areas were in the January through April plantings (Figs 4b, c and d). This is due to the decreasing average temperatures during the growing period in the months April through July (Figs 3a, c and d). The solar radiation follows the temperature pattern (Fig. 3). Many growers in the Highveld with supplementary irrigation facilities plant in January and February, and this is traditionally known as the early winter plantings. While the model predicts high simulated potential yields also in March and April, such plantings in practice will be at high risk from frost in June and July as the crop will be at the vegetative stage. Hence farmers restrict the early winter crop plantings to the months of January and February. In the cool temperate-like climatic pattern in the Nyanga Eastern Highlands, the highest simulated potential yield was 97.2 t/ha in the September plantings (Fig. 4a). This is because the September plantings experienced a gradual rise in average temperatures to ideal levels in the September through December growing months (Fig. 3b). Many growers with supplementary irrigation facilities reported good yields in the September and October plantings. They also use early maturing varieties such as BP 1 to take advantage of the good festive season prices in December when potato can actually run out of supply because of a steep demand. The simulated water-limited potential yields followed the same pattern as the simulated potential yields but is dependent on the rainfall pattern in all the areas (Fig. 4). Predictably, the simulated water-limited potential yield during the plantings of September through January exactly equalled the potential yields for plantings during the same months in Nyanga Eastern Highlands (Fig. 4a). This is most probably because the Nyanga Eastern Highlands experience a temperate climatic pattern with precipitation throughout the year. The precipitation peaked in the summer months of September through January, tailing off in February and March. In the Highveld, the crop completely failed in the dry winter plantings of April through July and yield rose with the summer rains (Figs 4b to 4d). The Highveld Karoi area is unique in that plantings in all the months gave comparable simulated potential yields, all above 81 t/ha with the highest of 90 t/ha in the January plantings. This is perhaps due to the narrow range in variation of the mean monthly temperature and radiation (Fig. 3d), the important climatic determinants of simulated potential yield in a given environment. In this part of the Highveld, it may be advisable for growers' planting dates to be guided more by the market trends than the potential yields because of the small differences in simulated potential yield on planting dates (Fig. 4d). The mean actual yield observed ranged from 8 % of the simulated potential yield in the A1 resettlement production system in the Nyanga Eastern Highlands to 35 % of the simulated potential yield in the large-scale commercial of the Harare Highveld agro-ecological zone. This translates to a yield gap of 65 and 92 % in the Highveld and Eastern Highlands, respectively (Fig. 1b). Hence in theory, there is scope to increase potato production in Zimbabwe through narrowing the huge existing yield gap. While this opportunity is available in all the different production systems, it is probably greatest in the A1 resettlement system where the technical efficiency is least with low level input use and poor management.

A significant ($p < 0.01$) negative linear relationship was found between the actual yield and the percent yield gap (data not shown): the yield gap decreased with increasing actual potato yields. Hence there is tremendous opportunity to increase potato production in the country through narrowing this gap. Probably the intensification route could be used to increase potato production and rapidly narrow this gap but with sustainable use of resources such as water, nutrients and biocides (Foley *et al.*, 2011; Van Ittersum *et al.*, 2013). Sustainable intensification would certainly require that growers have easy access to key potato production inputs. Such inputs include fertilisers, biocides and high yielding seed varieties. This could be a difficult proposition under the current socio-economic challenges

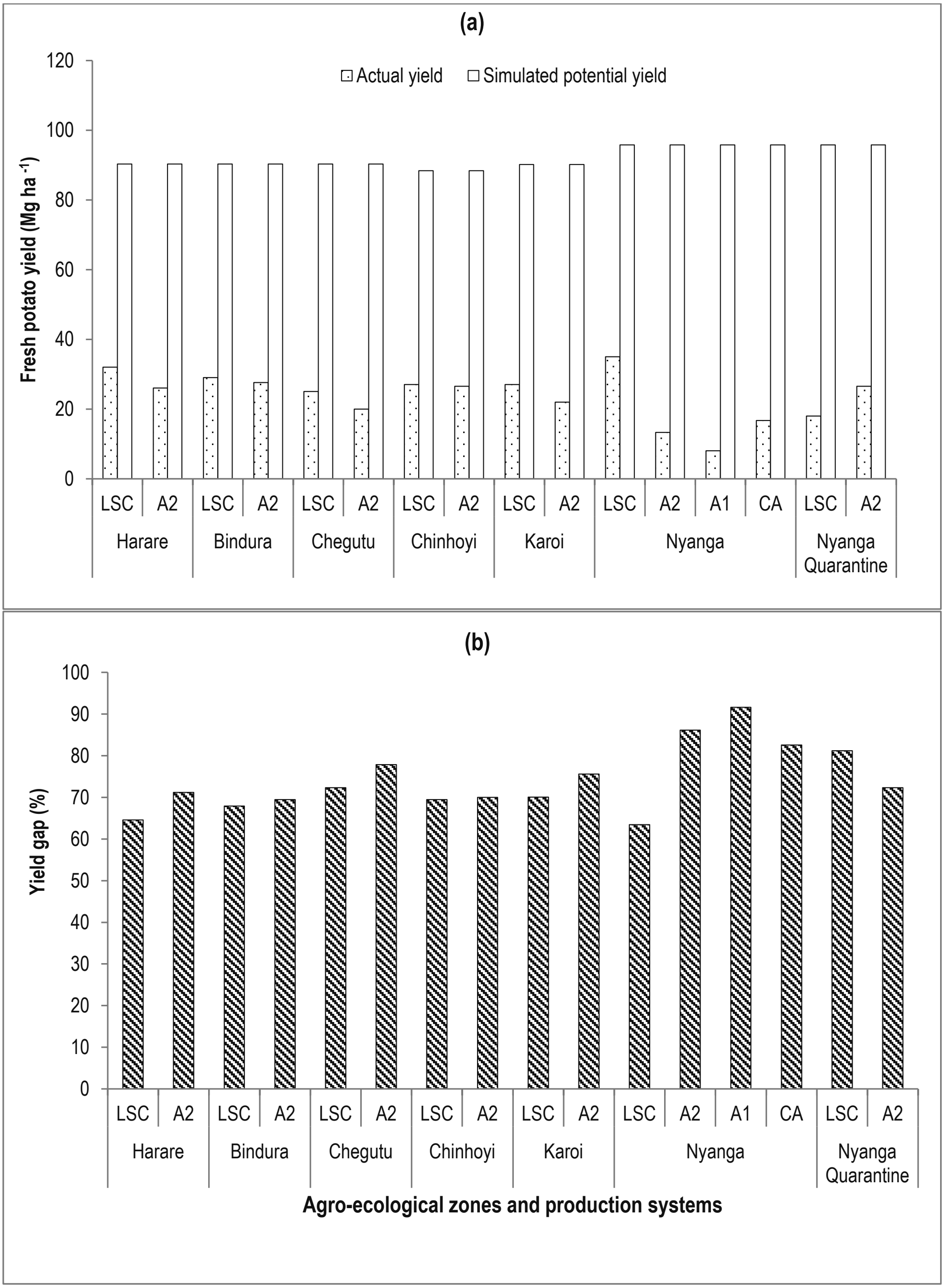

Fig. 1. Actual and average potential yield (simulated) (a) and yield gap percentage (b) of different agro-ecological zones and Irish potato production systems of Zimbabwe.

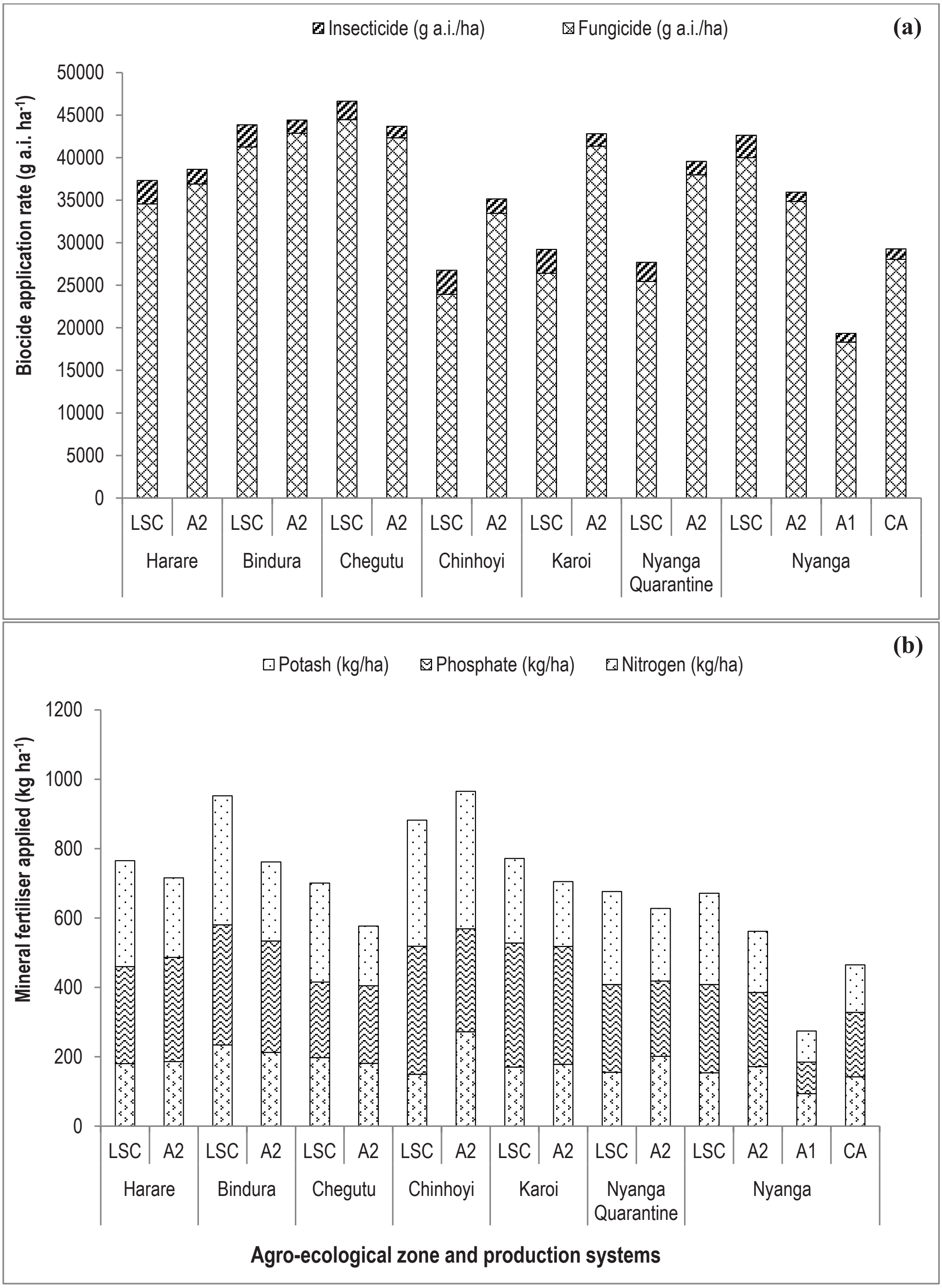

Fig. 2. Amount of biocides (a) and nitrogen (N), Phosphate (P_2O_5) and potash (K_2O) (b) applied to the potato crop in different agro-ecological zones and potato production systems in Zimbabwe.

the country is grappling with for over a decade now.

3.3 Water footprint: actual and potential water use

Simulated water use efficiencies based on evapotranspiration (WUE_{ET}) suggested that potato planted in summer (October through January) in the Nyanga Eastern Highlands had a higher water use efficiency than early winter (April through June) plantings (Fig. 5a). Warm summer temperatures accompanied by high radiation intensities (Fig. 3b) resulted in high evapotranspiration (Fig. 3b) to meet the high atmospheric evaporative demand. This high evapotranspiration was partly compensated for by the high potential yields. The average summer water use efficiency was 27 g potato l^{-1} against an average simulated potential yield of 91 t/ha; on the other hand, the average early winter water use efficiency was 19 g potato l^{-1} and the average simulated potential yield was 62 t/ha (Fig. 5a). Since the high potential yields coincided with high water use efficiencies and conversely low potential yield with low water use efficiency, the model clearly demonstrated harmony between land and water use efficiencies in the Eastern Highlands. The model demonstrated a similar pattern in the Highveld areas (Figs 5b to 5d).

In Fig. S1 (Supplementary material), the model simulations of water use efficiency under water-limited conditions showed that the crop failed in the dry winter (April through July) plantings in all the potato growing areas because of little or no rainfall received. Production was limited to summer only when precipitation is received. Noteworthy is the Nyanga Eastern Highlands case where water use efficiencies decreased from 17.3 g potato l^{-1} in August to 13.1 g potato l^{-1} in January against an increase in potential yield from 64 t/ha in August to 85 t/ha in January. Thus the model clearly demonstrated the presence of a trade-off between water and land use efficiency, as low water use efficiencies coincided with high potential yields with delayed plantings in summer. The decrease in simulated water use efficiency in January plantings is compensated for by an increase in simulated potential yield, and in the August plantings, the low simulated potential yield is compensated for by the high simulated water use efficiency. There is also in agreement with the general recommendations by the agricultural extension service, that growers under water-limited conditions should plant with the first effective rains received.

It was observed from the survey results that growers applied varying amounts of irrigation water across the different agro-ecological zones and production systems (Fig. 6a).

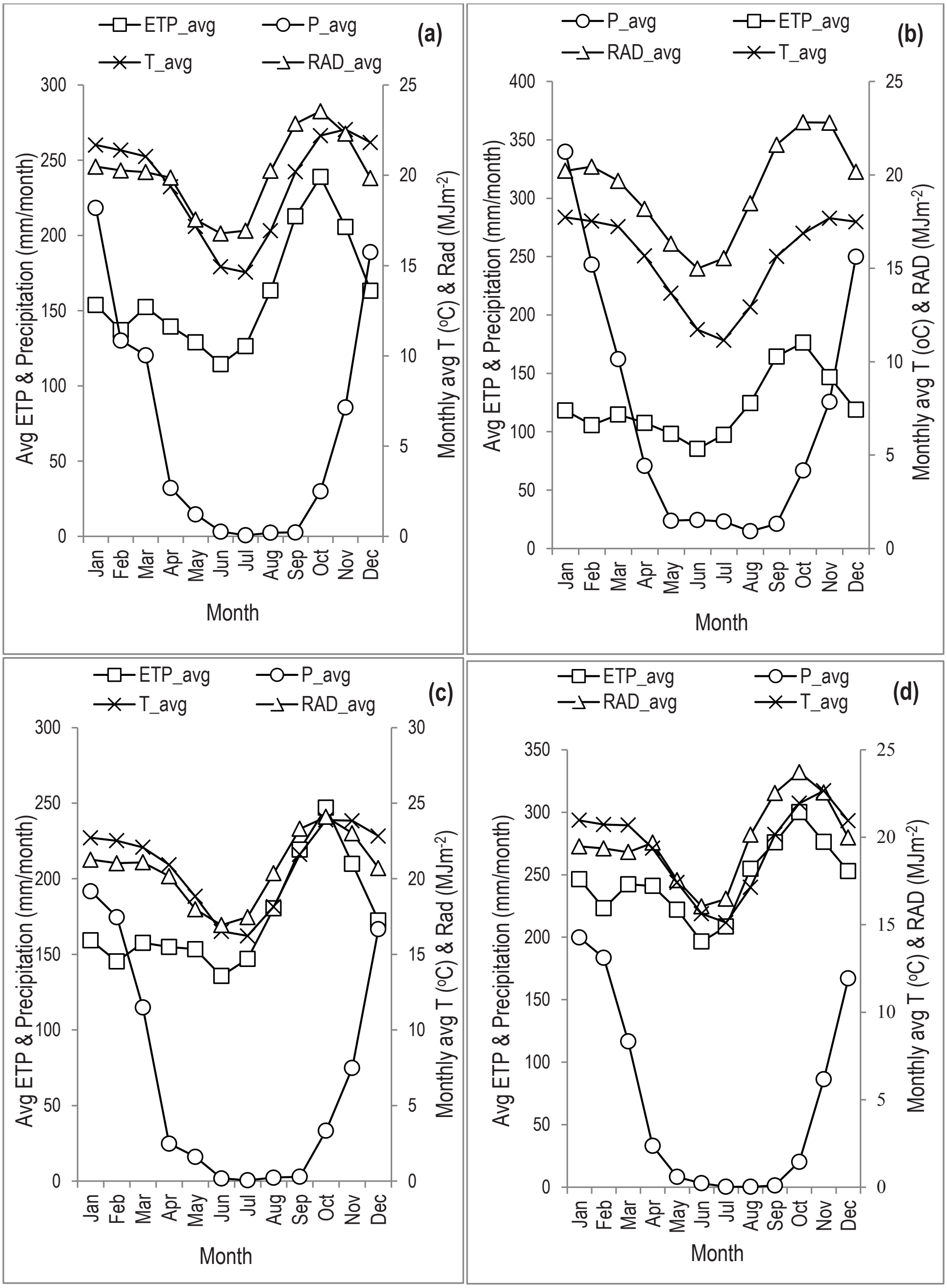

Fig. 3. Monthly average P (precipitation), ETP (evapotranspiration), T (temperature) and RAD (radiation) for (a) Harare, Bindura and Chegutu Highveld areas; (b) Nyanga Eastern Highlands; (c) Chinhoyi and (d) Karoi Highveld areas of Zimbabwe, using climatic data of the period 1985 to 2010.

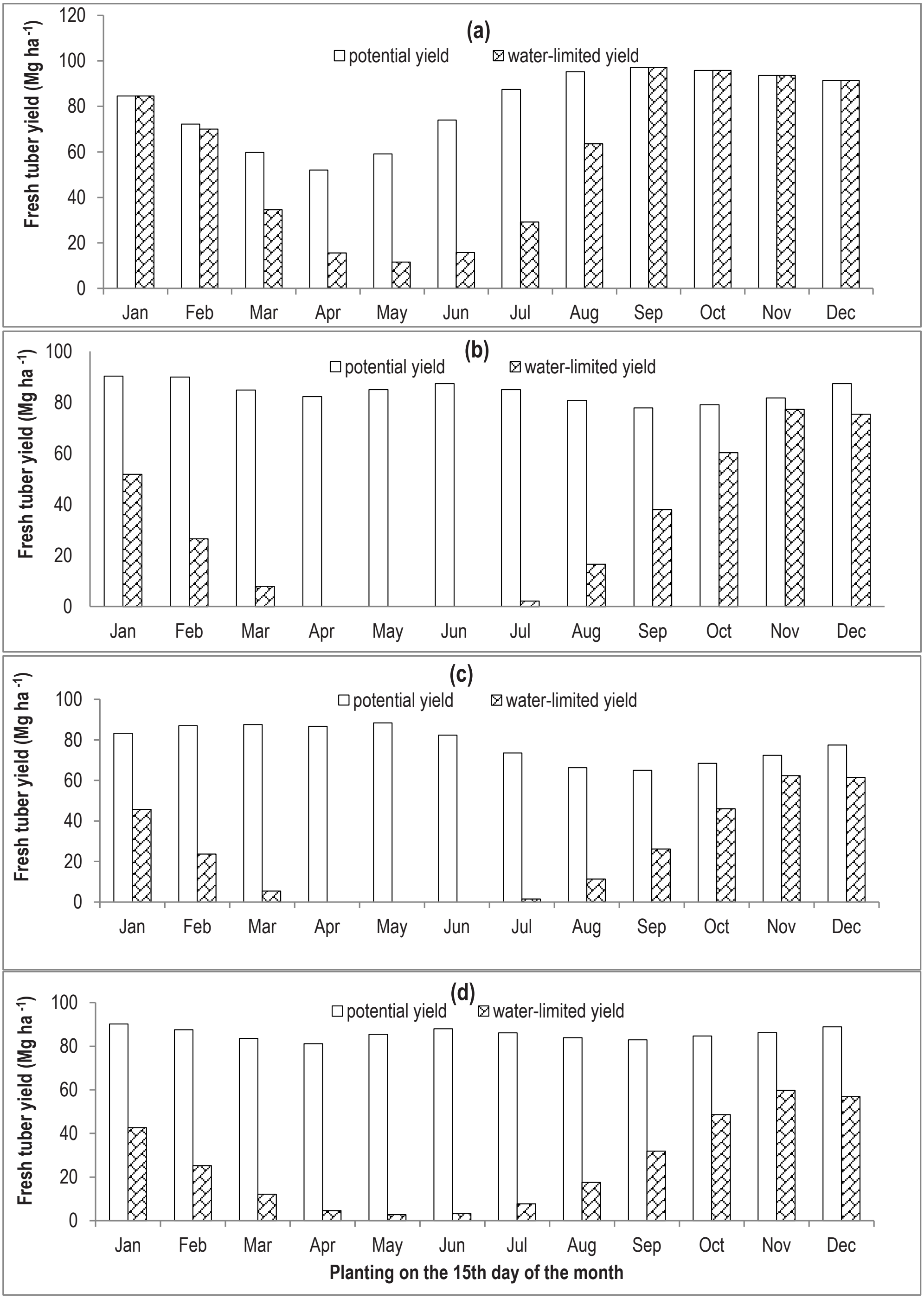

Fig. 4. Simulated potential and water-limited potato yield in Nyanga Eastern Highlands (a), Harare, Bindura and Chegutu (b), Chinhoyi (c), and Karoi (d) Highveld agro-ecological zones of Zimbabwe using average climatic data from 1985 to 2010.

Using the 26 years long weather data from 1985 through 2010, Karoi zone located in the Highveld had the highest mean monthly evapotranspiration of 245 mm (Fig. 3d) indicating a high atmospheric evaporative demand. Consequently, Karoi zone had the highest simulated irrigation need compared to the other zones in the study area. Predictably the lowest irrigation water applied was in the Nyanga Eastern Highlands (316 mm) because of the humid and high rainfall conditions experienced there thus decreasing the supplementary irrigation need. However, the high irrigation application observed (750 mm) in the Nyanga Eastern Highlands was unexpected; this was explained by the fact that the majority of the growers' irrigation systems are gravity-fed incurring no energy costs, hence the tendency to over-irrigate. Comparing with the simulated irrigation need, all growers generally over-apply water (Fig. 6a). For example, the simulated irrigation need in the Nyanga Eastern Highlands was 141 mm but growers applied more than 5 times of the water needed (Fig. 6a). Similar cases have been reported in Chile by Haverkort *et al*. (2014) where growers applied twice the amount of the calculated water need, and that the practice is common in most parts of the world where adequate irrigation water is easily available.

The actual water use efficiency based on irrigation only, being the ratio between the actual fresh potato yield and the amount of water supplied by irrigation was significantly different ($p < 0.05$) among the production systems (Table 1). Fig. 6b shows the water use efficiency based on irrigation water and rainfall, which ranged from 2 to 6 g potato l^{-1} in the Nyanga Eastern Highlands and the Chinhoyi Highveld zones respectively. On the other hand, the potential water use efficiency from irrigation and precipitation ranged from 9 to 17 g potato l^{-1} (Fig. S2, in Supplementary material). The huge gap observed between actual and potential water use efficiency shows the scope to improve crop management practices to increase actual yield while lowering irrigation water when necessary. The model simulations of water use efficiency based on irrigation gave high water use efficiency in summer plantings in all the agro-ecological zones (Fig. S3, in Supplementary material). This is because less irrigation water was applied as the summer precipitation received met most of the crop water requirements. Highest water use efficiency estimated was 958 g potato l^{-1} for October plantings in the Nyanga Eastern Highlands (Fig. S3), when most crop water requirements was met from rainfall received. The water use efficiency was lowest in the dry winter period when more irrigation was applied.

3.4 Nutrients footprint

A wide variation in mineral fertiliser application rate among all the sample growers was observed and it ranged from 94–272 kg N/ha, 91–369 kg P_2O_5/ha, and 90–396 kg K_2O/ha (Fig. 2). The average application rates were 180, 267 and 245 kg/ha of N, P_2O_5 and K_2O, respectively, which were higher than the average rates reported in neighbouring South Africa of 170 kg N/ha, 160 kg P_2O_5/ha and 120 kg K_2O/ha (FAO, 2005). The general fertiliser recommendation advised by the agricultural extension agency for potato production in Zimbabwe is 120, 280 and 180–240 kg/ha of N, P_2O_5 and K_2O, respectively for an average yield of 30 t/ha (Joyce, 1982; Manzira, 2011). Large scale commercial and A2 resettlement production systems generally use rates exceeding the general recommendations. Perhaps this caters for micro-climate and soil differences or is an insurance in the absence of soil analysis. Most of the sampled growers do not have soil tests to determine pH and background soil nutrition. Phosphate (P_2O_5) and potash (K_2O) nutrient use efficiencies were not significantly different ($p < 0.05$) among the production systems (Table 1), but nitrogen (N) use efficiency was. Nitrogen use efficiency ranged from 97 to 162 g potato g^{-1} N (Table 1). In a similar study in South Africa's Sandveld area, a nitrogen use efficiency range of 106–228 g potato g^{-1} N was reported (Franke *et al.*, 2011). This range is generally on the higher side compared to that recorded in the Zimbabwean case. Low nutrient use efficiencies may imply low crop yields or high fertiliser application rates and the risks of nutrients waste. The same study in South Africa reported mean potato actual yields of 45 Mg ha^{-1} and a range between 36 and 58 Mg ha^{-1} (Franke *et al.*, 2011), whereas in the Zimbabwean case, the potato actual yields averaged 19 Mg ha^{-1} and ranged from 8 to 28 Mg ha^{-1} (Table 1). Against the backdrop of high fertiliser application rates in Zimbabwe (Fig. 2) and the low potato actual yields, the inefficient fertiliser use in the Zimbabwean case is apparent. The range in P use efficiency was 93–105 g potato g^{-1} P_2O_5 and K use efficiency range was 97–123 g potato g^{-1} K_2O (Table 1). The wide range in nutrient use efficiencies reflects the actual yield gap existing among the growers. The source of this yield gap could be in the differences in potential yield and important cultural practices such use of certified seed, fertiliser, irrigation water, pest and disease management.

A Spearman's rank-order correlation test was carried out to determine the relationship between the fresh Irish potato yields and the corresponding nutrient application rate per ha in the different production systems in Zimbabwe. Weak relationships (r_s ranging from 0.01 to 0.35) which were all not statistically significant (Table 2) were observed in the large-scale

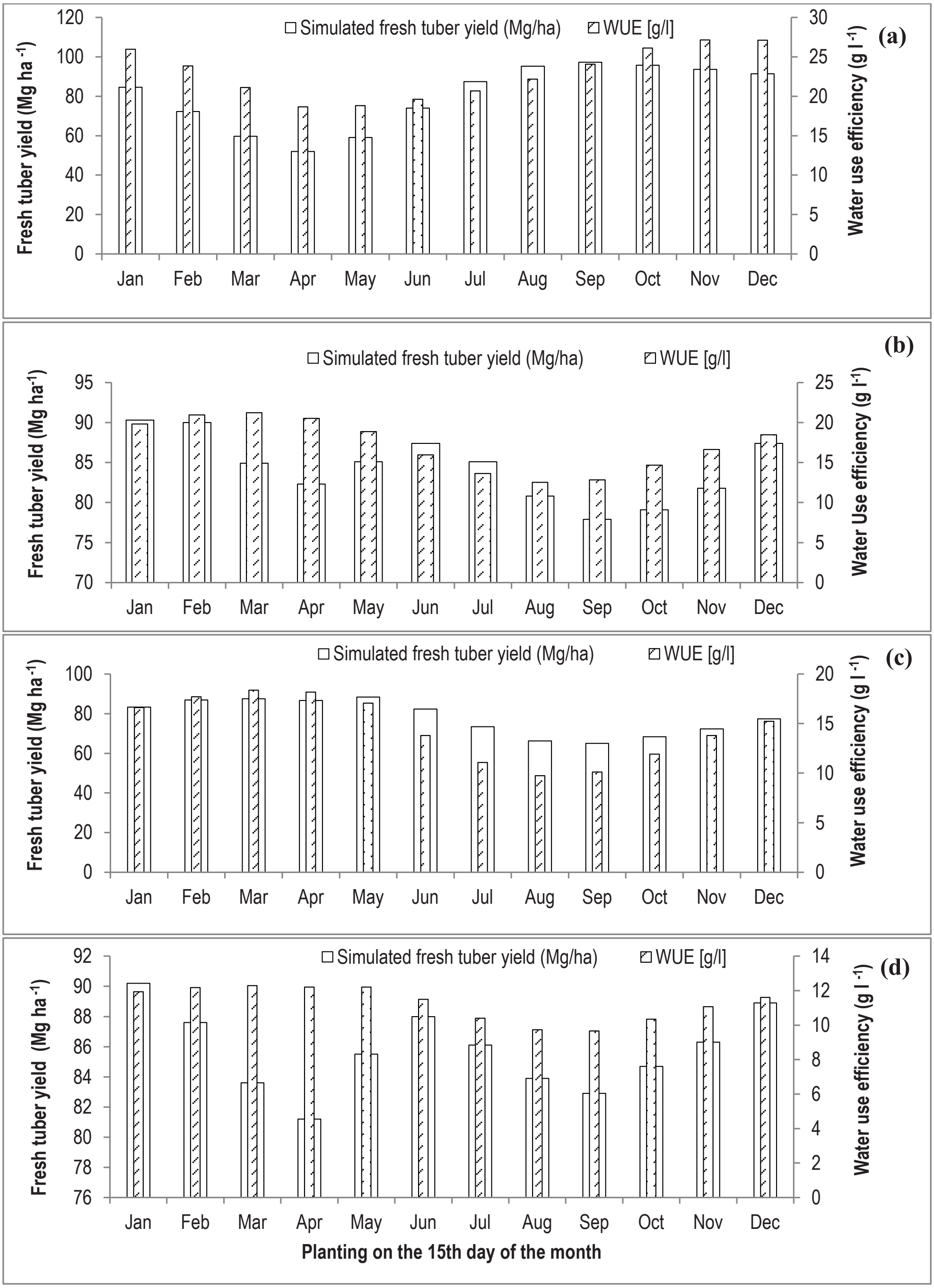

Fig. 5. Monthly simulated potato potential yield (left *y*-axis) and monthly Water Use Efficiency (WUE) based on Evapotranspiration by the crop and soil (right *y*-axis) in Nyanga (a) Harare, Bindura and Chegutu (b) Chinhoyi (c) and Karoi (d) agro-ecological zones of Zimbabwe using average climatic data from 1985 to 2010.

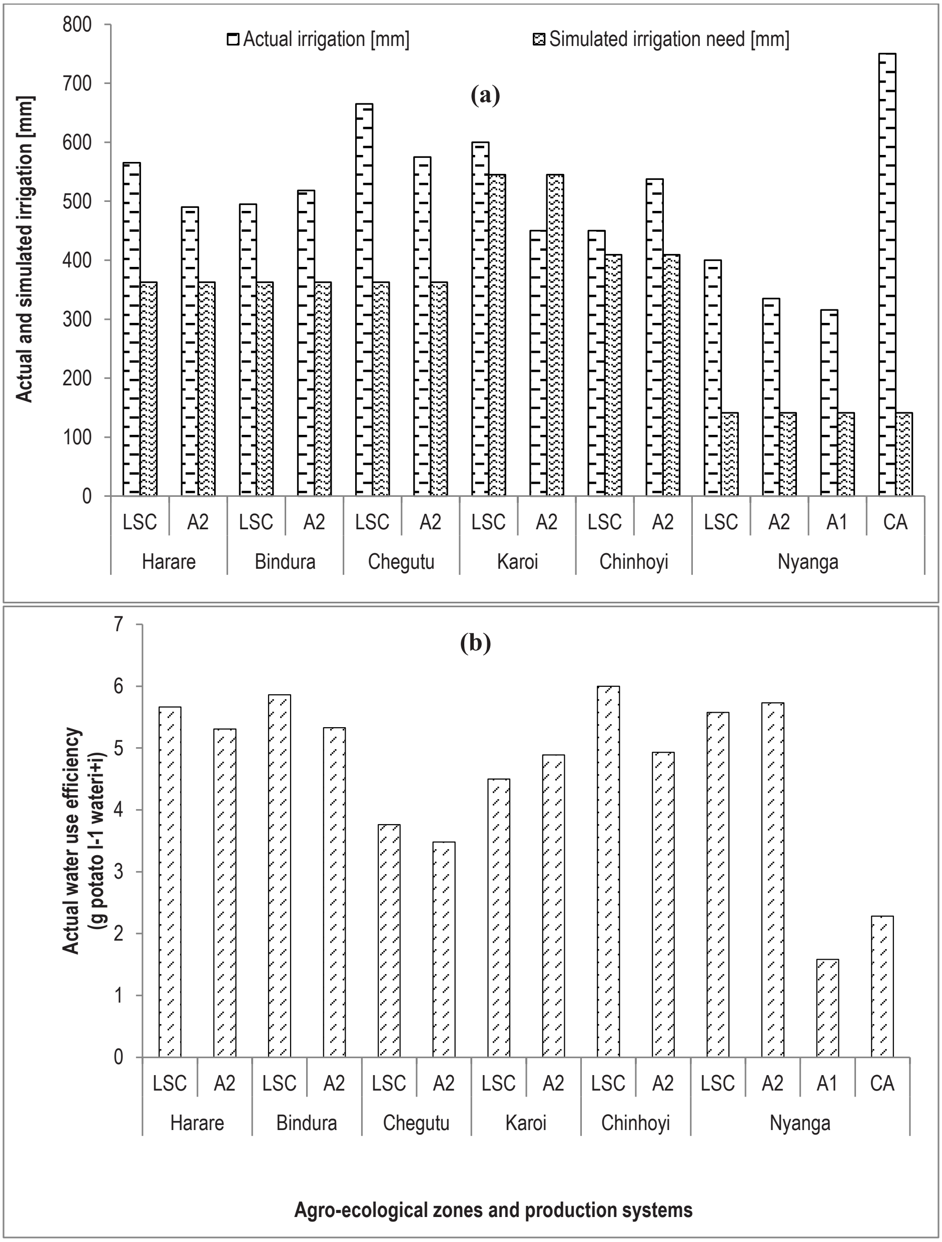

Fig. 6. Actual and simulated irrigation need (a) and actual water use efficiency (fresh yield/(irrigation + precipitation) (b) in different agro-ecological and potato production systems in Zimbabwe

commercial and A2 resettlement production systems. This implies that further increases in nutrient application rate may not result in yield gains, suggesting that probably the nutrient application rates in these high-input production systems were approaching the upper threshold levels. Other management factors besides fertiliser application rate could be more limiting to further yield increases. Hence the large-scale commercial and A2 resettlement growers must focus on the management of these other production resources to allow the maximum utilisation of the fertiliser inputs. This is in agreement with De Wit's assertion that research in agriculture and the environment should not be so much focussed toward the search for marginal returns of variable resources, but should rather focus on the search for the minimum of each production resource that is needed to allow maximum utilisation of all other resources (De Wit, 1992). Further, the large-scale commercial and A2 resettlement growers can even reduce the current high nutrient application rates without sacrificing potato yield through more efficient use of the nutrients by the potato crop and reduce losses to the environment (Fig. 2). A similar case was reported by Carberry *et al.* (2013) in the case of Chinese wheat farmers who used high N application rates.

On the other hand, in the smallholder production systems (A1 resettlement and the communal areas), there were strong, positive correlations between the Irish potato yields and the corresponding nutrient application rates (r_s ranged from 0.45 to 0.95) (Table 2). The yield-P_2O_5 and the yield-K_2O relationships in the communal area production systems were both statistically significant ($p < 0.05$) (Table 2). This implies that yield gains are possible in the smallholder production systems with further increases in nutrient application rates and the management of the other needed production resources already mentioned to increase the fertiliser use efficiencies. For example efficient pest and disease management is important. Spiertz (1980) observed that the longer plants remain healthy, the longer the roots remain active, hence nutrient uptake appeared to increase as a result of disease control. Also the use of phosphate to improve the efficiency of use of other available nutrient resources should be investigated (De Wit, 1992). Other important factors are the use of certified seed of high-yielding cultivars with greater stress tolerance, use of better fertilizers products, and better application methods (Dobermann, 2005). Higher yields were reported through a mix of these management measures with either maintaining or reducing N use (Dobermann, 2005). Hence it appears there is scope to increase potato yield in these production systems without necessarily increasing the already high nutrient application rates.

Meanwhile, the average actual potato yield in the communal area system of 17 t/ha (Table 1) is comparable to that in the large-scale commercial and A2 resettlement systems but with lower fertiliser application rates. Irish potato is a traditional and staple food crop with a

Table 2. Spearman rank-order correlation analysis of the fresh Irish potato yields and the corresponding nutrient application rate per ha in the different production systems in Zimbabwe, 2011–2014.

	Production system														
	Large-scale commercial				**A2 resettlement**				**A1 resettlement**				**Communal area**			
	Mean yield (kg/ha)	Mean nutrient application rate (kg nutrient/ha)			Mean yield (kg/ha)	Mean nutrient application rate (kg nutrient/ha)			Mean yield (kg/ha)	Mean nutrient application rate (kg nutrient/ha)			Mean yield (kg/ha)	Mean nutrient application rate (kg nutrient/ha)		
		N	P_2O_5	K_2O		N	P_2O_5	K_2O		N	P_2O_5	K_2O		N	P_2O_5	K_2O
	28	181	284	301	23	197	270	218	8	94	91	90	17	143	185	137
Test statistics																
n			15				23				5				18	
r_s		0.01	-0.35	-0.08		0.35	0.30	0.08		0.95	0.91	0.64		0.45	0.52	0.70
t-stat.		0.03	-1.33	-0.29		1.70	1.44	0.35		4.23	3.05	1.17		1.99	2.46	3.90
t-crit.		2.16	2.16	2.16		2.08	2.08	2.08		4.30	4.30	4.30		2.12	2.12	2.12
p		0.98	0.21	0.78		0.11	0.16	0.73		0.05	0.09	0.36		0.06	0.03	0.001
sig.		ns	ns	ns		ns	ns	ns		ns	ns	ns		ns	*	*

Key: sig. = significant, ns, correlation is not significant at the 0.05 level (2-tailed), *, correlation is significant at the 0.05 level (2-tailed).

long history of cultivation in the communal area sector of the Eastern Highlands. Possibly, the experience accumulated over the years has improved the management of other cultural practices in potato production leading to a more efficient fertiliser use.

3.5 Biocides footprint

Fungicides were the most frequently used biocides in Irish potato production in Zimbabwe in terms of both the number of sprays and quantities applied during the growth cycle of the crop. An average of 34.5 kg active ingredient (a.i.) fungicide per ha and 1.9 kg a.i./ha insecticide were applied during the growing period of the crop across all the production systems (Fig. 2). Also an average of 2.0 and 2.6 kg a.i. per ha herbicides and nematicides respectively was used (data not shown). The mean insecticide, fungicide and nematicide use efficiencies were significantly different ($p < 0.05$) among the production systems (Table 1). The herbicide use efficiency was not significantly different ($p > 0.05$) among the production systems (Table 1). The potato crop rotations practised by the growers could possibly have an impact on the insect and disease management. These rotations depended on the land holding available to the different production systems. From the growers' survey (data not shown), cropping area in the large-scale commercial and A2 resettlement production systems was in the range 17–900 ha and 16–33 ha, respectively. Potato area per planting range was 3 to 25 ha in the large-scale commercial and 1 to 23 ha in the A2 resettlement production system. Due to the large land holdings available to both systems, growers could all practice a minimum of 3 years potato rotation against a minimum of 4 years generally recommended by the agricultural extension agency. The average potato area per planting was 0.4 in the A1 resettlement and 1.1 ha in the communal area production system. Both smallholder production systems practised 1-year potato rotation, most probably due to the limitations of cropping land available. Possibly, this partly explains the significant difference in the mean fungicide ($p < 0.05$) and insecticide ($p < 0.001$) use efficiencies observed (Table 1).

A Spearman's rank-order correlation test was carried out to determine the relationship between the fresh Irish potato yields and the corresponding biocide application rate per ha in the different production systems in Zimbabwe. Weak yield-fungicide application rate relationships were observed both in the large-scale commercial ($r_s = 0.29$) and in the A2 resettlement ($r_s = 0.36$) production systems (Table 3). This indicates that further increases in fungicide application rate gives only marginal yield gains suggesting that the high-input production systems were approaching optimal or near optimal fungicide use. There were strong yield-fungicide application rates correlations in the smallholder A1 resettlement (r_s = -0.94) and communal area ($r_s = 0.76$, $p < 0.05$) production systems (Table 3). In the communal area production system, growers have an opportunity for significant potato yield increases through improving both the fungicide application rates and the management of other production resources. In the A1 resettlement production system, the strong negative correlation between yield and fungicide application rate suggests that increases in fungicide application rates are not warranted because of the depressed yield levels of only 8 t/ha (Table 3). Rather, growers should focus on the management of other production resources already alluded to for them to realise yield gains.

On the yield-insecticide application rates relationships, strong positive correlations were observed in all the production systems except in the large-scale commercial (Table 3). In the latter (large-scale commercial) production system, insecticide use has approached the upper threshold levels and that further increases result in only marginal yield gains. In the other production systems (A1, A2 and communal areas), insecticide use increases result in substantial yield gains. However, all the sampled growers across all the production systems were not aware of the concept of Integrated Pest Management (IPM). Hence there is scope to reduce biocide application rates while maintaining or even improving yields and consequently the biocide use efficiency through application of the IPM concept.

4. Conclusions and recommendations

Important conclusions were derived from the study of the resource footprints of Irish potato production systems in Zimbabwe. First, a wide yield gap of over 77 % was reported in the actual yields obtained by the growers in the country. Second, at least 65 to 92 % yield gap exists between the simulated potential yield and the actual yields reported by the growers. Hence a tremendous opportunity exists to increase potato production in the country by narrowing the yield gaps through increasing actual yields. The sustainable intensification approach is recommended. It is further recommended that reliance on government may not be helpful now and into the medium term because of the socio-political and economic challenges the country is experiencing. Hence the rest of the key stakeholders must work toward improving accessibility to inputs such as fertilisers, biocides and high yielding seed varieties

Table 3. Spearman rank-order correlation analysis of the fresh Irish potato yields and the corresponding nutrient application rate per ha in the different production systems in Zimbabwe, 2011–2014.

	Production system											
	Large-scale commercial			**A2 resettlement**			**A1 resettlement**			**Communal area**		
	Mean yield (kg/ha)	Mean biocide application rate (kg a.i./ha)		Mean yield (kg/ha)	Mean biocide application rate (kg a.i./ha)		Mean yield (kg/ha)	Mean biocide application rate (kg a.i./ha)		Mean yield (kg/ha)	Mean biocide application rate (kg a.i./ha)	
		Fung.	Insect.		Fung.	Insect.		Fung.	Insect.		Fung.	Insect.
	28	34.06	2.55	23	38.68	1.45	8	17.10	1.03	17	28.05	1.22
Test statistics												
n		15			23			5			18	
r_s		0.29	0.28		0.36	0.62		-0.94	0.63		0.76	0.83
t-stat.		1.07	1.04		1.77	3.66		-4.00	1.16		4.69	5.94
t-crit.		2.16	2.16		2.08	2.08		4.30	4.30		2.12	2.12
p		0.30	0.32		0.09	0.001		0.06	0.37		0.0002	0.0000
sig.		ns	ns		ns	**		ns	ns		**	**

Key: Fung.= fungicide, Insect. = insecticide, ns, correlation is not significant at the 0.05 level (2-tailed), *, correlation is significant at the 0.05 level (2-tailed), **, correlation is significant at the 0.01 level (2-tailed).

by growers. Third, the study identified planting months giving high yield potential which growers can exploit. These were November through July plantings in the Highveld, and plantings in September through January in the Eastern Highlands, although supplementary irrigation will be needed. The same planting months also coincide with the best potential water use efficiencies. Fourth, the huge gap observed between actual and potential water use efficiency shows the scope to improve crop management practices to increase actual yield while lowering irrigation water when necessary. And finally, all the growers were not aware of the concept of Integrated Pest Management (IPM). Hence learning and applying the IPM concept could improve the biocide use efficiency through lowering biocide application rates while maintaining or even improving yields.

For future studies, there is need to explore the possibilities to expand potato production frontiers beyond the major growing environments studied using modelling and long term climatic data. Through this and other ways, Irish potato will assert itself as indeed a strategic national food security crop in Zimbabwe.

Acknowledgements

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Supplementary material: Simulated water use efficiencies and potential yield.

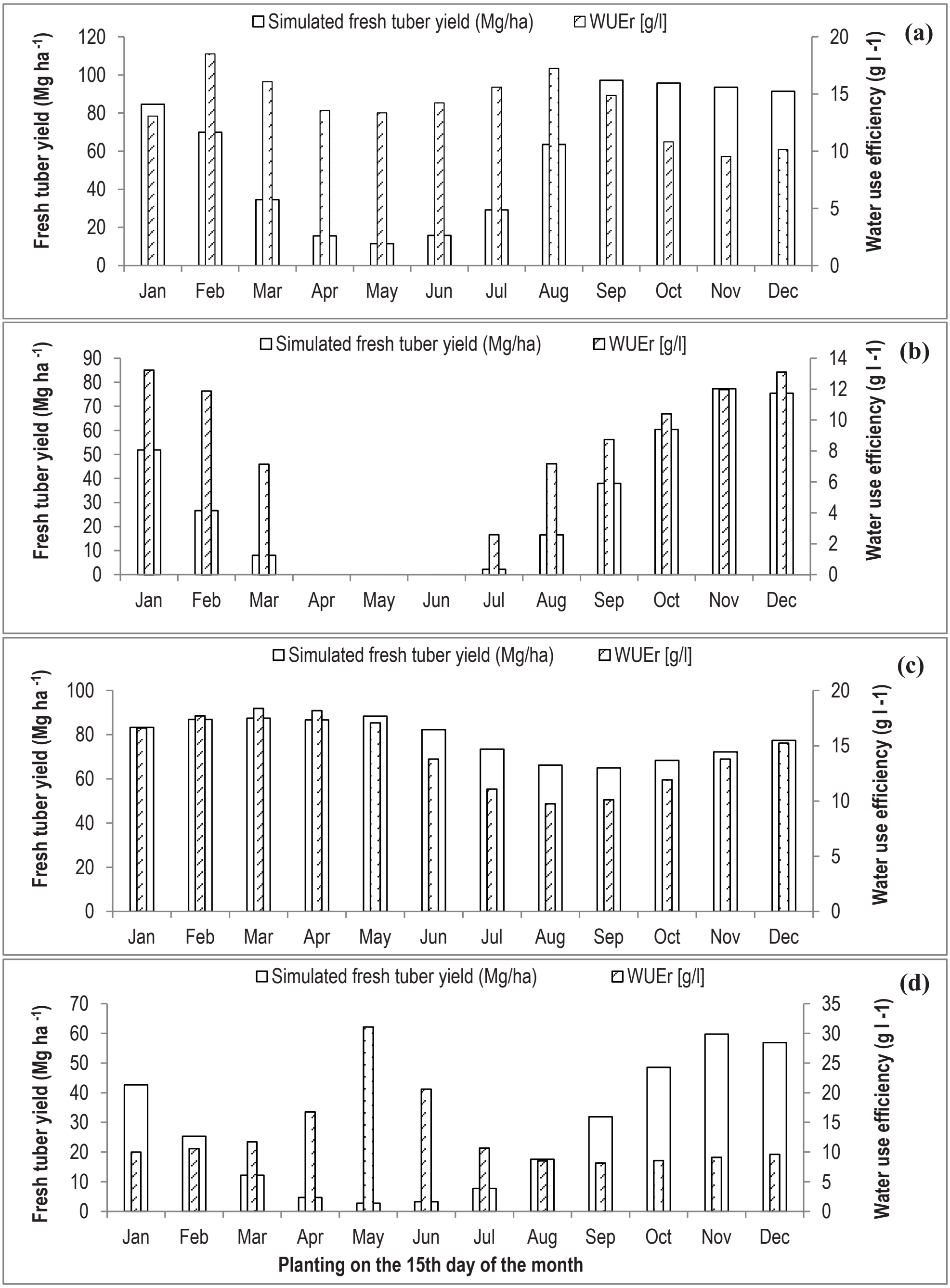

Fig. S1. Monthly simulated potato potential yield (left *y*-axis) and monthly Water Use Efficiency (WUE) based on rainfall (right *y*-axis) in Nyanga (a) Harare, Bindura and Chegutu (b) Chinhoyi (c) and Karoi (d) agro-ecological zones of Zimbabwe using average climatic data from 1985 to 2010.

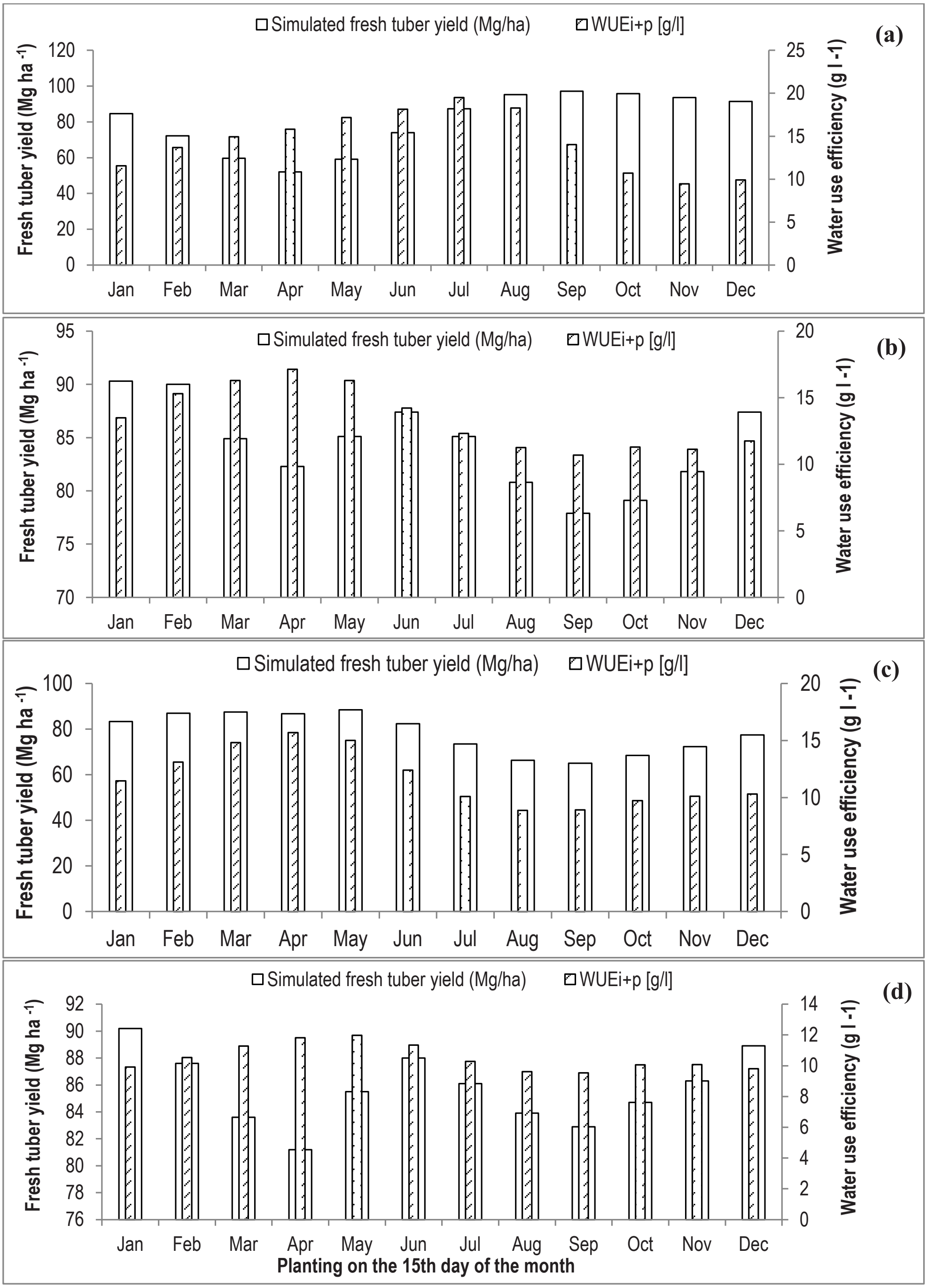

Fig. S2. Monthly simulated potato potential yield (left *y*-axis) and monthly Water Use Efficiency (WUE) based on irrigation and precipitation (right *y*-axis) in Nyanga (a) Harare, Bindura and Chegutu (b) Chinhoyi (c) and Karoi (d) agro-ecological zones of Zimbabwe using average climatic data from 1985 to 2010.

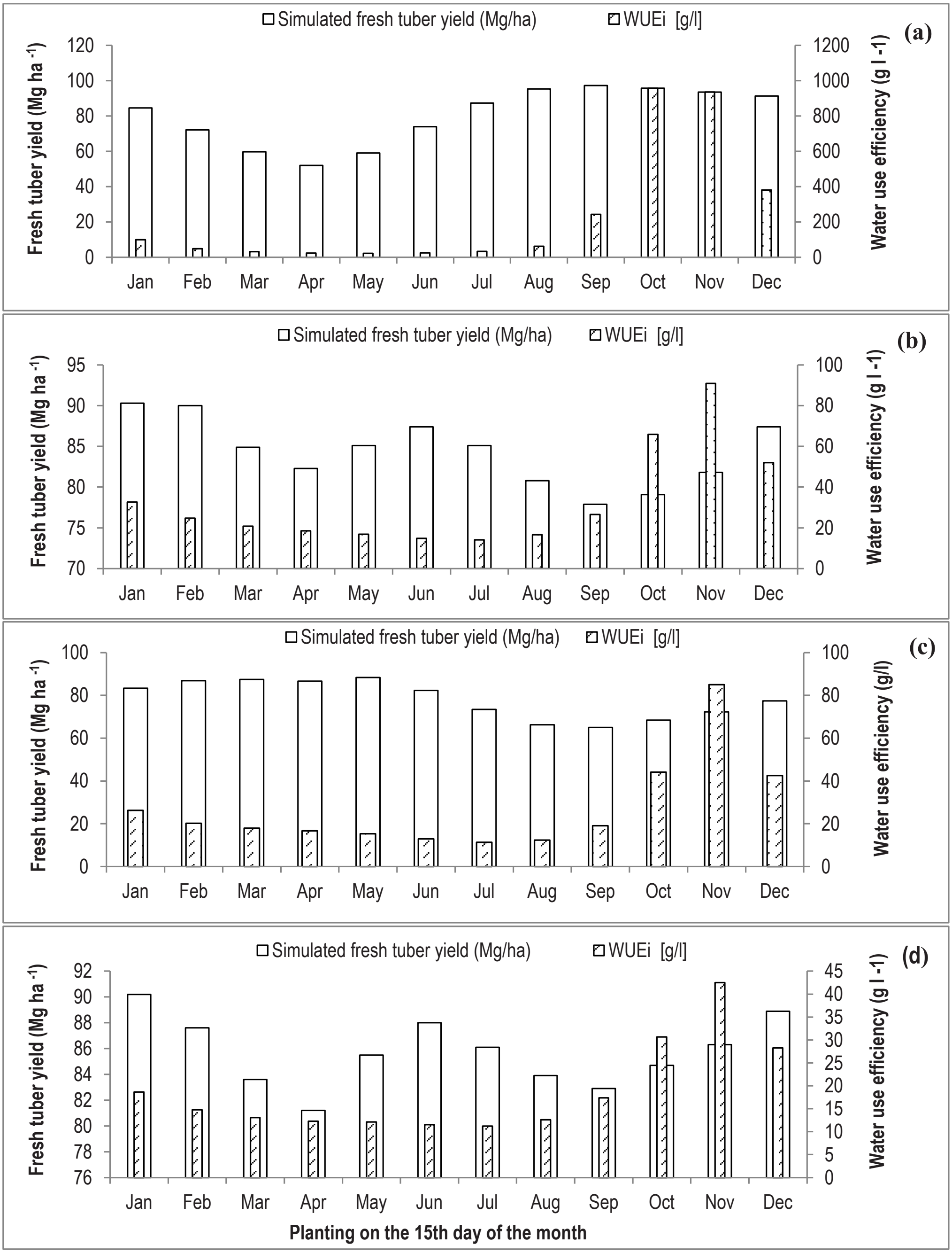

Fig. S3. Monthly simulated potato potential yield (left *y*-axis) and monthly Water Use Efficiency (WUE) based on irrigation (right *y*-axis) in Nyanga (a) Harare, Bindura and Chegutu (b) Chinhoyi (c) and Karoi (d) agro-ecological zones of Zimbabwe using average climatic data from 1985 to 2010.

Chapter 4

Carbon footprinting of Irish potato production systems in Zimbabwe

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Abstract

Agriculture contributes significantly to the world greenhouse gas (GHG) emissions. Farmers need to fine-tune agricultural practices to balance the trade-off between increasing productivity in order to feed the growing global population and lowering GHG emissions to mitigate climate change and its impact on agriculture. Major emission sources in cropping include manufacture and use of synthetic fertilisers and biocides, fossil fuel combustion in tractor use, soil-related emissions, and other practices. We conducted a survey on the major cultural practices in four potato production systems identified in Zimbabwe. These are the large scale commercial, communal area, A1 and A2 resettlement production systems. The resettlement production systems were formed from the radical Fast Track Land Reform Programme initiated in 2000, which completely changed the landscape of commercial agriculture in Zimbabwe. The A1 resettlement model resembles the communal area system with about 6 ha arable land per household and communal grazing land. The A2 resettlement model is similar to the privately owned large scale commercial farms but with smaller farm units of about 35 to 300 ha depending on the agro-ecological region. We used the survey data as input into the 'Cool Farm Tool-Potato' model. The model calculates the contributions of various production operations to the total GHG emission. Experienced growers were targeted and all had a good knowledge of their cultural practices. The average carbon footprint calculated was 251 kg CO_2 eq./t potato harvested, ranging from 216 to 286 kg CO_2 eq./t in the communal area and A2 resettlement production systems, respectively. The major drivers of the GHG emissions were fertiliser production and soil-related field emissions, which together accounted for on average 56 % of the total emissions across all the production systems. On a per-hectare basis, significant differences in total emissions were found between the four potato production systems. The total GHG emissions ranged from 1,946 to 6,211 kg CO_2 eq./ha in the A1 resettlement and large scale commercial production systems, respectively. Although mitigation options were not assessed, the model output displays the factors/farm operations and their respective emission estimates consequently allowing the grower to choose the inputs and operations to reduce the carbon footprint. Opportunities for benchmarking, as an incentive to improve emission performance, exist given the large variation in GHG emission among growers.

Key words: GHG emission, Irish potato, benchmarking, climate change mitigation, Cool Farm Tool-Potato, Zimbabwe.

1. Introduction

Agriculture faces the great challenge of increasing food production to meet the demands of a growing population projected to reach 9–10 billion by 2050, while at the same time decreasing agriculture's global environmental footprint (Bellarby *et al.*, 2014). In the developing countries, such as those in sub-Saharan Africa, rates of input use, especially mineral fertilisers for major cereal crops, are generally low thereby limiting yield (Mueller *et al.*, 2012). Opportunities therefore exist to increase crop yields in this region through increases of nutrient application rates. However, increasing synthetic fertiliser application rates on the underperforming farmlands will come at a cost by also increasing greenhouse gas (GHG) emissions (Bellarby *et al.*, 2014). The agricultural sector is estimated to have contributed about 10–12 % to global anthropogenic GHG emissions in 2005, and about 50 and 60 % of methane and nitrous oxide gas emissions, respectively (Smith *et al.*, 2008). Greenhouse gas emissions from agriculture are projected to increase further, with the highest emission growth rates anticipated in sub-Saharan Africa due to increased livestock populations and synthetic fertilisers use (Reay *et al.*, 2012). There is a need to increase food production, but there is equally a need to minimise the negative environmental impact of GHG emissions. This strategy, approach or process whose precise definition is subject to considerable debate has been termed *sustainable intensification* or *ecological intensification* (Struik and Kuyper, 2014; Garnett *et al.*, 2013). Struik and Kuyper (2014) argue that intensification could be viewed as a transitional process from agricultural practices generally accepted as unsustainable to those regarded as environmentally sustainable production practices. Applying this term in practice requires the quantification of the carbon footprint per unit of product or per unit cropped area while maintaining a record of input use, cultural practices and output to enable the assessment of production practices. The knowledge of the emission sources will assist in the determination of potential, 'climate smart' mitigation approaches. Moreover, such knowledge of the emission sources and their respective estimates will allow for benchmarking, where growers can compare their scores or performance against other growers at the local, regional, and national levels. Benchmarking uses the variation among growers on selected performance indicators as leverage or incentive to stimulate inter-farm competition and therefore continuously improve indicator performance (De Snoo, 2006). In this study, the carbon footprint of the different Irish potato production systems in Zimbabwe was assessed. Irish potato production in Zimbabwe is capital intensive (The

Herald, 2011). It is normally grown under full or supplemental irrigation often using underground water sources, thereby incurring huge pumping energy and the associated carbon costs. The general synthetic fertiliser recommendations are 120, 123, and 149 – 199 kg/ha of N, P, and K, respectively, for an average yield of 30 t/ha (FAO, 2006; Manzira, 2011). This fertiliser recommendation is much higher than the rates used in other countries in the region. For example, the recommended rates in Kenya were 90 kg N/ha and 101 kg P/ha (Kaguongo *et al*., 2008); in South Africa 170 kg N/ha, 70 kg P/ha and 100 kg K/ha (FAO, 2005) and in Ethiopia 110 kg N/ha, 18 kg P/ha and 83 kg K/ha (Haile and Mamo, 2013). Irish potato has been selected as the pilot crop in this case study because of the cultural practices that involve extensive soil disturbances such as deep ploughing, disc harrowing to achieve a fine tilth seedbed, and two or three ridging operations. These practices tend to stimulate soil carbon losses through enhanced decomposition and erosion (Saggar *et al*., 2011). In addition, agricultural extension services recommend generous fertiliser applications which may not always be efficiently used by the crop (FAO, 2006). Another routine practice is frequent (sometimes weekly) fungicides and insecticides sprayings. Svubure *et al.* (2015) discusses the general cultural practices employed by potato growers in Zimbabwe. In recent years, interest in potato growing and consumption has been on the rise (The Herald, 2011), and that led the government of Zimbabwe to declare Irish potato a national strategic food security crop on 18 May 2012 (The Herald, 2012). Irish potato is now included in the government-led input support programmes similar to that given to the other staple crop, maize. For example, seed potato growers will now be included in government initiated mechanisation and irrigation development programmes to boost their capacity. The potato industry will also be protected against unregulated potato imports into the country (The Herald, 2012). In the medium term, the country envisages to increase potato planting to about 30,000 ha annually (USAID-STAMP, 2011; The Herald, 2011; Ackerman, personal communication, 2013), up from a cropping area of about 3,500 ha reported in 2013 (FAOSTAT, 2013).

The main potato growing areas in the country are the Highveld and the Nyanga Eastern Highlands regions. The Highveld is a gently undulating plateau at altitudes above 1,200 m amsl (above mean sea level) covering about 25 % of the country's total area of nearly 390,000 km^2. This region experiences a variable climatic pattern but is generally characterized by mild winters from May to September and hot summers from November to March. Long term monthly average temperatures range from 15 °C in June/July to 23 °C in October/November. Precipitation mostly occurs in the summer months and averages around

750 to 900 mm. The Highveld region is suitable for intensive farming systems based on crops and livestock production. The Nyanga Eastern Highlands at higher elevations greater than 1,800 m amsl, comprises less than 5 % of the country's total area. The high elevation gives the region a temperate climate and vegetation. While some precipitation is received in all months of the year, the rainy season normally begins in October extending into April, making it the longest in the country. Annual precipitation exceeds 1,000 mm per annum which is the country's heaviest. Average monthly mean temperature ranges from about 11 °C in July to 18 °C in October. The favourable temperature and rainfall pattern enables the region to practise specialised and diversified farming that includes forestry, tea and coffee plantations, horticultural crops, and intensive livestock production. In both regions, irrigated potato is generally grown throughout the year. However, the following growing seasons are common: summer (November through March/April), early winter (February through May/June) and a late winter crop planted in June/July or early August in frost-prone areas and harvested in November/December. While growers use a range of soils for potato production in Zimbabwe, the medium textured loamy soils are commonly preferred.

Four production systems for Irish potato can be identified in Zimbabwe (Svubure *et al.*, 2015). These are the large scale commercial, communal area, A1 and A2 resettlement production systems. The A1 and A2 resettlement production systems were formed from the radical Fast Track Land Reform Programme (FTLRP) initiated in 2000, which completely restructured commercial agriculture in Zimbabwe. About 96 % of the original 12.5 million ha large-scale commercial farmland in 1980, was taken up for resettlement by 2010 (Moyo, 2011). The A1 resettlement model resembles the communal area system. Each A1 resettlement beneficiary household was allocated about 6 ha arable land for cropping and grazing land was communally owned. The government extension agency, the Agricultural, Technical and Extension Services (Agritex), estimates that there are more than 700 A1 resettlement potato growers contributing about 5 % of the estimated 4,000 ha potato annually planted. However, the majority of them were irregular, on and off growers. Experienced A1 resettlement production system growers with a minimum of 5 years continuous potato farming were only identified in the Nyanga Eastern Highlands (Svubure *et al.*, 2015). Agritex officials estimate their number to be less than 100. The communal area potato-based cropping system is similarly limited to the (Nyanga Eastern Highlands) where over 1,500 households plant about 800 ha potato annually (Svubure *et al.*, 2015). While both are smallholder potato-based cropping systems employing animal-drawn equipment for potato production, the communal area system is long established since potato is the staple food crop in this area. Both systems frequently employ gravity-fed irrigation systems hence benefiting large savings in irrigation energy costs (Svubure *et al.*, 2015). Due to the long history of potato cultivation, the communal area growers have consequently gained experience and improved management practices of the crop than the recent A1resettlement growers. Another production system is the A2 resettlement. The A2 resettlement model resembles the privately owned large scale commercial farms; however the allocated farm units were smaller ranging from about 35 to 300 ha depending on the agro-ecological region (MLRR, 2009). The A2 resettlement production system has limited potato growing experience, but the majority of growers have invested in irrigation facilities and mechanised potato production (Svubure *et al.*, 2015). According to Agritex officials, there are about 400 A2 resettlement potato growers accounting for about 50 % of the annual planted crop. However, about 50 % of the A2 resettlement growers have at least 5 years continuous potato growing experience while the remainder are on and off growers. The large scale commercial production system has a long history of potato cultivation dating back to the early twentieth century (Joyce, 1982). In the process, the large scale commercial growers acquired skills and knowledge of growing the crop consequently improving crop management practices over the years. Of the estimated 2,400 ha crop in 2000 when the land reform programme started, the large scale production systems contributed more than 80 % with the balance grown by the communal area system in Nyanga district (FAOSTAT, 2013). Besides, the large scale potato production system is highly mechanized with irrigation facilities and tractor-drawn equipment for land preparation, planting, spraying, harvesting and potato grading (Rukuni and Eicher, 1994). However, fewer than 400 individually owned white large scale commercial farms remained by 2009, from about 4,500 in 1999 following the agrarian reforms (MLRR, 2009). Less than 50 growers are currently involved in potato production accounting for about 30 % of the current annual planted crop (Svubure *et al.,* 2015).

Total GHG emissions in croplands come from several sources (Hillier *et al*., 2009; 2011). These include loss of carbon from extensive soil movement and turning during land preparation operations, fossil fuel use in the manufacture and use of synthetic fertilisers and biocides, tractor use and irrigation, and from the management of crop residues (Hillier *et al*., 2011). Currently, GHG emission estimates from African agriculture are primarily based on the International Panel on Climate Change (IPCC) emission factor approaches (Hickman *et al*., 2011). Such guidelines may not properly account for the site-specific field level farmer management practices (Hickman *et al*., 2011; IPCC, 2006). The alternative approach is the use of statistical and process-based models which require model input data such as soil profile characterisation and weather data (Hickman *et al*., 2011). Such data is largely insufficient or unavailable in Zimbabwe and in most sub-Saharan African countries (Quiroz *et al*., 2014). Decision support tools that assess the impact of cultural practices on GHG emissions at the farm/field level, enabling the grower to decide on management practices lowering emissions have been recently developed (Hillier *et al*., 2011). This case study used an open source software tool, called the 'Cool Farm Tool' (CFT) (Hillier *et al*., 2011) model to estimate the GHG emissions of the different Irish potato production systems in Zimbabwe and identify practices that contribute the most to the GHG emissions. The CFT-Potato model integrates several globally-determined empirical models and uses them to calculate GHG emissions as CO_2 equivalents (Hillier *et al*., 2011). GHG emission studies in Zimbabwe have been limited to measurements of fluxes of N_2O, CO_2 and CH_4 in experimental plots for cereal or cereal/legume rotations on regular croplands and in some agroforestry systems (e.g., Chikowo *et al*., 2004; Rees *et al.,* 2006; Mapanda *et al*., 2011). So far, no studies on GHG emissions of potato production systems in Zimbabwe have been documented, providing no benchmark to assess future interventions to lower GHG emissions in potato production. The input data for the CFT-Potato model are the inputs and cultural practices growers employ in crop production. Such information is usually readily available especially from experienced growers, hence there is tremendous opportunity to use the CFT-Potato model and grower surveys at a wide scale to identify cultural practices, their GHG emission estimates and potential management approaches for mitigation.

The first objective of this case study was to employ the approach of growers' survey data and use of the CFT-Potato model to distinguish the four potato production systems that appeared after the land reform in terms of yields, inputs and efficient use of energy as reflected in CO_2 balances. We expect the four systems to have very different resource use efficiencies and aim to quantify those differences using the CFT-Potato model. This model is very suitable to assess such differences in efficiency because a) all inputs and operations are dealt with; b) there is no need to measure actual energy use by farmers because the tool already has many conversions embedded; c) by bringing it down to a single figure estimate of GHG emission (e.g., kg CO_2 eq./t), it is immediately obvious which system is most efficient. By looking at the factors most contributing to the GHG emission estimate, the tool allows rapid appraisal of each system. The second objective of our study was to identify practices which contribute the most to the GHG emission and derive from them generic means to make these systems more efficient. Finally the study also aimed to suggest possible mitigation measures to growers of the four distinct potato production systems.

2. Materials and methods

2.1 Study area

A growers' survey was conducted during the period 2011 through 2014. The Nyanga Eastern Highlands and the Highveld, the regions currently active in Irish potato production in Zimbabwe, were targeted for the survey. Covering nearly 117,000 km^2, the extensive nature of the study area coupled with the unpaved road network made access to the growers' farms rather challenging.

2.2 Sampling and data collection

Data was collected on all the major cultural practices employed by the different grower categories in potato production in Zimbabwe. The cultural practices included land preparation, planting, fertiliser use, weed and pest management, water management, energy use and harvesting. Only growers with a minimum of five continuous years of potato growing experience were interviewed. This requirement made the data collected credible because such experienced growers had well-established routine practices such as land preparation, fertiliser application rates, and through harvesting practices. Generally all growers and/or their managers could readily respond to the questions asked on their practices in potato production. Soil samples were also collected mainly for texture, pH, organic matter and NPK analyses. The department of Agritex in each area selected the qualifying growers. Appointments were made in advance and the selected growers were visited for the data collection exercise.

In this study, three large scale commercial growers and four A2 resettlement growers were interviewed from the Quarantine area located in the Nyanga Eastern Highlands region. The Quarantine area is a demarcated area established by a statutory instrument in 1956 when the government started a potato breeding programme (Joyce, 1982). It is responsible for the initial three multiplications of foundation seed to produce grade AA1 through AA3 seed potato. Grade AA3 seed leaves the Quarantine area for further multiplications mainly in the

Highveld to produce grade A1 through A3 seed potato, all of which are used for ware potato production. There are currently 27 growers, both large scale commercial and A2 resettlement in this area and only 21 are active (Ackerman, personal communication, 2012). Outside the Quarantine area, other growers interviewed within the Nyanga Eastern Highlands region were 18 communal area, 4 A1 resettlement, and one of the four remaining large scale commercial growers. In the extensive Highveld, a total of 11 and 14 large scale commercial and A2 resettlement growers respectively were interviewed. The Highveld had no communal area and A1 resettlement growers with the minimum five years continuous potato growing experience. Table 1 gives a summary of the number of growers interviewed.

2.3 Calculation of GHG emission estimates

The CFT-potato model used in this study is the Cool Farm Tool Potato Version 2 derivative as described by Haverkort and Hillier (2011), with entries unrelated to potato production such as livestock and cereal-related operations first removed. The CFT-Potato model was adapted to estimate emissions from the seed material through storage of the harvested potato product.
The model has been constructed from several sub-models. The Ecoinvent database (Ecoinvent, 2007) provided the GHG emissions from the manufacture and distribution of a wide range of fertilizer types. Emissions of nitrous oxide from fertilizer application were estimated using the multivariate empirical model of Bouwman *et al.* (2002) which factors into consideration the fertilizer type, rate, climate and soil characteristics. The NO and NH_3 were based on the FAO/IFA (2001) model. Conversion of NO and NH_3 to N_2O used the 0.01 factor as given in IPCC (2006). Leaching was assumed to occur at a rate of 0.3 times the N value applied for moist climate zones only, and the conversion factor to N_2O of 0.01 is also employed. The CO_2 emissions from soils due to urea and lime application are accounted for using IPCC emissions factors 0.20 and 0.12 respectively (IPCC, 2006). The CO_2 emissions or accumulations in soils depend on climate, soil characteristics, tillage practices and crop residue management (Ogle et al*.,* 2005). The effects of manure and compost addition on soil C stocks are derived from the data of Smith *et al.* (1997). For biocides and crop growth regulators, the tool uses the value 20.5 kg CO_2 equivalent per product application per ha (Audsley,1997). Direct energy usage conversions on farm field operations were taken from ASABE technical standards (ASABE 2006a, b), while the GHG protocol (2003) provided

Table 1. Number of growers per production system interviewed in the Highveld and Eastern Nyanga Highlands regions of Zimbabwe, in the period 2011–2014.

Agro-ecological region	**Sampling area**	**Production system**			
		Large-scale commercial	A2 resettlement	A1 resettlement	Communal area
Nyanga Eastern Highlands	Nyanga Quarantine area	3	4	0	0
	Nyanga district*	1	5	4	18
Highveld	Harare	5	2	0	0
	Bindura	2	5	0	0
	Chegutu	2	2	0	0
	Chinhoyi	1	2	0	0
	Karoi	1	3	0	0
Total		**15**	**23**	**4**	**18**

*Excluding the Quarantine area

country-specific grid electricity emissions. An important feature of the CFT-Potato model is that it has been piloted before on several different farming systems, countries and commodities (Hillier *et al*., 2009; Haverkort and Hillier, 2011; Hillier *et al*., 2011; Cool Farm Tool Institute, 2012; Bellarby *et al*., 2014).

2.4 Data analysis

Individual farm values of greenhouse gas (GHG) emissions from different sources under the different production systems were subjected to analysis of variance (ANOVA) of an unbalanced design using GenStat regression (VSN International, 2011). The agro-ecological regions were treated as blocks. The individual farm GHG emission values from the different sources were due to the treatment (or management) effect of the different production systems. The mean GHG emission values due to the different production systems were separated using the least significance difference (LSD) test at 5 % where the F-test showed significant effects. Further analysis of the relationship between the fresh potato yield in the different production systems and their respective total GHG emissions and N application rates were done using the Spearman Rank Correlation tests and the associated t statistics (Gomez and Gomez, 1984).

3. Results

3.1 Input data to the CFT-Potato model

Tables 2 and 3 summarize the mean values and range of the growers' interview data used as input into the CFT-Potato model. The growers were derived from the four Irish potato production systems in Zimbabwe. Each grower data set was run separately and the mean GHG emissions for each activity were computed for each production system. Due to the wide yield variation (8–28 t/ha) (Table 2) it was advisable to compare the GHG emissions between the systems in both per tonne potato produced as well as on a per ha basis. Growers normally band apply basal fertilizer by hand along the planting furrows opened. When plants are about 4 weeks after emergence (or about 25 cm tall), a nitrogen top-dressing is hand-applied followed by the first ridging which is also done to control weeds. The second ridging is done three weeks later and usually follows a top dressing of sulphate of potash (50 % K_2O) applied by hand as well. A notable practice in potato production in Zimbabwe is the high fertiliser application rates which are not matched with correspondingly high yield levels (Table 2), suggesting inefficient fertiliser use (Svubure *et al.*, 2015). For example, rather high N application rates were recorded even in the smallholder systems which were in the range 45 – 164 and 80 – 244 kg N/ha in the A1 resettlement and communal area systems, respectively (Table 2). The large scale commercial and A2 resettlement growers use tractor-drawn ridgers which require diesel; while A1 resettlement and communal area growers use animal-drawn ridgers requiring no diesel for the operation. Land preparation, spraying and other field operations by large scale and A2 resettlement growers are carried out by tractor drawn implements consuming diesel whereas these operations are done by animal-drawn implements in the smallholder production systems. However, domesticated animals are not carbon neutral. Direct emissions from livestock include CH_4 from enteric fermentation and manure, and N_2O from excreted urine and manure. A recent study in neighbouring Swaziland estimated GHG emissions from livestock at 850 Gg CO_2 eq. in 2010 (Dlamini and Dube, 2014). While animals are important for the smallholder cropping systems for draft power provisions and other uses, the CFT-Potato model does not consider entries not directly related to potato production such as livestock as already alluded to. Including the relatively large contributions of livestock into the computations of GHG emissions in smallholder potato production will potentially confound the estimates. Consequently, the CFT-Potato model is adapted to estimate only emissions from the seed material through storage of the harvested potato product. Ground water (borehole) is the main irrigation water source for large scale commercial and A2 resettlement growers in the Highveld region hence requiring high pumping energy costs. The pumping depths ranged from 10 to 70 m (Table 3). Further increasing the pumping energy costs were the horizontal water conveyance distances. The range was 100 to 850 m and 200 to 1,125 m in the A2 resettlement and large scale commercial systems, respectively (Table 3). In the Nyanga Eastern Highlands, surface irrigation water sources are used and the majority of the irrigation systems are gravity-fed hence growers benefit large savings in pumping energy costs and the associated GHG emissions (Table 3). Also in the Quarantine area, seed potato production is rain-fed only because of the risk of Bacterial wilt from the soil-borne bacterium *Ralstonia solanacearum* from irrigation water sediments. Hence both the large scale commercial and A2 resettlement growers in the Quarantine area do not have irrigation systems and consequently have no irrigation-induced GHG emissions (Ackerman, personal communication, 2012).

Table 2. Crop management, and field energy use data (average, minimum and maximum values) in the four Irish potato production systems in Zimbabwe used as input for the CFT-Potato model.

Input	Large scale commercial		A2 resettlement		A1 resettlement		Communal area	
	avg	range	avg	range	avg	range	avg	range
Farm general information								
Yield (total) (t/ha)	28	12 – 45	23	12 – 36	8	7 – 13	17	8 – 45
Yield (marketed) (t/ha)	26	11 – 43	21	10 – 34	8	7 – 11	16	7 – 43
Seed rate (t/ha)	2.3	2.0 – 2.5	2.2	0.9 – 3.0	1.0	0.6 – 1.5	1.6	0.5 – 3.0
Crop management								
Soil texture	f	f–c	c	f–c	c	c	m	f–c
Soil organic matter (%)	2.6	0.2 – 8.2	2.0	0.2 – 8.6	1.7	0.5 – 4.2	3.2	0.3 – 7.8
pH	5.3	4.3 – 7.1	5.4	4.1 – 7.1	4.6	4.1 – 4.9	4.3	4.1 – 5.0
N	181	60 – 240	197	91 – 360	94	45 – 164	143	80 – 244
P_2O_5	284	144 – 405	270	150 – 627	91	38 – 150	185	75 – 315
K_2O	301	100 – 480	218	64 – 408	90	44 – 120	137	49 – 216
Seed treatments (no. of applications/ha)	1	1 – 1	1	1 – 1	1	1 – 1	1	1 – 1
Soil treatment (nematicide, kg/ha)	20	13 – 30	22	13 – 26	17	17 – 17	20	17 – 25
Biocides (no. of applications/ha)	25	10 – 33	22	14 – 41	11	9 – 14	18	11 – 28
Field energy use								
Fuel type: (diesel/petrol)	diesel	diesel	diesel	diesel	0	0	0	0
Ploughing: Mouldboard (no. opp./ha)	1	1 – 1	1	1 – 1	0	0	0	0
Seedbed preparations (no. opp. /ha):								
Ridging	2	2 – 2	2	2 – 2	0	0	0	0
Disc harrowing	1	1 – 1	1	1 – 1	0	0	0	0
Roller harrowing	1	1 – 1	1	1 – 1	0	0	0	0
Planting furrow opening	1	1 – 1	1	1 – 1	0	0	0	0
Fertiliser spreading	1	1 – 1	1	1 – 1	0	0	0	0
Harvesting:								
Potato windrower (no. of opp.)	1	1 – 1	1	1 – 1	0	0	0	0

Note: f = fine; m = medium; c = coarse; avg = average; no. = number; opp. = operations.

Table 3. Irrigation, on-farm, and off-site transportation data (average, minimum and maximum values) in the four Irish potato production systems in Zimbabwe used as input for the CFT-Potato model.

Input	Large scale commercial		A2 resettlement		A1 resettlement		Communal area	
	average	range	average	range	average	range	average	range
Irrigation:								
Percentage of area irrigated	100	100 – 100	100	100 – 100	0	0	0	0
Irrigation system type	rain gun	rain gun – pivot	rain gun	rain gun – pivot	0	0	0	0
Pumping depth (m)	43	10 -70	30	10 – 70	0	0	0	0
Horizontal water transport distance (m)	615	200 – 1125	361	100 – 850	0	0	0	0
Total irrigation water applied to the area (mm)	550	350 – 720	465	300 – 850	0	0	0	0
Grid electricity use (yes/no)	yes	yes	yes	yes	0	0	0	0
Diesel use (yes/no)	no	no	no	no	0	0	0	0
On-farm transportation per ha								
Average distance: farm house/sheds to fields (km)	6	5 – 8	5	2 – 10	0	0	0	0
Seed transport (t)	2.3	2.0 – 2.5	2.2	0.9 – 3.0	0	0	0	0
Fertiliser transport (t)	1.6	1.0 – 2.2	1.7	0.9 – 3.0	0	0	0	0
Harvested potato transport (t)	27	12 – 45	22	12 – 36	0	0	0	0
Monitoring and supervision (km)	399	315 – 504	307	126 – 630	0	0	0	0
Off-site transportation								
Road transportation (seed, fertiliser, produce) (t)	40	36 – 44	26	23 – 34	2	1– 2	3	2 – 3

3.2 Greenhouse gas emissions per tonne of Irish potato

The average estimated carbon footprint for the four potato production systems was 251 kg CO_2 eq./t potato (Table 4). The least carbon footprint was 216 kg CO_2 eq./t potato for the communal area production system, while the A2 resettlement system had the highest of 286 kg CO_2eq./t potato (Table 4). Recent studies on the Chilean potato cropping systems reported carbon footprints in the range 50 kg CO_2 eq./t potato for a low-input subsistence cropping system at Putre to over 200 kg CO_2 eq./t potato for a high-input La Serena late crop (Haverkort *et al*., 2014). The high level carbon footprint was mainly due to electricity used for pumping irrigation water and high N fertilisation (Haverkort *et al*., 2014). The study further concluded that the estimated mean carbon footprint across all potato production systems in Chile was 122 kg CO_2 eq./t potato, with 35 % contribution from fertiliser production, 25 % fertilizer-induced, and 15 % from seed production (Haverkort *et al*., 2014). These are generally lower than those from the Zimbabwean potato production systems. On the basis of similar studies in the Netherlands, Haverkort and Hillier (2011) reported even lower CO_2 emissions ranging from 77 to 116 kg CO_2 eq./t potato. While the potato production systems and environments cited here are different from those in Zimbabwe, these relatively low CO_2 emissions suggest that there is scope to lower the emissions in the Zimbabwean case. The major driver of the total CO_2 emissions in potato production in Zimbabwe is fertiliser production emissions which accounted for an average of 38 % of the total emissions across all the production systems (Table S1, in supplemental material). Combining fertiliser production with fertiliser-induced emissions, fertilisation accounted for 45–65 % of the total CO_2 equivalent emissions across the four potato production systems (Table S1). Fertiliser usage by potato growers in Zimbabwe is generally on the high rate. For example, while the general nitrogen (N) fertiliser recommendation by agricultural extension service is 120 kg N/ha (FAO, 2006), more than 70 % of the growers interviewed in the study exceed this rate. On average, their N application rate is 154 kg N/ha and the range is 45–360 kg N/ha (Table 2). Fertilisation emission depends on the fertiliser type, application rate and the soil characteristics (Hillier *et al*., 2011). In the communal area production system, fertilisation emission accounts for more than 60 % of the total emissions per tonne fresh potato produced (Table S1). This is mainly due to the high fertiliser application rates applied, coupled by non-emitting operations such as gravity-fed irrigation and the use of animal-drawn equipment. Greenhouse gas emission from animal use in potato production was not included in the

Table 4. Average, minimum, and maximum values of CO_2 costs of producing 1ton potato in the different potato production systems of Zimbabwe, 2011–2014.

Activity	**Production system**							
	Large scale commercial (kg CO_2 eq./t potato)		**A2 resettlement** (kg CO_2 eq./t potato)		**A1 resettlement** (kg CO_2 eq./t potato)		**Communal area** (kg CO_2 eq./t potato)	
	Average	**Range**	**Average**	**Range**	**Average**	**Range**	**Average**	**Range**
Seed production	33	10 – 77	42	11 – 97	38	21 – 69	31	4 – 72
Fertiliser production	83	35 – 167	103	41 – 173	91	57 – 135	100	29 – 154
Background soil N_2O	9	4 – 24	11	4 – 36	28	18 – 32	13	3 – 22
Fertiliser induced field emissions	25	5 – 56	32	10 – 94	32	18 – 48	28	6 – 48
Pesticides	26	11 – 36	31	15 – 50	41	29 – 56	36	10 – 58
Field energy use (excl. irrigation)	8	5 – 14	9	5 – 16	0	0 – 0	0	0 – 0
Irrigation	73	0 – 193	51	0 – 160	0	0 – 0	0	0 – 0
Grading, cooling and storage	0	0 – 0	0	0 – 0	0	0 – 0	0	0 – 0
Off-site transport	0.4	0 – 1	0.5	0.2 – 0.8	0.5	0 – 1	0.5	0 – 1
Cover crop and residue management	5	3 – 8	5	4 – 8	11	8 – 12	7	3 – 11
Total	**263**		**286**		**240**		**216**	

Key: eq. = equivalent; excl. = excluding.

computations. Data on the time animal draft power was allocated to potato production versus the time allotted to other possible animal-driven farm activities was not collected in the study to objectively assign a generic animal emission value. While in the large-scale and A2 resettlement systems, besides high fertiliser application rates, there is substantial irrigation and tractor energy costs (Table S1). In fact irrigation accounted for 28 and 18 % of the total CO_2 emission equivalents in the large-scale commercial and A2 resettlement production systems, respectively (Table S1).

A Spearman's rank-order correlation test was carried out to determine the relationship between total N-fertiliser applied and the corresponding GHG emissions (in kg CO_2 eq./t potato) in the different potato production systems in Zimbabwe. Weak, positive correlations were observed in the large-scale commercial ($r_s = 0.28$), A2 resettlement ($r_s = 0.42$), and in the communal area ($r_s = 0.27$) production systems (Table 5). This implies that further increases in N-fertiliser use in these high-input production systems result in only marginal increases in GHG emission per t potato. In the A1 resettlement production system, a strong, positive correlation which was not significant ($r_s = 0.92$, $p > 0.05$) was observed between N-fertiliser use and the corresponding GHG emission per t potato produced (Table 5). The A1 resettlement is a low-input use system (Table 2), and increases in N-fertiliser application rate will result in substantial GHG emissions per t potato produced.

Predictably, strong, negative correlations between fresh potato yield and the total CO_2 emissions per tonne fresh potato were found in the large-scale commercial ($r_s = -0.56$, $p < 0.05$), A2 resettlement ($r_s = -0.57$, $p < 0.01$), and in the communal area ($r_s = -0.78$, $p < 0.01$) production systems (Table 6). This indicates that increasing potato yields in these systems causes significant reductions in total GHG emissions per tonne fresh potato produced in these systems. Hence there is tremendous potential to reduce total emissions through improving the yields in the high-input use potato production systems. However, in the A1 resettlement production system, a strong, positive correlation, which was not significant ($r_s = 0.76$, $p > 0.05$) was observed between fresh potato yield and the corresponding total CO_2 emissions per tonne fresh potato produced (Table 6). The A1 resettlement is a low-input production system and a yield gain from an increase in input use, such as N-fertiliser application, will lead to substantial increase in total CO_2 emissions per tonne fresh potato produced until the threshold of high-input use level is reached.

Table 5. Spearman rank-order correlation analysis of the nitrogen (N) application rate and the corresponding greenhouse gas (GHG) emissions produced in the different production systems in Zimbabwe, 2011–2014.

	Production system											
	Large-scale commercial			**A2 resettlement**			**A1 resettlement**			**Communal area**		
	Mean N use rate (kg N/ha)	Mean GHG emission (in kg CO_2 eq.)		Mean N use rate (kg N/ha)	Mean GHG emission (in kg CO_2 eq.)		Mean N use rate (kg N/ha)	Mean GHG emission (in kg CO_2 eq.)		Mean N use rate (kg N/ha)	Mean GHG emission (in kg CO_2 eq.)	
		per t	per ha		per t	per ha		per t	per ha		per t	per ha
	181	263	6211	197	286	5337	94	240	1946	143	216	2868
Test statistics												
n	15			23			4			18		
r_s		0.28	0.54		0.42	0.76		0.92	0.80		0.27	0.84
t-stat.		1.07	2.33		2.11	5.30		3.37	2.29		1.12	6.12
t-crit.		2.16	2.16		2.08	2.08		4.30	3.18		2.12	2.12
p		0.31^{ns}	0.04*		0.04*	0.00**		0.08^{ns}	0.12^{ns}		0.28^{ns}	0.00**

Key: eq. = equivalent, ns, correlation is not significant at the 0.05 level (2-tailed), *, correlation is significant at the 0.05 level (2-tailed), **, correlation is significant at the 0.01 level (2-tailed).

Table 6. Spearman rank-order correlation analysis of the fresh Irish potato yields and the corresponding greenhouse gas (GHG) emissions produced in the different production systems in Zimbabwe, 2011–2014.

	Production system											
	Large-scale commercial			**A2 resettlement**			**A1 resettlement**			**Communal area**		
	Mean yield (t/ha)	Mean GHG emission (in kg CO_2 eq.)		Mean yield (t/ha)	Mean GHG emission (in kg CO_2 eq.)		Mean yield (t/ha)	Mean GHG emission (in kg CO_2 eq.)		Mean yield (t/ha)	Mean GHG emission (in kg CO_2 eq.)	
		per t	per ha		per t	per ha		per t	per ha		per t	per ha
	28	263	6211	23	286	5337	8	240	1946	17	216	2868
Test statistics												
n		15			23			4			18	
r_s		-0.56	0.19		-0.57	0.17		0.76	0.95		-0.78	0.16
t-stat.		-2.43	0.69		-3.16	0.81		1.66	5.30		-4.96	0.66
t-crit.		2.16	2.16		2.08	2.08		4.30	3.18		2.12	2.12
p		0.03*	0.50^{ns}		0.005*	0.43^{ns}		0.24	0.01*		0.0001**	0.52^{ns}

Key: eq. = equivalent, ns, correlation is not significant at the 0.05 level (2-tailed),*, correlation is significant at the 0.05 level (2-tailed), **, correlation is significant at the 0.01 level (2-tailed).

3.3 Greenhouse gas emissions per hectare

Significant differences ($p < 0.001$) in total GHG emissions (in kg CO_2 eq./ha) were found between the four potato production systems in Zimbabwe (Table 7). The total GHG emissions ranged from 1,946 kg CO_2 eq./ha in the A1 resettlement to 6,211 kg CO_2 eq./ha in the large-scale production systems (Table 7). With the exception of soil-related factors, which include fertiliser-induced field emissions, background soil N_2O, cover cropping and residue management, the rest of the factors were significantly different across all the potato production systems (Table 7). The soil-related GHG emissions from the smallholder potato systems were comparable to measurements reported by Mapanda *et al*. (2011) as fluxes of N_2O, CO_2 and CH_4 from soil grown to maize (*Zea mays* L.) under different nitrogen (N) fertiliser treatments in Zimbabwe. Using the static chamber methodology involving gas chromatography, Mapanda *et al*. (2011) estimated emissions of 0.1 to 0.5 kg N_2O-N/ha, 711 to 1,574 kg CO_2-C/ha and −2.6 to 5.8 kg CH_4-C/ha. Also in the Siaya district in Kenya, total GHG emissions of 2,600 kg CO_2 eq./ha were reported from maize production of 1.7 t/ha (Palm *et al*., 2010). Case studies in Europe reported even much lower GHG emissions. For example, in east Scotland, mean carbon footprints across conventional, integrated and organic farm types ranged from 125 kg CO_2 eq./ha/yr for leguminous crops to 540 kg CO_2 eq./ha/yr for Irish potato (Hillier *et al*., 2009).

Fertiliser production was again the major driver of the GHG emissions per hectare further demonstrating the dependence of GHG emissions on fertiliser usage (Table 7). Irrigation emissions in the A2 resettlement and large scale commercial systems were next followed by soil-related emissions (Table 7). Substantial GHG emissions from seed production and pesticides use were also recorded, while emissions from the rest of the factors were modest (Table 7). Examining the emissions variation from the different sources within each production system, wide ranges exist (Table S2, in supplemental material). This suggests that it is possible for growers to copy practices from well performing neighbours within the same production systems and biophysical conditions to lower their emissions.

A Spearman's rank-order correlation test was carried out to determine the relationship between total N applied and the corresponding GHG emissions (in kg CO_2 eq./ha) in the different potato production systems in Zimbabwe. There were strong, positive correlations between total N applied and the corresponding GHG emissions (in kg CO_2 eq./ha) (Table 5). Except in the A1 resettlement production system, the correlations in the other production

Table 7. Mean values of greenhouse gas (GHG) emissions (in kg CO_2 eq./ha) of Irish potato farming in the different Production systems in Zimbabwe, 2011–2014.

Production system	**Factors**							
	Seed production	**Fertiliser production**	**Soil-related**	**Pesticides**	**Energy use (excl. irrigation)**	**Irrigation**	**Off-site transport**	**Total**
Large-scale commercial	718^a	1908^a	866	610^a	196^a	1903^a	9^a	6211^a
A2-resettlement	723^a	1917^a	898	571^a	173^b	1047^b	9^a	5337^b
A1-resettlement	299^b	768^c	564	311^c	0^c	0^c	4^c	1946^d
Communal area	384^b	1359^b	646	472^b	0^c	0^c	6^b	2868^c
LSD	141*	332*	ns	73*	13**	359*	1**	670**
CV (%)	37	31	37	21	17	64	26	23

Key: eq. = equivalent, excl = excluding, na = not applicable, * denotes significant difference at $p < 0.05$, ** denotes significance at $p < .001$, ns denotes non-significance at $p < 0.05$, mean values in the same column followed by the same letter are not significantly different.

systems, large-scale commercial ($r_s = 0.54$, $p < 0.05$), A2 resettlement ($r_s = 0.76$, $p < 0.01$), and the communal area ($r_s = 0.84$, $p < 0.01$) were all statistically significant (Table 5). This shows the strong impact of N-fertiliser application on total greenhouse gas emission per ha. Increases in N-fertiliser application rates in these production systems which already use high amounts of N-fertilisers (Table 2) are at the cost of GHG emission.

Weak positive correlations between total GHG emission per unit of land (in kg CO_2 eq./ha) and the corresponding actual fresh potato yield per unit of land were observed in the large-scale commercial ($r_s = 0.19$), A2 resettlement ($r_s = 0.17$), and in the communal area ($r_s = 0.16$) in Table 6. This suggests that increases in fresh potato yield through increasing inputs such as N-fertiliser in the already high-input use production systems result in modest increases in GHG per ha. In the low-input A1 resettlement production system, significant, strong, positive correlations ($r_s = 0.95$, $p < 0.05$), between total GHG emission per ha and the corresponding actual fresh potato yield per ha were observed (Table 6). This result indicates that increasing synthetic fertiliser application rates to improve yield comes at the cost of more GHG emissions on a per ha basis in the low-input use systems.

4. Discussion

4.1 GHG mitigation opportunities

Achieving higher yields across all production systems could be the main driver to reduce the GHG emission on a per-tonne-produce basis. Meanwhile, the mean actual potato yield across the potato production systems in Zimbabwe is low. It ranges from 8 t/ha in the A1 resettlement to 28 t/ha in the large scale production system. In addition, yield variation within the production systems is very wide. For example, the largest yield range of 8 to 45 t/ha was reported in the communal area production indicating a tremendous opportunity to improve yield in this system. The initial step therefore, would be to narrow this actual yield gap. The concept of closing yield gaps to increase food production has recently come under extensive discussion (Mueller *et al*., 2012; Tittonell and Giller, 2013; Smith *et al*., 2013). Hence one strategy to reduce GHG emissions on a per-tonne-produce basis is to improve yield. Moreover, considering the wide range of emissions for each activity across the production systems, there is opportunity for growers in the upper end of the range to initially lower emissions toward the mean emissions and progressively toward the lower end. For example, considering emissions due to fertiliser production, the widest range is in the large scale and A2 resettlement production systems. This suggests that these two systems have the greatest prospect to lower emissions through increasing yields while even lowering fertiliser application rates. Probably lack of knowledge of the emission sources and the requisite mitigation strategies among the Zimbabwean potato growers is the challenge.

Another dimension in the Zimbabwean case is the fact that the generous N applications are not matched by correspondingly high potato yields. This may imply the need for re-visiting fertiliser recommendations in potato production. Such studies should recommend application rates that match the availability of N in the soil with plant need or uptake to prevent over-application. Related to this fact could be the genetic yield potential of the old cultivars released in the 1980s that growers are currently using (Joyce, 1982). The potato breeding programme in Zimbabwe has been dysfunctional since the late 1990s to date, hence new cultivars with high yield potential, locally adapted and probably with high N uptake efficiency have not been made available to growers (Mazarire, personal communication, 2014). Reducing N application should be possible by growers currently over-applying N in order to reduce its impact on total GHG emissions (Desjardins *et al*., 2001; Lal, 2004). However, the trade-off in this mitigation strategy is large gains in the efficiency of N uptake so as to maintain yields. According to Janzen *et al.* (2003), no more than 60 % of applied N is taken-up by plants. Given the high cost of N fertiliser, there is the economic incentive to balance productivity and cost, and whatever reduction in N fertiliser realised will most likely lead to some decline in total GHG emission.

Extensive soil disturbance is another common cultural practice already alluded to in Zimbabwe potato production. No-till or reduced tillage practices could be encouraged in order to reduce the ridging operations from two or three to only one. Hillier *et al.* (2011) reported a reduction of soil GHG emission of 429 kg CO_2 eq./ha due to reduced or no-till farming. Operations contributing relatively small amounts to the total GHG emissions but with easily implementable measures could be targeted as well. To illustrate, pesticide application by tractor can be replaced by a ‘spraying gang’ of men with knapsack sprayers. One large-scale commercial grower encountered in the study sample introduced a spraying team of ten workers in 2007/8 during fuel shortages in Zimbabwe, and is still using this practice. Other growers tank-mix a number of biocides to minimise tractor trips in the field thereby reducing energy-related emissions. Growers can employ the CFT-Potato model as an important first step to practically explore mitigation options. In this study, mitigation options were not assessed. Rather drawing from literature, possible mitigation activities were suggested for specific farm operations in the Zimbabwean case. The model output displays the factors or farm operations and their respective emissions and in this way it allows the user to choose the factors or farm operations to work on for reducing the carbon footprint. For example, the grower may decide to first target farm operations contributing the most to the total GHG emissions. In the Zimbabwean case, fertiliser production is the main contributor, followed by irrigation in the A2 resettlement and large-scale commercial production systems, then soil-related, pesticides and the rest of the operations.

4.2 Benchmarking greenhouse gas emission performances of growers

Although benchmarking was not assessed in this study, opportunities for it exist in the Zimbabwe potato case because of a large variation in amounts of GHG emission among the growers. The variation in GHG emission, is related to the variation in grower cultural practices such as nutrient and pesticide application rates, irrigation water use, mechanisation and potato yield both within and across production systems. Benchmarking should allow growers to compare their performance with that of fellow growers, especially within the production systems on several aspects of potato farming (Tzilivakis and Lewis, 2004; Wainwright *et al*., 2005; De Snoo, 2006). During the data collection exercise in Zimbabwe, many potato farmer groups were encountered in the different areas and these institutional arrangements could be used as platforms or arena for operationalising benchmarking. Many growers interviewed had no idea of their own performance on GHG emissions. While they could respond easily to their cultural practices and input use rates in potato production, they had no idea how they compared to other potato growers in their local area or region. Moreover there is good farmer coordination by agricultural extension officials who frequently convene meetings to discuss farming-related issues. Hence there is a strong possibility to use benchmarking as a tool for growers to adopt more sustainable approaches in potato growing in Zimbabwe.

5. Conclusions and recommendations

The CFT-Potato model allows for the estimation of the contribution of a range of farm operations to the total GHG emission of potato under different production systems with relative ease. It showed that there were large differences among production systems and among farmers within each production system in performance. The analysis helps growers to decide practical steps to explore mitigation options and benchmarking for continuous improvement. The study recommends potato growers in Zimbabwe to use this open source software to gain knowledge of GHG emission practices and especially the overriding importance of fertiliser usage in determining the carbon footprint of potato production and the need to account for it.

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Supplemental material: GHG emissions in the different potato production systems of Zimbabwe, 2011–2014.

Table S1. Absolute and relative CO_2 costs of producing 1t potato in the four different potato production systems of Zimbabwe, 2011–2014.

Activity	**Production system**							
	Large-scale commercial		**A2 resettlement**		**A1 resettlement**		**Communal area**	
	kg CO_2 eq. per potato	**%**	**kg CO2 eq. per potato**	**%**	**kg CO2 eq. per potato**	**%**	**kg CO2 eq. per potato**	**%**
Seed production	33	13	42	15	38	16	31	14
Fertiliser production	83	32	103	36	91	38	100	46
Background soil N_2O	9	3	11	4	28	12	13	6
Fertiliser induced field emissions	25	10	32	11	32	13	28	13
Pesticides	26	10	31	11	41	17	36	17
Field energy use (excl. irrigation)	8	3	9	3	0	0	0	0
Irrigation	73	28	51	18	0	0	0	0
Grading, cooling and storage	0	0	0	0	0	0	0	0
Off-site transport	0.4	0	0.5	0	0.5	0	0.5	0
Cover crop and residue management	5	2	5	2	11	5	7	3
Total	**263**	**100**	**286**	**100**	**240**	**100**	**216**	**100**

Key: eq. = equivalent; excl. = excluding.

Table S2. Greenhouse gas (GHG) emissions (average, minimum, and maximum values) in kg CO_2 eq./ha of Irish potato farming in four different potato production systems in Zimbabwe, 2011–2014.

Production system	**Factors**														**Total**
	Seed production		**Fertiliser production**		**Soil-related**		**Pesticides**		**Energy use (excl. irrigation)**		**Irrigation**		**Off-site transport**		
	avg	**range**	**avg**	**range**	**avg**	**range**	**avg**	**range**	**avg**	**range**	**avg**	**range**	**avg**	**range**	
LSC	718	440–1198	1198	1264–2709	866	495–1181	610	328–800	196	142–245	1903	0–3478	9	5–10	6211
A2	723	266–1194	1917	1051–3569	898	445–2106	571	414–964	173	116–215	1047	0–2557	9	4–12	5337
A1	299	139–498	768	384–1482	564	405–817	311	275–377	0	0	0	0	4	2–6	1946
CA	384	81–758	1359	850–2441	646	400–966	472	336–664	0	0	0	0	6	2–12	2868

Key: avg = average; eq. = equivalent; excl. = excluding; LSC = Large scale commercial; CA = communal area; A1 = A1 resettlement; A2 = A2 resettlement.

Chapter 5

Analysis of the Irish potato value chain in Zimbabwe

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Abstract

The performance of the Irish potato sector in Zimbabwe is not well understood nor documented. Using the value chain analysis tool, this paper aims to evaluate the potato industry in the country, identify opportunities and constraints, and suggest strategies to enhance the competitiveness and profitability of the sector. A desk study was undertaken as a preliminary investigation, and the likely stakeholders active in the potato industry were identified. Quantitative data were collected on the identified stakeholders using structured questionnaires. Field observations and local knowledge were used in addition to expert elicitation using a checklist of questions. The results indicated that the Zimbabwean Irish potato value chain is complex, linking seven main stakeholder groups, and with multiple pathways the potato produce can take from the field of production. Over 65 % of potato production is processed primarily as French fries and less than 35 % is for household fresh potato consumption. The average fresh potato household per capita consumption was 34 kg per year, while the total per capita consumption was 9 kg per year. Gross margin estimated at each linkage was at least 13 %. Government policy supports potato production, and stakeholders were determined to upgrade the potato industry. The major factors impacting on the value chain performance relate to high production costs, low yields, and lack of farmer training. Potato marketing is hampered by the poor state of the road network, and lack of good sanitary facilities at the municipal markets. It is recommended to lower production costs, supply high yielding cultivars, provide credit facilities, guarantee land ownership, and improve the country's road network.

Key words: value chain analysis, Irish potato, Zimbabwe

1. Introduction

The Zimbabwean Irish potato industry recorded substantial growth in cropping area, production and average yield in the last decade. Production has reached the highest level of 58,000 tonnes from a peak cropping area of 3,500 ha in 2013 (FAOSTAT, 2013). Irish potato has become the most important horticultural crop in the country and the third most important carbohydrate food source after maize and wheat (The Herald, 2011). In addition, the industry received a major policy boost from the government, when Irish potato was declared a national strategic food security crop on 18 May 2012 (The Herald, 2012). Previously, only maize had the national strategic food security crop status. Again, potato is now included in various government input and mechanisation support schemes (The Herald, 2012). Prior to 2000, the predominantly white large-scale commercial farmers dominated potato production in Zimbabwe (FAOSTAT, 2013; Chapter 2, this thesis). However, the government's aggressive land reform programme, so-called the Fast Track Land Reform Program (FTLRP), initiated in 2000 essentially dismantled the large-scale commercial farming sector. By 2010, when the reform programme was officially concluded, over 12 million ha of the initial 12.5 million ha large-scale commercial farmland in 1980, was taken-up for resettlement (Moyo, 2011). Two resettlement models were used, the A1 and A2 resettlement models. Beneficiary households under the A1 resettlement model were allocated about 6 ha arable land and shared grazing land. Under the A2 resettlement model, beneficiary households were allocated self-contained farm units ranging from about 35 ha in the high rainfall regions through 300 ha in the drier parts of the country. Some of the resettled farmers have since started growing potato in addition to the already existing communal area potato farmers and the few remaining large-scale commercial farmers (Chapter 2, this thesis). More than a decade after the historic land reforms, an analysis of the potato production systems in Zimbabwe has been recently conducted (Chapter 2, this thesis). The analysis gave insight into the different grower categories existing, the natural resource base owned, input use, average fresh potato yield, infrastructure for potato production available, production constraints and possible solutions (Chapter 2, this thesis). However, the value chain of potato in Zimbabwe has not yet been mapped and the other key players have not been clearly identified and characterised. Hence, the value chain performance of the Zimbabwean potato industry is not well understood.

A value chain can be understood as the range of actions or activities required to bring a product or service from conception, through production, to delivery to final consumers, and eventual disposal after use (Kaplinsky and Morris, 2001). Prominent in a value chain, is the economic value addition and financial loss for chain actors at different linkages in the chain, and the sum value of the whole chain operating as an interactive entity (Gelli *et al*., 2015). Value chain actors generally include input suppliers, producers, processors, and markets. Supporting the value chain are normally a range of technical, financial and business service providers. The local and national government regulations and practices provide the environment in which the chain is embedded (Kula *et al*., 2006). Additionally, due to globalisation and the rise of international trade, global rules and standards can also form part of the environment surrounding a chain (Figueiredo Junior *et al*., 2014).

Value chain concepts have been extensively used in development interventions since the mid-1990s. Value chain analysis is a method of analysis for the design and implementation of interventions (Gelli *et al*., 2015). The analysis answers where, how, and why value is created and added along the chain (Hawkes and Ruel, 2011). Therefore, the analysis leads to an understanding of why the value chain has a certain structure, and how it could be leveraged for change to enhance development. Taylor (2005) viewed value chain analysis as a diagnostic tool, defined as a "multi-dimensional assessment of the performance of value chains, including the analysis of product flows, information flows and the management and control of the value chain". Value chains have been applied in different disciplines and sectors. For example, government and funding agencies have applied value chain analysis to enhance competitive strategies in business, address business relations, and constraints (Hawkes and Ruel, 2011; Altenburg, 2007). With the advent of globalisation in the early 1990s, value chain analysis has also been used as a tool to study the processes, re-organisation, causes and consequences of global industrial integration (Gereffi, 1994). Aid agencies have used value chain strategies in pro-poor agricultural development projects with goals such as poverty-reduction, market and product identification, vertical and horizontal linkages among participants (Ton *et al*., 2011; Trienekens, 2011). Value chain analysis has also proved to be a useful tool in addressing gender issues in agricultural development (USAID, 2011). Specific issues addressed include understanding the different roles of men and women in designing agricultural value chain activities, fostering equitable participation, and equitable benefit-sharing mechanisms between men and women from their contributions to the value chain (USAID, 2011).

Interest in food value chain development has grown because development agencies have realised that success in the increasingly complex agro-food markets requires stronger collaboration among value chain actors (Humphrey and Memedovic, 2006). Growing urban demand for value-added foods, more stringent quality and food safety standards, and the advent of niche markets all have contributed to the increased interest in food value chain development (Gelli *et al*., 2015). Recently, value chain interventions have considered nutrition, that is, in terms of improved nutrition of smallholder producers and of consumers in peri-urban and urban settings, besides increased income for smallholders and other stakeholders along the value chain (Hawkes, 2013). Food supply chains can provide opportunities to promote nutrition and health, due to the key role in determining food availability, affordability, quality, and acceptability (Hawkes and Ruel, 2011).

In Zimbabwe, the performance of the Irish potato industry is not well understood and neither is it documented. It is important to evaluate the potato sector in the country, identify opportunities and constraints, and suggest strategies to enhance its competitiveness and profitability. This study on the Irish potato value chain in Zimbabwe was conducted during the period 2011 through 2014. The specific objectives of the study were: (1) to identify and map the main actors in the value chain and the relationship between them, (2) to describe the activities performed by each actor, (3) to determine the value chain performance, (4) to identify the constraints and opportunities within each segment, and (5) to suggest strategies to enhance the competitiveness and profitability of the Irish potato industry in Zimbabwe.

2. Materials and methods

2.1 Data collection

A desk study was undertaken as a preliminary investigation in order to identify in advance, the likely stakeholders active in the potato industry in Zimbabwe for interviews. The stakeholders studied were involved in potato production, distribution, wholesaling, processing, retailing, service provision, and in household consumption. Specific stakeholders identified included seed potato growers, ware potato growers, distributors (traders), processors (hotels, restaurants and fast-foods outlets), urban fruit and vegetable market, wholesalers, retail supermarket chains, household consumers, and service providers. Formal surveys using structured questionnaires were conducted on the identified stakeholders to collect quantitative data. In addition, field observations and local knowledge were also used.

Expert elicitation using a checklist of questions was also employed to gather opinions of authorities in the Irish potato sector in Zimbabwe, especially where there was uncertainty due to insufficient data or when such data was unattainable because of constraints or lack of resources. These experts had opinions on strategies to improve the potato value chain performance in Zimbabwe based on their accumulated experience and knowledge, including their insight in the limitations and strengths of the available data on the potato sector. The experts were drawn from both public and private institutions that regularly interface with actors in the potato industry. The government agencies that provided some of the experts included agricultural extension, Agritex, the Crop Breeding Institute, CBI and the Seed Services Institute. Experts from private institutions consulted included the Potato Seed Coop, a private seed potato company, and two experienced seed potato growers, one from the Highveld, and the other from the Eastern Nyanga Highlands.

2.2 Sampling

In each stakeholder group, a representative sample was taken for the interviews. Questions asked focussed on several issues, including those on factors that give an indication on value addition or losses, and factors impacting on value chain performance. Seed and ware potato growers were sampled from the Highveld and Nyanga Eastern Highlands, the main potato growing regions in the country (Chapter 2, this thesis). There are four potato production systems in the country namely, the large-scale commercial, communal area, A2 and A1 resettlement (Chapter 2, this thesis). All were included in the sample. A total of 3 large scale commercial and 4 A2 resettlement growers out of the 21 active growers involved in the initial seed potato multiplication were sampled. Ware potato growers sampled included 12 large scale commercial, 19 A2 resettlement, 5 A1 resettlement and 18 communal area growers. All were experienced growers who could easily respond to questions on their respective farm operations in potato production. The government extension agency, Agritex, selected the growers in each area, briefed them about the study and asked whether they were willing to participate in it. If they agreed, appointments were made and the selected growers were visited for the data collection exercise. In order to establish the estimated cost of seed and ware potato production in the respective production systems, data was collected on essentially all the grower operations. Most growers revealed their potato selling prices.

A total of 14 metropolitan areas and 4 rural service centres were selected for the study on potato wholesaling, retailing, processing, and household potato consumption. Two of the rural service centres selected were located in the main potato growing areas, while the other two were not. The Horticulture Division of Agritex assisted with preparatory arrangements for interviews with selected wholesalers, Urban Fruit and Vegetable (UFV) open markets, retail supermarkets, and processors. The Horticulture Division regularly interacts with fruit and vegetable stakeholders in urban and rural service centres. A total of 13 establishments engaged in the wholesale distribution of fresh potato were sampled from the 14 selected metropolitan areas in the country, but 7 metropolitan areas did not have wholesalers. The major formal wholesale establishments interviewed countrywide were: Wholesale Fruiterers, Favco, Sunspun, Harare Produce Sales, Manica Produce Sales, Willsgrove, PGS, Valley Fresh, and Honeydew Farm. The UFV open market retailing are located in urban residential areas usually under an outbuilding or shed, owned by the respective municipal authorities. Within it, tables or stalls are allocated from which table/stallholders sell fresh fruit and vegetables to customers. A total of 121 stallholders were interviewed from the 14 selected metropolitan areas in Zimbabwe; and 19 stallholders from 4 rural service centres. The selected stallholders had Irish potato as one of their trading commodities. Mbare Open Market (Mbare Musika), located in the capital city, Harare is the hub of fruit and vegetable trading in the country, being the largest fresh produce wholesale market (Knowledge Transfer Africa, 2013; The Sunday Mail, 2014). Mbare Musika wholesale market is made up of individual stallholders. A total of 16 stallholders, representing about 40 % of the stallholders who specialized in Irish potato wholesale trading were interviewed. On potato retailing, a total of 50 selected supermarkets in 14 metropolitan areas of Zimbabwe were interviewed. Fresh potato processing in Zimbabwe is mainly into French fries (or fresh chips), is done by hotels, restaurants, and fast-food outlets. A total of 62 selected hotels, restaurants and fast-foods outlets located in 14 metropolitan areas were interviewed. In the same metropolitan areas, household interviews on potato consumption were conducted. The interviewed were asked the household size, amount of potato bought per month, and about the frequency of potato-based meals consumption over a recall period of the past 7 days. The number of household interviews ranged from 150 to 250 per metropolitan area depending on the population size. Service providers interviewed included government agencies such as the Seed Services Institute, the Crop Breeding Institute, and the extension agency, Agritex. Some fertiliser and biocide companies were also interviewed and these include: the Zimbabwe Fertiliser Company (ZFC), Windmill, Omnia, Agricura, and a few new, upcoming smaller players.

2.3 Data analysis

The data collected from the surveys was collated according to the different actor categories and tabulated. Descriptive statistics that included mean, range, and percentage were employed to analyse the data. The information gleaned from expert elicitation was particularly useful on opinions and strategies to improve the potato value chain performance in the country.

3. Results and discussion

3.1 Value chain mapping

The Irish potato value chain in Zimbabwe is fractious and complex, with multiple pathways from the field of production to the end user. Fig. 1 shows the potato value chain in Zimbabwe. It includes seven main stakeholder groups, several service providers, all functioning in a socio-economic and political environment. The stakeholder groups are:

(1) Producers: two types of potato are produced; 88 % is ware potato while 12 % is seed potato. The seed potato are for regeneration purposes, while the ware potato are produced for consumption.

(2) Transporters (or middlemen): almost the entire crop of the smallholder (A1 resettlement and communal area) growers is bought by middlemen who transport it to the wholesale market. They also buy about 50 % of the A2 resettlement growers' crop and less than 10 % of the large-scale commercial growers' crop.

(3) Wholesalers: buy most of the potato of the middlemen, more than 60 % of the large-scale commercial crop and about 30 % of the A2 resettlement growers' crop for onward distribution to retail and processing.

(4) Retailers: supply household consumers and also processors.

(5) Processors: develop a client base and deal mainly with French fries. More than 65 % of ware potato goes to the processing market (Ackerman, personal communication, 2013).

(6) Public consumers: form the client base for the processing sector.

(7) Household consumers: buy potato for home consumption from the wholesale, retail, and sometimes directly from the farms.

3.2 Seed and ware potato growers

Initial seed potato multiplication is carried out in a demarcated zone called the Quarantine area. This decreed area is located at altitudes above 1,800 m above mean sea level (amsl) in the Nyanga National Park, Nyanga district (Joyce, 1982; Chapter 2, this thesis). The government potato breeding programme at the Nyanga Experiment supplies virus free foundation seed to growers in the Quarantine area, and the seed undergoes three multiplications to produce grade AA1 through AA3 seed (Joyce 1982; Chapter 2, this thesis). This area must be completely free of other solanaceous plants. Production is carried out under rain-fed conditions because of the risk of Bacterial wilt from the soil-borne bacterium *Ralstonia solanacearum* in sediments in the irrigation water. Hence growers in the Quarantine area do not have irrigation systems (Ackerman, personal communication, 2012). Grade AA3 seed is then sent out of the Quarantine area for further multiplication into class A1 through A3. All of grade A1, A2 and A3 seed potato is then used for ware potato production. The Highveld region, located in the central part of the country at altitudes between 1200 and 1800 m amsl, dominates the later seed multiplication phase. Growers of A1 through A3 seed potato are contracted by seed potato companies, which in turn register them to the government seed services agency for joint monitoring and certification. All seed potato (A1 through A3) is certified and sold to ware potato growers by seed companies (Fig. 1). One of the key seed companies interviewed was the Seed Potato Coop in Harare. It is a cooperative of both double ‘A’ (Quarantine growers) and single ‘A’ seed growers.

Fig. 2 summarises the cost and gross margin estimates of Irish potato production in the different production systems in Zimbabwe. It was very difficult from the survey to obtain sufficient information on the capital investment and variable (running) costs involved in potato production by the different systems. Few growers provided details on the production costs (Table S5, in supplementary material). High costs of potato production were recorded, ranging from US$ 2122 in the A1 resettlement system to over US$ 9500 per ha in the large-scale commercial system (Fig. 2). This translated to production costs of US$ 265 and US$ 344 per ton in the A1 resettlement and large-scale commercial systems respectively (Table S5). Seed and fertiliser were the most expensive inputs, with a combined contribution of 40 and 72 % of the total variable costs in the large-scale commercial and A1 resettlement production systems, respectively (Table S5). Growers raised concern over high production costs of potato before (The Herald, 2011b).

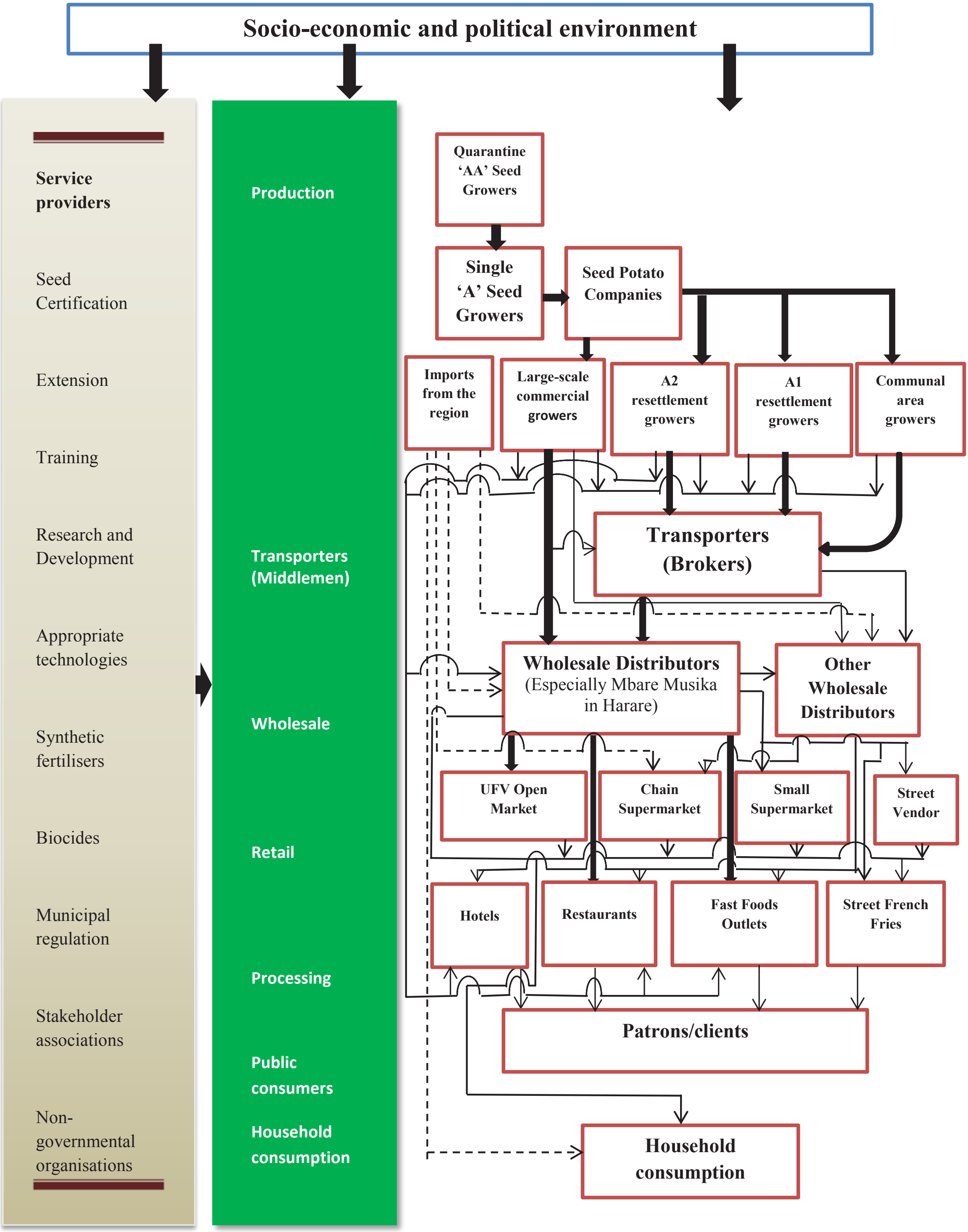

Fig. 1. The Irish potato value chain in Zimbabwe.

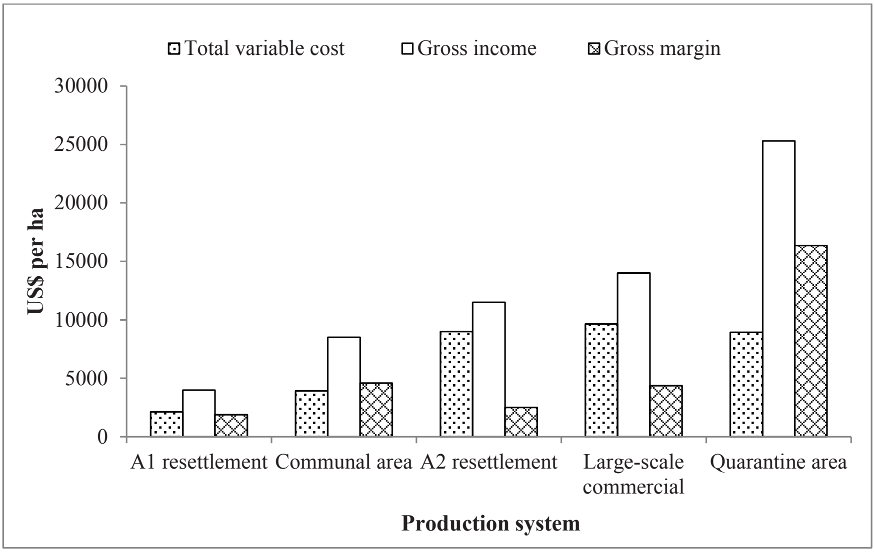

Fig. 2. Characteristic production budget summary per ha of Irish potato in the different potato production systems in Zimbabwe, 2011–2015.

However, estimates of returns show very good profitability (Table S5). Per single US$ total variable cost invested, the return ranged from US$ 0.28 in the A2 resettlement to US$ 1.89 in the Quarantine seed production systems (Table S5). Similar returns have been reported before (The Herald, 2011a). Growers have however raised lack of credit facilities to fund production, because they do not have collateral security asked by commercial lending institutions. In the past, farmland was used as collateral security. But the FTLRP nationalised land ownership, hence it could no longer be used as collateral security against a loan. The majority of growers use savings, which is risky in the event of crop failure. Therefore, restoring private land ownership to enable funding of production is one of the key issues important to leverage the performance of the potato value chain in Zimbabwe.

In 2010, the government banned the importation of ware potato primarily to protect the local growers against cheap South African potato (Chimoio, 2013). Besides, there is also the threat of introducing the potato cyst nematodes, *Globodera rostochiensis* and *Globodera pallida*, which are parasites of worldwide significance attacking the crop. These have not been reported in Zimbabwe, and will be very difficult to eradicate once they are introduced into the soils (Manzira, 2010). In South Africa, the cyst nematode has been reported and is treated as a prohibited pest and any infection is not tolerated (Knoetze *et al*., 2006). Hence, Zimbabwe has very stringent requirements on importation of South African seed potato

(Manzira, 2010). However, there are reports of smuggling of ware potato into the country especially from neighbouring South Africa (Dube, 2013). Hence, the threat of ware potato imports into the country is an important issue to the production of the crop and its value chain performance.

Experts estimate annual potato planting area at around 6,000 ha and annual production at nearly 120,000 t (Ackerman, personal communication, 2013; Manzira, personal communication, 2013). However, the Food and Agricultural Organisation of the United Nations (FAO) estimates reported a peak production of 58,000 t over a cropping area of 3,500 ha in 2013 (FAOSTAT, 2013). The FAO estimates appears a gross under-estimation of potato production in the country. In this study, more than twice the volume of crop in the FAO estimates was traded in the value chain. Meanwhile, the potato industry in Zimbabwe has an ambitious plan to increase the potato planting area to 30,000 ha annually in the medium term (USAID-STAMP, 2011; The Herald, 2011a; Ackerman, personal communication, 2013). This is buoyed by several factors. The seed potato sector argues that they have the capacity to supply sufficient quantities for the planned area, and that any seed shortages will be augmented by imports from South Africa (The Herald, 2011a). Ware potato consumption is rising (The Herald, 2013; Ackerman, personal communication, 2013). The envisaged increased potato supply due to enlarged production area and higher yields will most likely bring down prices from the current levels and increase affordability and consumption (The Herald, 2013). Also noteworthy in the potato production sector of the value chain is the low yield levels, which range from 8 t/ha in the A1 resettlement to 28 t/ha in the large-scale commercial production system (Table S5). Potato growers in Zimbabwe generally use high levels of synthetic fertilizers and biocides (Chapter 2, this thesis). Management interventions, such as better nutrient management, use of high-yielding cultivars, water management, and integrated pest and disease management can improve fertiliser use efficiency of potato and increase yield, while reducing both fertiliser and biocides application rates (Lassaletta *et al*., 2014; Chapter 2, this thesis). Consequently, growers can realise better returns even at lower producer prices from the current levels. This will have the effect of increasing consumer affordability and consumption, and increase the potato sector growth in the country.

3.3 Transporters/middlemen

The middlemen hire transport and buy almost the entire crop of the smallholder, A1-

resettlement and communal area growers. They also buy about 50 % of the A2 resettlement growers' crop and less than 10 % of the large-scale commercial growers crop. Some of the middlemen who have been in the business for a long time (more than 5 years) now have their own transport. More than 70 % of the middlemen crop is sold to the Mbare Musika wholesale market and the remainder is taken up by wholesale markets in other metropolitan areas (Fig. 1). After buying the crop at prices ranging from 0.4 to 0.8 US$ per kg, the middlemen sell to the wholesalers at a gross margin of 16 to 18 %. Price variations depend on potato quality and also on demand and supply trends. The majority of large-scale commercial and A2 resettlement growers have their own transport, hence link directly to the wholesale market by-passing the transporters.

The growers-transporters-wholesalers is a very significant potato pathway in the value chain, through which almost the entire crop of the smallholder producers and about 50 % of the A2 resettlement growers' crop passes. The transporters have a double role of sourcing and transporting inputs such as fertilisers back to the growers. They are also important for market information to the smallholder producers. The often poor state of the road network negatively affects this pathway in the value chain performance.

3.4 Wholesale distribution

The pathway becomes more fractious and complex as wholesalers directly distribute the crop to processing, retail and household consumption (Fig. 1). Wholesaling is dominated by Mbare Musika, with more than 75 % of the wholesale market share. Wholesalers in other metropolitan areas sometimes source their potato from Mbare Musika. Mbare Musika therefore, remains a competitive group of wholesalers compared with other wholesalers. Individual stallholders distribute mean monthly potato volumes of about 120 t, ranging from 1 to 405 t (Table 1). These volumes translate to an average of 5,000 t potato per month for the entire Mbare Musika wholesale market, and experts estimate that this amount represents about 65 % of annual potato production in the country. Sales peak to nearly 2.5 times during the Christmas festive season when the highest sales are recorded (Table 1). Losses ranged from 0.1 to 7 % of the mean monthly sales (Table 1). Stallholders reported that losses were mainly due to rotting, especially during the rainy season in the months November through April. Also when the market activity is low, the tuber quality deteriorates due to shriveling and sprouting, hence prices fall. After buying the crop at prices ranging from 0.47 to 0.93

US$ per kg, the wholesalers add a gross margin of 13 to 22 % depending on the tuber size and quality. However, Mbare Musika wholesalers raised the issue of poor sanitation at the market, a problem they have repeatedly raised with the Municipality of Harare.

Besides, Mbare Musika, the city of Harare with a population of over 1.5 million people (ZimStat, 2012) had the highest concentration of formal wholesale establishments, while 7 of the 14 main metropolitan areas sampled in the study had no formal wholesale establishments (Table 2). Mean monthly sales of potato ranged from 9 t in Mutare to 300 t in Bulawayo metropolitan (Table 2). The lowest loss estimate of 0.1 % of the mean monthly potato sales was recorded in Bulawayo mainly because of the high demand driven turnover (Table 1).

Table 1. Fresh potato sales at the Mbare Open Market, Harare, Zimbabwe derived from interviews data conducted in the period 2011-2014.

Stall-holder	**Mean values and spread [Mg/month]**			**Loss estimate**
	Mean	*Least*	*Highest*	**[% of monthly mean]**
1	1	0.5	3	5
2	5	2	7	1
3	75	45	200	2
4	310	150	700	0.2
5	63	9	250	7
6	54	23	260	5
7	130	45	355	5
8	280	200	370	6
9	170	135	400	5
10	75	45	225	3
11	405	300	690	4
12	196	60	450	5
13	85	23	315	3
14	9	7	180	5
15	6	2	14	0.1
16	60	45	270	2
AVERAGE	**120**	**68**	**293**	**4**

Table 2. Fresh potato wholesaling in selected metropolitan areas of Zimbabwe, derived from interviews data conducted in the period 2011-2014.

Urban area	**Population***	**Mean values and spread [Mg/month]**			**Loss estimate [% of monthly mean]**	**Wholesalers interviewed [n]**
		Mean	*Least*	*Highest*		
Harare	1,485,000	26	23	38	3	7
Bulawayo	653,000	300	240	600	1	1
Mutare	187,600	9	0.6	15	2	1
Gweru	158,000	45	30	60	3	1
Kwekwe	101,000	30	18	36	4	1
Kadoma	92,500	0	0	0	na	na
Masvingo	87,900	0	0	0	na	na
Chinhoyi	78,000	0	0	0	na	na
Marondera	62,000	0	0	0	na	na
Chegutu	50,600	0	0	0	na	na
Bindura	43,600	45	27	225	5	1
Rusape	30,300	0	0	0	na	na
Nyanga	24,000	54	45	120	1	1
Karoi	28,600	0	0	0	na	na

Key: na = not applicable; *2012 population census (ZimStat, 2012).

3.5 Urban Fruit and Vegetable open markets

The UFV open markets are an important link to household potato consumption. They are located in the metropolitan residential areas and also in the rural service centres. In the metropolitan areas, they are regulated by the municipal authorities. Potato supplies are sourced mainly from the Mbare Musika wholesale market and UFV open markets pack smaller 500 g and 1 kg potato units for sale, usually at US$ 0.50 and US$ 1.00 respectively. Monthly potato sales range from 2 to 164 t in the metropolitan areas (Table 3) and from 0.3 to 3.4 t in the rural service centres (Table 4). Generally, the volumes of potato traded by UFV open markets far outweigh that handled by the formal wholesale and retail markets. Larger metropolitan areas, such as Harare and Bulawayo, had low loss estimates mainly because of high demand and record high turnover. Besides potato, the UFV open market deals with other fruit and vegetables. Poor sanitation was a problem this study observed at most of the UFV open market centres across all the metropolitan areas visited. Householders expressed the desire to buy potato, fruits and other vegetables from clean and healthy facilities.

Table 3. Fresh potato sales in the UFV Open Markets of selected metropolitan areas of Zimbabwe, derived from interviews data conducted in the period 2011-2014.

Urban area	Population	Mean values and spread [Mg/month]			Loss estimate [% of monthly mean]	Stallholders interviewed [n]
		Mean	*Least*	*Highest*		
Harare	1,485,000	164	82	337	3	16
Bulawayo	653,000	23	15	27	2	15
Mutare	187,600	4	2	8	4	11
Gweru	158,000	3	2	44	3	7
Kwekwe	101,000	2	2	3	12	5
Kadoma	92,500	2	2	4	6	8
Masvingo	87,900	2	1	5	7	10
Chinhoyi	78,000	3	2	4	8	11
Marondera	62,000	5	3	9	6	6
Chegutu	50,600	2	1	5	6	9
Bindura	43,600	5	3	12	8	7
Rusape	30,300	4	2	9	6	4
Nyanga	24,000	4	2	6	9	7
Karoi	28,600	2	1	3	8	5

3.6 Retail supermarkets

Chain supermarkets obtain their supplies mainly from the formal wholesalers, who endeavour to meet the quality standards demanded. However, in times of shortages, the chain supermarkets also source their potato from the informal Mbare Musika wholesale market. One large-scale commercial grower interviewed had recently installed a potato washing machine. The grower was supplying washed potato to selected chain supermarkets in the affluent suburbs of the major metropolitan areas such as Harare and Bulawayo.

Table 4. Fresh potato sales in the UFV Open Markets of selected rural service centres of Zimbabwe, derived from interviews data conducted in the period 2011-2014.

Rural Service Centre	**District**	**Mean values and spread [Mg/month]**			**Loss estimate [% of monthly mean]**	**Stallholders interviewed [n]**
		Mean	*Least*	*Highest*		
Juru	Murehwa	1.2	0.6	2.0	10	4
Magunje	Karoi	0.4	0.2	1.9	4	5
Murambinda	Buhera	3.4	2.4	5.2	6	4
Murombedzi	Zvimba	0.3	0.2	0.5	7	6

Small supermarkets and street vendors source their potato mainly from the Mbare Musika wholesale market. Mean monthly sales in selected supermarkets and other retail outlets in the sampled metropolitan areas ranged from 0.1 to 12.9 t (Table 5). Loss estimates were substantial, ranging from 0.3 to 8.5 % of the mean monthly sales volume (Table 5). This suggests the slow movement of potato in supermarket retailing probably because of the high price compared with that offered by the UFV open markets.

3.7 Processing

Potato processing in Zimbabwe is mainly into French fries by hotels, restaurants, fast foods outlets, and recently along the streets. The crisps industry was almost non-existent when a dominant subsidiary of Cairns Group involved in crisps production closed citing the difficult macro-economic environment and the stiff competition from cheaper imports from neighboring South Africa (Sibanda, 2013). In Zimbabwe, potato processing into French fries is decentralized and particular hotels, restaurants, and fast foods outlet chains have their own processing units that supplies them. Unlike in South Africa, the potato processing structure is highly concentrated and oligopolistic with a few firms such as McCains, Lamberts Bay Foods, and Natures Choice dominating the Frozen French Fries market (Hanekom *et al*., 2010). In Mozambique, all potato are consumed as fresh potato and there is no industrial processing into food or non-food products (MoEA, 2014). Hence these potential industries are still unexplored. Similarly in Ethiopia, large scale potato processing is non-existent (Emana and Nigussie, 2011). However, in large cities like Addis Ababa, it is common to see hotels, restaurants, street vendors and cafes prepare French fries from potato (Emana and Nigussie, 2011).

Fresh potato for processing is sourced mainly from Mbare Musika wholesale market and from other wholesale distributors (Fig. 1). A few large-scale commercial and A2 resettlement growers are also contracted by processing entities for fresh potato supplies (Fig. 1). Mean monthly volumes of potato per individual processing entity ranged from 0.4 to53 t in the metropolitan areas sampled (Table 6). In the rural service centres, the mean monthly volumes were only 0.2 to 0.6 t per individual processing establishment (Table 7). Loss estimates for the processing industry were in the range 0.03–1 % (Tables 6 and 7). The

Table 5. Fresh potato retailing of Zimbabwe, derived from interviews data conducted in the period 2011-2014.

Urban area	Population	Mean values and spread [Mg/month]			Loss estimate [% of monthly mean]	Number interviewed [n]
		Mean	*Least*	*Highest*		
Harare	1,485,000	7.6	5.8	13.8	0.7	7
Bulawayo	653,000	12.9	4.6	25.2	1.7	5
Mutare	187,600	1.7	0.8	2.8	4.0	4
Gweru	158,000	1.7	1.2	2.6	0.5	3
Kwekwe	101,000	1.0	0.5	1.9	6.5	3
Kadoma	92,500	0.3	0.1	0.4	3.2	3
Masvingo	87,900	1.0	0.7	3.1	1.5	3
Chinhoyi	78,000	2.1	0.9	3.0	1.5	4
Marondera	62,000	0.3	0.1	0.5	8.5	3
Chegutu	50,600	0.2	0.1	0.5	2.9	3
Bindura	43,600	0.7	0.4	1.3	0.3	3
Rusape	30,300	0.1	0.1	0.1	1.8	3
Nyanga	24,000	4.8	0.6	6.7	5.5	3
Karoi	28,600	0.5	0.3	2.8	0.3	3

processing industry demands high quality potato to minimize losses. Should they encounter high losses, some processing establishments ask for replacements from the supplier, a clause included in their contractual agreement. Expert elicitation indicated that about 65 % of ware potato production in the country is used by the processing industry for the production of French fries. This could be a fair estimate as observations attest the food sector as one of the fastest growing industries in the country today. Street French fries is a recent development being observed in the country. Most respondents were reluctant to reveal their percent gross margin. However, a few gave an indication that a 15 kg fresh potato pocket would give about 28 portions French fries selling at US$ 1 per portion. Fresh potato prices from Mbare Musika wholesale market to processing entities range from 0.53 to 1.1 US$, suggesting lucrative gross margins for processing even if losses were factored in. These high gross margin percentages probably explain the rapid growth in the potato processing sector being observed.

Table 6. Fresh potato processing into French Fries by selected hotels, restaurants and fast-foods outlets in certain metropolitan areas of Zimbabwe derived from interviews data conducted in the period 2011-2014.

Urban area	**Population***	**Mean values and spread [Mg/month]**			**Loss estimate [% of monthly mean]**	**Number interviewed [n]**
		Mean	*Least*	*Highest*		
Harare	1,485,000	53.4	42.5	63.3	0.1	6
Bulawayo	653,000	28.6	25.6	32.8	0.1	6
Mutare	187,600	2.4	0.8	3.7	0.1	3
Gweru	158,000	0.4	0.9	0.6	0.03	3
Kwekwe	101,000	2.3	1.5	3.3	0.5	6
Kadoma	92,500	2.9	2.3	3.3	0.03	3
Masvingo	87,900	1.7	1.0	3.2	1.0	4
Chinhoyi	78,000	2.1	0.9	3.0	0.2	4
Marondera	62,000	1.1	0.7	3.1	1.2	5
Chegutu	50,600	0.7	0.4	1.4	0.2	3
Bindura	43,600	2.1	1.4	3.5	1.0	5
Rusape	30,300	2.4	1.3	3.8	0.3	3
Nyanga	24,000	0.7	0.5	1.8	1.0	8
Karoi	28,600	1.0	0.7	1.6	0.4	3

3.8 Household consumption

Less than 35 % of ware potato production in the country goes to household consumption as fresh potato. The UFV Open Markets are the main sources of fresh potato supply as they are located in the residential areas and besides, have smaller packaging with competitive pricing. Other supply sources include the retail chain supermarkets, small supermarkets and street vendors (Fig. 1). Some Harare residents bought their fresh potato supplies from the Mbare Musika wholesale market (Fig. 1). Tables S1 through S4, show the household potato consumption in selected metropolitan areas and rural service centres. The mean potato household per capita consumption was 34 kg per year. On average households have potato-based meals three times in a week. In Nyanga district, potato is the staple crop, and the highest average household per capita consumption of about 70 kg per year was recorded (Table S4). With an annual population of 13.1 million people (ZimStat, 2012), and annual potato production of nearly 120,000 t, the total consumption per capita in the country is about 9 kg per year. Total per capita consumption of potato in 1984 was only 2 kg (Joyce, 1988). Hence, a substantial growth in total potato consumption has been recorded. The total per capita consumption of potato in South Africa is about 32 kg per person per annum, while for developing countries it is estimated at 14 kg per capita per annum (PSA, 2010). Household potato in Zimbabwe was consumed mainly as boiled, mixed with vegetables, whole fried or sometimes as French fries. Householders pay an average of US$ 1 per kg fresh potato across all metropolitan areas. Respondents reported that potato from South Africa was about 50 %

Table 7. Fresh potato processing into French Fries by selected restaurants and fast-foods outlets in certain Rural Service Centres of Zimbabwe derived from interviews data conducted in the period 2011-2014.

Rural Service Centre	**District**	**Mean values and spread [Mg/month]**			**Loss estimate [% of monthly mean]**	**Number interviewed [n]**
		Mean	*Least*	*Highest*		
Juru	Murehwa	0.2	0.1	0.4	0.2	4
Magunje	Karoi	0.3	0.2	0.4	1.0	3
Murambinda	Buhera	0.4	0.1	0.6	0.5	6
Murombedzi	Zvimba	0.6	0.4	0.9	0.5	3

cheaper; this probably explains why potato smuggling into the country was increasing (Chimoio, 2013).

3.9 Service providers

Key service providers to the potato value chain actors were identified (Fig. 1). For example, the government Seed Services Institute oversees seed certification in Zimbabwe. This mandate is enshrined under the Seeds Act [Chapter 19:13] of 1971 and its enabling regulations, the Seed Regulations (1971), and Seeds Certification Scheme Notice (2000). According to these regulations, registered seed potato companies are given the Certifying Agency status by the Seed Services Institute, the designated Certifying Authority. The seed potato company certifies the seed of its contracted growers under the monitoring and control of the Certifying Authority. Growers interviewed expressed concern over the high cost of certified seed, which contributes 23 to 45 % of the estimated variable cost of production (Table S5). Some growers indicated that often they use retained ware potato as seed to reduce production costs. The Crop Breeding Institute (CBI) is another separate government agency responsible for crop breeding including potato. However, due to financial challenges the government currently faces, the national potato breeding programme is not functioning well. Consequently, CBI has not been able to release any new potato cultivar since the 1990s (Mazarire, personal communication, 2014). Another important government agency is agricultural extension, Agritex. It is responsible for free farmer training and advisory services. Extension services are similarly hindered by financial problems, and growers generally lack the much needed technical support. The majority of the resettlement growers interviewed said that they needed training to improve on their skills and knowledge of the ‘new’ crop, potato. Besides, most agricultural development activities including extension and training focused on the staple food crop maize, and little attention on horticultural production.

Various fertilizer types and biocides used for potato production are now readily available in cities and towns. Besides selling fertiliser and biocides, they also offer free technical services in the form of flyers. Growers cited the problem of high cost of fertiliser. In addition to the high costs, growers incur extra cost of transporting the fertilizer to the farm, hence increasing production costs.

Various stakeholder associations were interviewed. One of them was the Fresh Produce Marketing Association of Zimbabwe (FPMAZ). It is an umbrella body representing most farmers, wholesalers and retailers involved in the formal marketing and production of fresh fruit and vegetables. The association coordinates its membership to ensure consistence of supply throughout the year, and establishing standards for fresh fruit and vegetables. The FPMAZ also works closely with informal traders, mostly those at Mbare Musika wholesale market in Harare. A few non-governmental organisations (NGOs) working with smallholder farmers in fruit and vegetable production and marketing were identified. In addition to giving financial assistance to the farmers, the NGOs also run capacity development training programmes for the farmers, to enable them to participate fully in the various horticultural value chains (USAID-STAMP, 2011; SNV, 2014). These NGOs include the Smallholder Technology and Access To Markets Programme (USAID-STAMP), and the Dutch SNV (Netherlands Development Organisation) (USAID-STAMP, 2011; SNV, 2014).

4. Conclusion and recommendations

The Irish potato value chain in Zimbabwe is quite complex, linking nine main stakeholder groups, and with multiple pathways through which potato can take from the field of production to consumers. Several opportunities exist that chain players should focus on in order to improve the potato value chain performance. Irish potato is now a national strategic food security crop, hence stakeholders should take advantage of this, and implore government to give the crop the necessary support it deserves. The potato value chain has the advantage of local supply monopoly ever since the government imposed a ban on ware potato imports. Sustainable profit margins exists at each link along the chain, a good indicator that the value chain is competitive. The ambitious plan to increase the potato planting area to 30,000 ha annually in the medium term is a positive signal by the potato industry. The thrust is to increase ware potato supply and bring down prices to increase affordability and consumption. Such an approach will likely contribute to the growth of the potato sector in the country. However, the potato value chain in Zimbabwe faces several challenges that may threaten its performance and sustainability. High production costs of ware potato accompanied by low yield levels is a huge problem in the value chain which research should prioritise. Growers need high yielding cultivars and lower production costs in order to realise good returns. This will have the effect of lowering prices and increase potato consumption, and consequently contribute to the growth of the entire potato sector. Meanwhile, growers need training to improve on their skills and knowledge of potato production. Another important issue to be explored is the restoration of private land ownership to enable funding, since most growers have expressed the lack of credit facilities for production. The threat of the introduction of the cyst nematode through ware potato smuggling into the country from neighbouring South Africa needs to be addressed through increased government surveillance of the entry ports. Once the cyst nematode is introduced into the soils, it will be very difficult to eradicate and it can reduce ware potato production. Another challenge is the often poor state of the road network. This affects the smooth transportation of potato to the market and also fertiliser back to the farms. With only about 19 % of the roads paved, the bad roads lead to high depreciation and maintenance costs of trucks, making potato transportation expensive. In addition, the unimproved roads also lead to loss of potato quality during transportation. Similar challenges were reported in Kenya where only 11 % of the roads are paved, which means 89 % are unimproved (Janssens *et al*., 2013). In the Tigary region of Ethiopia, poor road access to production areas, shortage of trucks, high transportation costs and perishability were cited as key problems of potato transportation (Emana and Nigussie, 2011). With widespread poverty, goods distribution challenges are likely to be common in Africa. Another threat is the lack of good sanitary conditions at most UFV open markets visited, including at the busy Mbare Musika wholesale market.

This value chain analysis has demonstrated that the Irish potato industry in Zimbabwe generates very considerable levels of value-addition, leading to profitable businesses at each stage of the value-chain. However, the industry faces several significant challenges and indeed opportunities as already alluded to. These challenges and opportunities provide a strong argument for action by all the stakeholders within the value-chain, government and the other service providers in the ways already suggested. Such action would serve both to safeguard the current profitability and other benefits being generated in the sector, and to increase such benefits in the future. Value chain analysis has not been widely adopted in the Irish potato sector in Zimbabwe while focus was instead on research and interventions on the technical production issues. This paper has demonstrated that value chain analysis is a useful tool to identify critical factors impacting on the performance of the potato sector. A better understanding of these factors can inform the necessary interventions to improve the performance of the sector.

Supplementary material. Household potato consumption in selected metropolitan areas, and Rural Service Centres of Zimbabwe derived from household interviews data conducted in the period 2011-2014.

Table S1. Household potato consumption (average, minimum and maximum values) in the large[*] metropolitan areas of Zimbabwe derived from household interviews data conducted in the period 2011-2014.

Urban area name	Household characteristic	Average	Range
Bulawayo	*Household size*		
	low density	4.7	1 – 10
	high density	5.4	2 – 10
	Weekly potato-based meals		
	low density	3.8	1 – 7
	high density	3.0	0 – 7
	Potato consumption		
	low density [kg/c/yr[#]]	34.5	3 – 91
	high density [kg/c/yr[#]]	21.4	0 – 80
Harare	*Household size*		
	low density	4.2	2 – 6
	high density	4.1	2 – 9
	Weekly potato-based meals		
	low density	3.3	0 – 7
	high density	3.0	1 – 7
	Potato consumption		
	low density[kg/c/yr[#]]	44.5	0 – 88
	high density[kg/c/yr[#]]	39.7	4 – 90

Key: [*] = population above 650,000 people (ZimStat, 2012), [#] = kilograms per capita per year

Table S2. Household potato consumption (average, minimum and maximum values) in selected medium[*] metropolitan areas of Zimbabwe derived from household interview data conducted in the period 2011-2014.

Urban area name	Household characteristic	Average	Range
Gweru	*Household size*		
	low density	2.5	1 – 4
	high density	4.4	1 – 10
	Weekly potato-based meals		
	low density	4.2	1 – 6
	high density	3.1	0 – 7
	Potato consumption		
	low density [kg/c/yr[#]]	33.2	12 – 44
	high density [kg/c/yr[#]]	31.4	0 – 64
	Household size		
Kadoma	low density	4.2	1 – 8
	high density	4.2	1 – 15
	Weekly potato-based meals	3.9	1 – 7
	low density	3.2	1 – 7
	high density		
	Potato consumption		
	low density[kg/c/yr[#]]	49.8	7 – 66
	high density[kg/c/yr[#]]	50.3	2 – 68
Kwekwe	*Household size*		
	low density	4.3	2 – 6
	high density	4.7	1 – 11
	Weekly potato-based meals		
	low density	2.6	1 – 6
	high density	3.1	1 – 7
	Potato consumption		
	low density[kg/c/yr[#]]	25.2	6 – 34
	high density[kg/c/yr[#]]	34.7	8 – 69
Masvingo			
	Household size		
	low density	3.3	2 – 6
	high density	4.7	2 – 9
	Weekly potato-based meals		
	low density	2.7	0 – 7
	high density	3.0	0 – 7
	Potato consumption		
	low density[kg/c/yr[#]]	18.5	0 – 34
	high density[kg/c/yr[#]]	32.5	0 – 67
Mutare	*Household size*		
	low density	4.3	3 – 6
	high density	4.4	2 – 8
	Weekly potato-based meals		
	low density	2.3	1 – 7
	high density	2.9	0 – 7
	Potato consumption		
	low density[kg/c/yr[#]]	17.2	6 – 33
	high density[kg/c/yr[#]]	37.8	0 – 65

Key: [*] = population range 90-200,000 people (ZimStat, 2012), [#] = kilograms per capita per year

Table S3. Household potato consumption (average, minimum and maximum values) in selected small[*] metropolitan areas of Zimbabwe derived from household interview data conducted in the period 2011-2014.

Urban area name	Household characteristic	Average	Range
Bindura	***Household size***		
	low density	3.8	3 – 5
	high density	3.5	3 – 5
	Weekly potato-based meals		
	low density	4.1	2 – 5
	high density	4.0	2 – 7
	Potato consumption		
	low density [kg/c/yr[#]]	25.2	12 – 35
	high density [kg/c/yr[#]]	36.4	28 – 64
Chegutu	***Household size***		
	low density	4.2	2 – 7
	high density	4.1	1 – 9
	Weekly potato-based meals	3.8	1 – 7
	low density	3.1	1 – 7
	high density		
	Potato consumption		
	low density[kg/c/yr[#]]	24.2	5 – 48
	high density[kg/c/yr[#]]	26.5	6 – 56
Chinhoyi	***Household size***		
	low density	5.9	4 – 9
	high density	4.5	1 – 9
	Weekly potato-based meals	3.1	1 – 5
	low density	3.7	1 – 7
	high density		
	Potato consumption		
	low density[kg/c/yr[#]]	28.4	22 – 54
	high density[kg/c/yr[#]]	18.0	7 – 44
Karoi	***Household size***		
	low density	3.9	2 – 8
	high density	4.6	1 – 10
	Weekly potato-based meals		
	low density	4.4	1 – 7
	high density	3.6	1 – 10
	Potato consumption		
	low density[kg/c/yr[#]]	37.0	10 – 64
	high density[kg/c/yr[#]]	35.2	6 – 55
Marondera	***Household size***		
	low density	4.2	3 – 8
	high density	4.3	3 – 9
	Weekly potato-based meals		
	low density	3.5	1 – 5
	high density	4.3	1 – 7
	Potato consumption		
	low density[kg/c/yr[#]]	36.5	18 – 57
	high density[kg/c/yr[#]]	44.6	12 – 66

Key: [*] = population below 80,000 people (ZimStat, 2012), [#] = kilograms per capita per year

Table S4. Household potato consumption (average, minimum and maximum values) in selected rural service centres of Zimbabwe derived from household interview data conducted in the period 2011-2014.

Rural service centre	Potato growing area	Household characteristic	Average	Range
Juru	Harare	Household size	5.0	2 – 7
		Weekly potato-based meals	1.6	0 – 3
		Potato consumption [kg/c/yr#]	16.5	0 – 29
Magunje	Karoi	Household size	4.8	1 – 16
		Weekly potato-based meals	3.3	1 – 14
		Potato consumption [kg/c/yr#]	43.3	2 – 74
Masembura	Bindura	Household size	4.6	1 – 10
		Weekly potato-based meals	2.0	0 – 7
		Potato consumption [kg/c/yr#]	25.0	0 – 79
Murombedzi	Chegutu	Household size	4.2	1 – 10
		Weekly potato-based meals	3.3	1 – 8
		Potato consumption [kg/c/yr#]	37.6	3 – 70
Tombo 1	Nyanga	Household size	5.6	1 – 12
		Weekly potato-based meals	3.4	1 – 7
		Potato consumption [kg/c/yr#]	70.2	54 – 100

Key: # = kilograms per capita per year

Table S5. Characteristic gross margin analysis per ha of Irish potato production in the different potato production systems in Zimbabwe, 2011 to 2014.

Item	**A1 resettlement (n = 5)**		**Communal area (n = 18)**		**A2 resettlement (n = 6)**		**Large-scale commercial (n = 7)**		**Quarantine area (n = 3)**	
	Cost (US$)	% of TVC	Cost (US$)	% of TVC	Cost (US$)	% of TVC	Cost (US$)	% of TVC	Cost (US$)	% of TVC
Seed	990	45	1570	39	2200	24	2270	23	2500	27
Fertiliser	600	27	1250	31	1600	17	1700	17	1700	18
Biocide	350	16	750	19	950	10	1080	11	1250	14
Transport (inputs to farm)	40	2	50	1	70	1	80	1	80	1
Land preparation	0	0	0	0	145	2	145	1	145	2
Planting	0	0	0	0	55	1	55	1	55	1
Spraying	0	0	0	0	250	3	250	3	350	4
Ridging	0	0	0	0	110	1	110	1	0	0
Irrigation	0	0	0	0	750	8	750	8	0	0
Harvesting	0	0	0	0	80	1	80	1	80	1
Packing materials	100	5	225	6	305	3	370	4	305	3
Transport (produce to market)	0	0	0	0	1550	17	1800	18	1550	17
Labour	0	0	0	0	750	8	750	8	750	8
Sub-total	2080		3845		8815		9440		8765	
Miscellaneous cost (2% of sub-total)	42		77		176		189		175	
TVC per ha (US$ ha^{-1})	2122		3922		8991		9629		8940	
TVC per tonne (US$ t^{-1})	265		231		391		344		389	
Average yield (t ha^{-1})	8		17		23		28		23	
Blend selling price (US$ t^{-1})	500		500		500		500		1100	
GI (US$ ha^{-1})	4000		8500		11500		14000		25300	
GM per ha (US$ ha^{-1})	1878		4578		2509		4371		16360	
GM per tonne (US$ t^{-1})	235		269		109		156		111	
GM per 1 US$ TVC	0.89		1.17		0.28		0.45		1.83	

Key: TVC = Total Variable Cost; GI = Gross Income; GM = Gross Margin; US$ = United States Dollar.

Chapter 6

A quantitative framework for evaluating sustainability of Irish potato cropping systems in Zimbabwe

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Abstract

Frameworks to evaluate the sustainability of cropping systems in developing countries are scarce. This study proposes a framework to select easily quantifiable indicators that can be used to assess and communicate the sustainability of cropping systems in developing countries. The widely accepted social, economic and environmental dimensions of sustainability were covered using pre-defined criteria from which in turn the indicators were drawn. An initial large list of indicators was established based on literature review and expert opinion, and through a filtering process the list was reduced to 16 representative core indicators. Using the case of Irish potato-based cropping systems, a grower survey was conducted to collect data on potato production practices in four different potato cropping systems in Zimbabwe. The grower survey data was used to calculate the sustainability indicators expressed as resource use efficiencies based on the actual potato yields. The survey data also served as input into the Cool Farm Tool-Potato model to estimate greenhouse gas emissions from farm operations involved in potato production. With the help of local agricultural extension officers, focus group discussions were held with farmers of each production system to decide on the sustainable and unsustainable indicator threshold levels. The participatory nature of the framework involving farmers and local extension officers secures the buy-in of key stakeholders important for operationalisation, monitoring and evaluation.

Key words: Cropping systems, Sustainability indicators, Irish potato, Sustainability dimensions, Zimbabwe.

1. Introduction

The need for sustainability of agricultural production systems is now widely recognised. Sustainable agricultural systems are robust and persevere over an indefinite period of time while delivering favourable economic, social and environmental outcomes (Hansen, 1996; Pretty, 2007). The thrust towards sustainability of wide-ranging agricultural or food systems needs to be monitored and evaluated regularly. Consequently, the question of what framework or protocol to use to select easily quantifiable indicators arises.

Indicators can be viewed as quantitative measurements against which performance of certain management interventions can be assessed (Pannell and Glenn, 2000). Effective indicators communicate technical and complex phenomena in a quantitative manner that targeted users can readily understand and relate to (Becker, 2004; Ramos and Caeiro, 2010). In this way, stakeholders can translate sustainability indicators into policy and subsequently into action to implement the policy. Indicators also serve to provide development trends or indicate trajectory tracking progress (Patterson, 2006). Therefore, this implies that a benchmark is needed against which the indicator can be evaluated. The benchmarks or reference values for each indicator can include results from experimental plots under the best treatments, data from best performing farmers or technologies, or comparisons with neighbouring countries.

Another important dimension is the participation of the end user stakeholders in indicator conceptualisation and development. Such involvement capacitates the users, and most likely they will appreciate and apply the indicators (Mascarenhasa *et al*., 2014). Breckenridge *et al*. (1995) argued that indicators for natural resource management have been commonly identified, evaluated and selected by researchers. This renders the indicators less meaningful because the local communities will require training and equipment to use them, provisions seldom given. In order to avoid this trap, meaningful participation of all stakeholders in the entire process of indicator identification, evaluation and selection is essential (Reed and Dougill, 2002). However, involving stakeholders and their respective interest groups to develop sustainability indicators is a complex process, even for experts (Vaidya and Mayer, 2014). There is potential for conflicting perceptions, and diverse socio-economic preferences rendering the process a challenge (Johnson, 1999). Notwithstanding these setbacks, participatory approaches are emerging as more holistic methods of assessing sustainability and indicator sets develop (Vaidya and Mayer, 2014).

While sustainability assessments are increasingly seen as important tools to assist the transition towards sustainable development, very few assessment processes are being implemented anywhere in the world (Pope *et al*., 2004). Especially in the developing world, use of the many tools or methods developed to assess agricultural sustainability is hampered by lack of data (König *et al*., 2012). In the last decade, scientists have come up with many integrated frameworks to aid decision-making in sustainability assessment processes (Paracchini *et al*., 2011; Vaidya and Mayer, 2014). However, the main focus especially in the developing world was on land use and natural resources management (Reed and Dougill, 2002; Reidsma *et al*., 2011; Purushothaman *et al*., 2012; König *et al*., 2012). Few studies though focused on cropping sustainability frameworks, for example the cases in Bangladesh (Roy and Chan, 2012), and Benin in Sub-Saharan Africa (Yegbemey *et al*., 2014).

Zimbabwe, like most countries in southern Africa, has a very strong smallholder cropping system based on maize (*Zea mays*), and its sustainability has received increased research efforts in the last two decades (Carter and Murwira, 1995; Smaling, 1998; Waddington *et al*., 2007; Kurwakumire, 2014; Nezomba, 2015). Communal area farming in Zimbabwe is practised on about 50 % of the total land area of 390,000 km^2 (Campbell *et al*., 1997). Research efforts in the smallholder maize-based cropping systems centred on soil fertility (Kumwenda *et al*., 1996; Waddington *et al*., 2004; 2007), soil organic matter (Swift and Woomer, 1993), soil erosion (Elwell, 1984), and crop yields as proxy of sustainability indicators of the system. However, no base levels of each of these indicators were selected as benchmarks to assess progress, and no relevant early-warning information was provided on the environmental, economic, and social state of this system. In order to address these concerns, there is a need to define a framework to assess the sustainability of cropping systems in Zimbabwe that can be applied to develop the most relevant indicators to guide decision making by all stakeholders. It is to this end that the framework for evaluating sustainability of cropping systems described in this study was devised. A practical application is provided through the example of Irish potato (*Solanum tuberosum*) cropping systems in the Eastern Highlands of Zimbabwe.

2. Contextualisation of the study area

Zimbabwe undertook a fundamental land reform programme at the turn of the millennium when about 96 % of the original 12.5 million ha large-scale commercial farmland in 1980, was taken up for resettlement by 2010 (Moyo, 2011). Two resettlement models were used. The A1 resettlement model where beneficiary households were allocated about 6 ha arable land and communal grazing land; and the A2 resettlement model with self-contained farm units ranging from about 35 to 300 ha depending on the agro-ecological environment. In Nyanga district (Fig. 1), the resettled farmers have since started growing potato adding growers to the already existing communal area potato farmers and the few remaining large scale commercial farmers (Svubure *et al*., 2015).

Substantial growth in Irish potato annual planting area, output and average yield has been witnessed in the last decade. Total annual production increased steadily from about 36,500 t in 2001 to over 58,000 tonnes in 2013 due to constant increases in both cropped area and yield (FAOSTAT, 2013). However, experts estimate annual potato planting area at around 6,000 ha and annual production at nearly 120,000 t (Ackerman, personal communication, 2013; Manzira, personal communication, 2013). Irish potato has become the most important horticultural crop in the country and the third most important carbohydrate food source after maize and wheat (The Herald, 2011). Besides, stakeholders in the potato industry have an ambitious plan to increase planting area to 30,000 ha annually in the medium term (USAID-STAMP, 2011; The Herald, 2011; Ackerman, personal communication, 2013). This is motivated by the rising potato demand and by assurances of sufficient seed potato quantities from the seed companies (The Herald, 2011; Ackerman, personal communication, 2013). In addition, the government provided a major policy boost to the industry by declaring Irish potato a national strategic food security crop on 18 May 2012 (The Herald, 2012). Hence together with maize, potato is now included in the government input and mechanisation support schemes (The Herald, 2012).

The cropping system in southern Nyanga (Fig. 1) is Irish potato-based, making the area a natural choice for this study. Irish potato is the staple food crop in this area. In terms of rainfall and temperature pattern, the Eastern Highlands which covers virtually the whole of southern Nyanga provides the best agro-ecological environment for potato production in Zimbabwe. The high elevations greater than 1,800 m above mean sea level gives the Eastern Highlands a characteristic temperate micro-climate and vegetation. Using average climatic data for the period 1985 through 2010, mean monthly minimum temperature ranges from 5 °C in July to 13 °C in January; whereas mean monthly maximum temperature ranges from 17 to 23 °C in July and November respectively (Fig. 2). The rainy season runs from October till April, but the Eastern Highlands receive rainfall throughout the year, with monthly

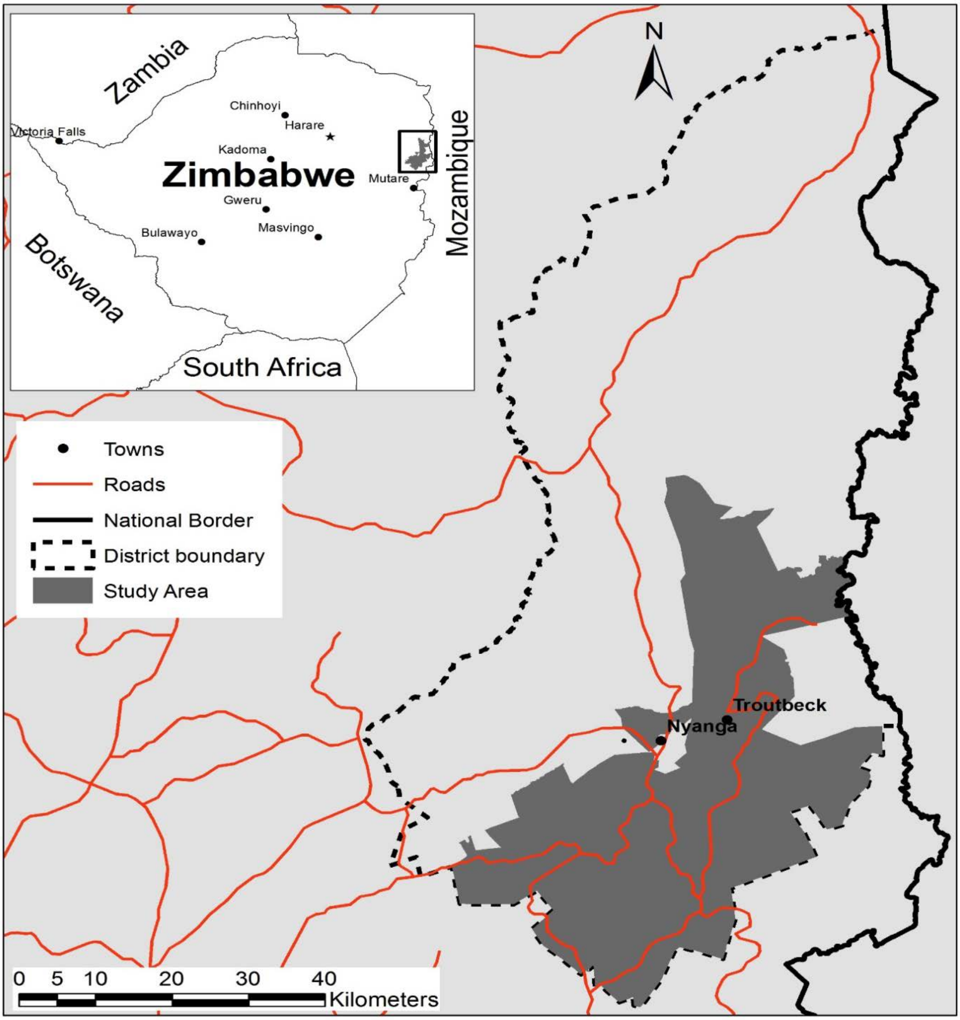

Fig. 1. Map of Nyanga district in Zimbabwe showing location of the study area.

precipitation ranging from 14 mm in August to 340 mm in January (Fig. 2). Potato is generally grown throughout the year; supplementary irrigation is applied during the relatively dry winter months. However, the following growing calendar is common: summer crop (November through March), early winter crop (February through May) and a late winter crop planted in June/July or early August in frost-prone areas and harvested in November/December.

A total of four potato-based cropping systems can be distinguished in Nyanga district mainly due to the effect of management and mechanisation levels. These are the communal and A1 resettlement (smallholder) systems, and the large-scale commercial and A2 resettlement (large-scale) systems (Svubure *et al*., 2015). However, within each production system, heterogeneity may exist as the mix of opportunities available to one farming household may be quite different from that available to another leading to correspondingly different cropping management practices (Campbell *et al*., 1997). Some A2 resettlement and large-scale commercial farmers are located in a designated Quarantine area in southern Nyanga (Fig. 1).

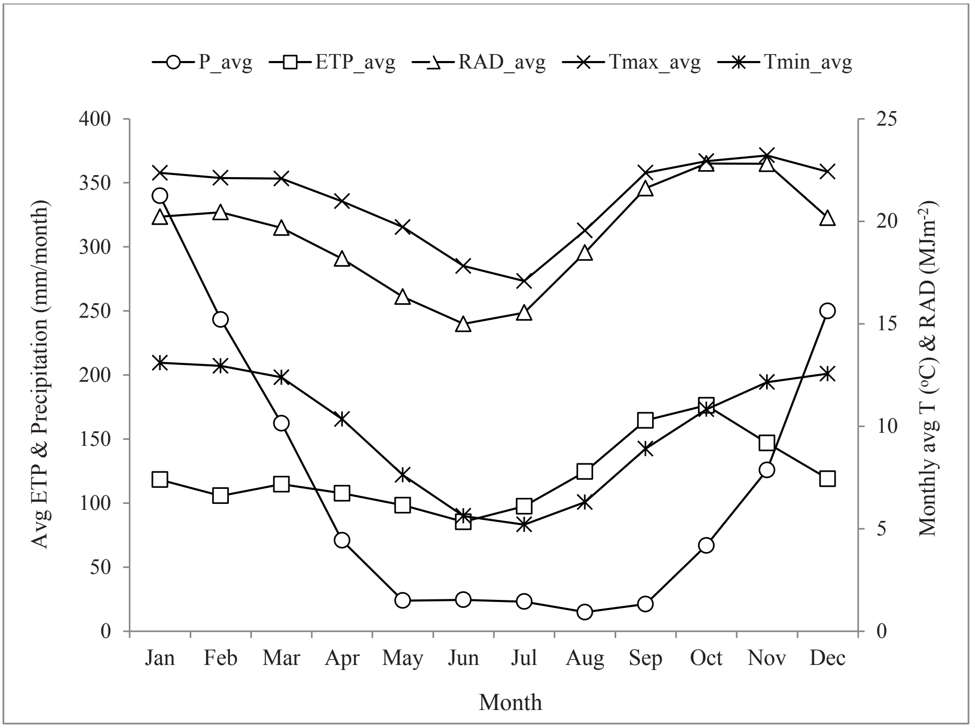

Fig. 2. Monthly average precipitation (P), evapotranspiration (ETP), minimum temperature (Tmin), maximum temperature (Tmax) and radiation (RAD) in Nyanga Eastern Highlands of Zimbabwe, using climatic data of the period 1985 to 2010 obtained from the Meteorological Services Department of Zimbabwe.

It is an isolated zone created by a statutory instrument in 1956 when the government started a potato breeding programme, and is responsible for the initial potato seed multiplications (Joyce, 1982). No other solanaceous plants are allowed in this area to maintain disease-free tubers. The seed potato is rain-fed because of the risk of Bacterial wilt from the soil-borne bacterium *Ralstonia solanacearum*, causal organism of brown rot which can be found in sediments in the irrigation water. For this reason, Quarantine area growers do not have irrigation systems (Ackerman, personal communication, 2012).

3. Framework for evaluating sustainability of Irish potato cropping in Zimbabwe

Drawing from the concept of expert-assisted participatory approach (Vaidya and Mayer, 2014), the cropping systems sustainability assessment framework was developed (Fig. 3). This approach involves stakeholder participation in the entire process of indicator identification, evaluation and selection with the help of experts. In this study, two kinds of stakeholder groups were involved: end-user (farmers) and expert stakeholders. Participating the farmers (end-users) in the entire process was important to ensure that indicators selected accurately measure what is locally relevant. Besides, engagement of the local farmers may help build community capacity to address future sustainability challenges or other challenges requiring a community-based approach (Fraser *et al*., 2006). In the expert stakeholder group, participants included were drawn from both the private and public sectors with knowledge and influence on the Irish potato sector in Zimbabwe (Santana-Medina *et al*., 2013). The proposed framework is meant to be simple to enable farmers to apply it themselves with limited input from outside organisations such as the government extension agency, Agritex, which is mandated anyway to offer free advisory services to the farming community. For example, farmers should be able to measure actual potato yield, input use and keep such records in order to monitor changes over time. The framework described later is made up of six steps, and while it incorporates scientific issues, these can simultaneously aid policy making and action by end users.

The remainder of the chapter is organised as follows: first a generic description of the proposed framework (Fig. 3) used to evaluate the sustainability of the Irish potato cropping systems in Zimbabwe is given. Second, the case study on Irish potato is outlined. Third, the results of application of the framework in southern Nyanga district (Fig. 1) are presented. The fourth section discusses the empirical results of the application of the framework, while the final section provides key conclusions derived from this case study.

3.1 Understanding sustainability of cropping systems

The initial step involved defining the boundaries of spatial and temporal scales of analysis of the crop production systems in Zimbabwe. Perhaps even more important than an indicator of condition in a system, is the management practice that yields the condition. Campbell *et al.* (1997) argues that the cropping systems in Zimbabwe can be distinguished by cultural practices used, technology level, and also socio-political, and economic circumstances. For example, the smallholder (communal and A1 resettlement) systems are markedly different from the large scale (A2 resettlement and large scale commercial) systems, even when located adjacent to each other under the same bio-physical conditions. Also some heterogeneity exists within each cropping system due to differences in access to resources (Campbell *et al.*, 1997). This consequently leads to different approaches in potato production practices such as input use. Nevertheless, the different production systems are still of interest as spatial scales in sustainability assessments. While the objectives and criteria for selecting indicators is the same, the targets and time scale to achieve them will likely be different between the different cropping systems. Sustainability entails continuity into an indefinite period of time (Hansen, 1996), but circumstances change which require revision of indicator targets from time to time. Hence the time scale boundaries were also discussed during this first step in the framework.

3.2 Listing, filtering and identification of representative indicators

The second step of the framework involved listing of possible indicators and filtering them to identify the most relevant ones. The listing, based on literature review and expert elicitation categorised the indicators along the environmental, economic and social dimensions which cover the sustainability of crop production systems. For each sustainability dimension, the criteria for indicator selection included ease of measurability (Gómez-Limón and Sanchez-Fernandez, 2010; Roy and Chan, 2012; van Asselt *et al.*, 2014), and indicator responsiveness to changes in management practices or natural variability (Campbell *et al.*, 1997; Bélanger *et al.*, 2012).

3.3 Data collection to measure indicators

In step 3 of the framework, field surveys, and expert elicitation were undertaken to collect all data relevant for computing the possible indicators.

3.4 Benchmark/sustainability limits

In step 4, benchmark or sustainability limits are set against which the indicators are evaluated. Relevant simulation models when available can be used to set benchmarks or performance limits under different crop production scenarios. If the models cannot provide limits for certain indicators, government policy targets or legal limits, if available, can be used. Another alternative is to use the best performance available as the benchmark or sustainability limit as was applied by Haverkort *et al*. (2009) in a similar study. Stakeholder consensus on a sustainable limit and expert elicitation are yet other possible approaches. In this study the sustainability indicators were expressed as resource use efficiencies based on the actual yields, and generally indicator values below the average were considered unsustainable. definition.

3.5 Decision making process

The fifth step involves indicator selection by end user stakeholders with the help of experts.
In the context of this study, the end user stakeholders referred to were the farmers in the different potato production systems in Zimbabwe, and participation meant their involvement together with agricultural extension officers in indicator selection and time frames to attain sustainability. The role of researchers was mainly to coordinate the group focus discussions toward achieving consensus. Several assessments on cropping sustainability convert the data of base indicators into indices or scores and aggregate them into composite indicators as overall evaluation of performance (Gómez-Limón and Sanchez-Fernandez, 2010; Yegbemey *et al*., 2014; van Asselt *et al*., 2014). Gómez-Limón and Sanchez-Fernandez (2010) urges the use of such indices with caution in all cases, asserting that a single measure cannot accurately appraise agricultural performance. However, there are pros and cons on the use of composite indicators (Saisana and Tarantola, 2002). In the proposed framework for evaluating sustainability of Irish potato cropping systems in Zimbabwe described here, the indicators used were expressed as resource use efficiencies. Once the actual indicator values were established in step 3, the decision making process (step 5) established the desired levels of resource use efficiency, which represented the desired level of sustainability.

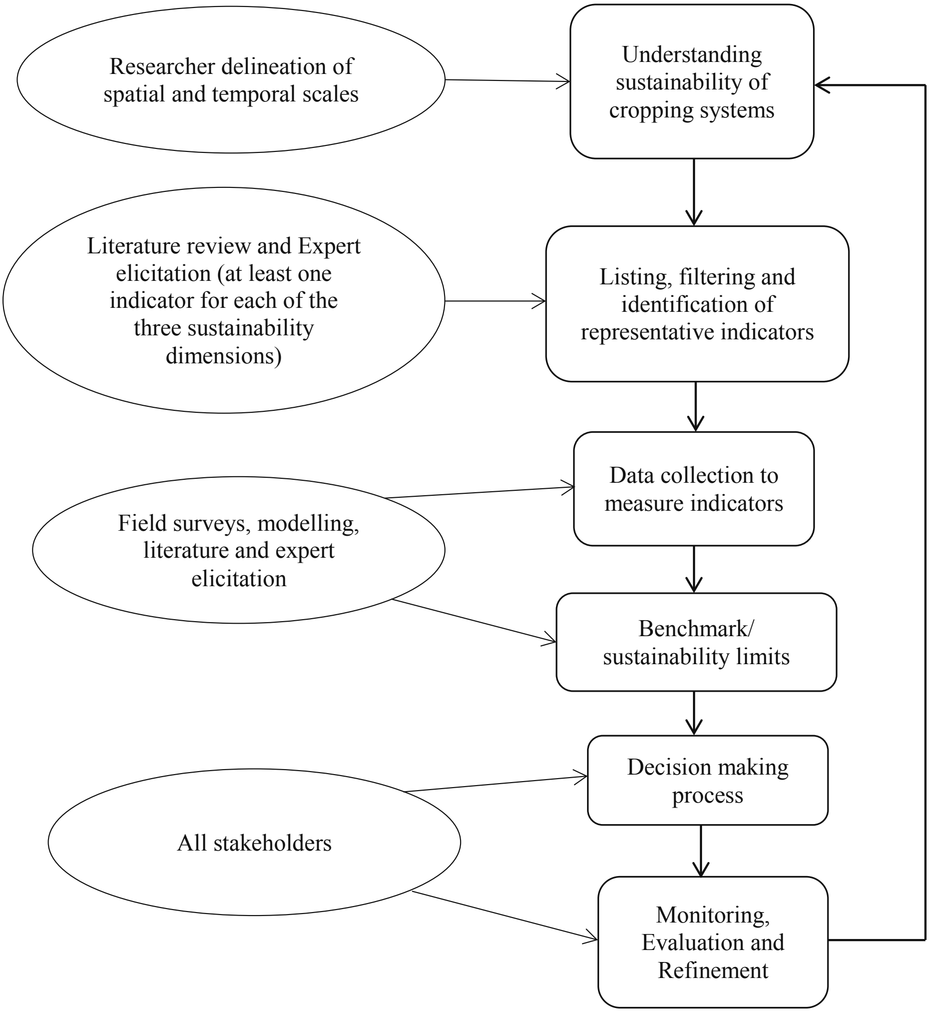

Fig. 3. Proposed framework for evaluating sustainability of Irish potato cropping systems in Zimbabwe

3.6 Monitoring, evaluation and refinement

Finally, in step 6 grower performance is evaluated from time to time to monitor progress toward attaining sustainability. Refinement is an integral part of the continuous monitoring and evaluation process to improve the framework as it unfolds in practice. Using a crop production ecology approach of sustainable cropping, Haverkort *et al.* (2009) described how sustainability indicator values expressed as resource use efficiency may move from unacceptably low values to sustainable levels over a grace period of time. In this framework, a similar approach is proposed where a grace period of time is allowed for growers with unsustainable indicator values to attain sustainability. While some growers can evaluate themselves, the department of Agritex is expected to help the majority of the growers. For example, at the end of each harvest season, the actual potato yield of each grower was measured and compared with the unsustainable threshold. The ultimate objective is continuous movement of the farmer threshold to the desired direction of sustainability.

4. The case study

4.1 Delineating the spatial and temporal scales

In order to test the application of the framework, the sustainability of the different potato cropping systems in southern Nyanga district (Fig. 1) was studied. Thus the four different potato production systems namely the smallholder (communal and A1 resettlement) systems and the large scale (A2 resettlement and large scale commercial) systems were delineated as the spatial scales in this study. Annual time-lines were used to capture the progression of indicator values toward agreed sustainability values.

4.2 Data collection

The data collection process included first the listing of relevant indicators through a literature review and expert elicitation process, followed by conducting a grower survey to establish the potato production practices in the different systems. The grower survey data was used first to calculate the sustainability indicators expressed as resource use efficiencies based on the actual yields, and second as input data to the Cool Farm Tool (CFT)-Potato model (Haverkort and Hillier, 2011). The CFT-Potato model was used to estimate greenhouse gas (GHG) emissions from farm operations involved in potato production. Finally and with the help of the local extension officers, focus group discussions were held with growers of each production system to decide on the pilot indicators including the associated threshold levels of sustainability.

For each dimension of sustainability, relevant indicators were listed mainly from extensive review of literature and expert elicitation. The panel of experts were drawn from both the public agricultural service and from private institutions in the potato sector. A total of four experienced agricultural extension officers from the government extension agency, Agritex office in Nyanga, were consulted. The potato breeder with the government's Crop Breeding Institute (CBI), and officers responsible for the Nyanga Experiment Station located in Nyanga, where potato breeding work is undertaken, were also consulted. Another key expert was one prominent large-scale commercial seed potato grower located in the Quarantine area. Also consulted was an officer from the Seed Potato Coop, the only seed potato company currently active in the country. The composition of this pool of experts was based on their vast knowledge of and experience in the potato-based cropping systems in the study area. Indicators chosen were those that could be computed easily from the data directly provided from the growers at minimum cost.

Grower data collected included land preparation, planting, input use, inputs cost estimate, weed and pest management, water management, energy use, harvesting and marketing. Selection of growers for the survey was limited to those growers with a minimum of 5 continuous years potato farming experience, making the data collected dependable. The sample included three large-scale commercial growers and four A2 resettlement growers from the Quarantine area where only 21 out of the 27 growers in the area are active (Ackerman, personal communication, 2012). A further 18 communal area growers, 5 A1 resettlement growers and one of the four remaining large scale commercial growers, all outside the Quarantine area completed the study sample. Agritex officials estimated the A1 resettlement growers to number less than 100 in Nyanga, while over 1,500 communal area households plant about 800 ha potato annually (Svubure *et al.*, 2015). Generally all growers or their managers could readily respond to the questions asked on their potato growing practices.

The CFT-Potato model as described by Haverkort and Hillier (2011) was used to estimate GHG emissions from operations undertaken in potato production, from the seed material through storage of the harvested potato product. The model output reports the factors or farm operations and their respective estimates of GHG emission (e.g., in kg CO_2 eq./t), and sums them up into a single value and this immediately tells which system is more efficient or sustainable. Each grower data set was run separately and the mean GHG emissions for each activity were computed for each production system.

After calculating all the indicators for each farmer, group focus discussions were then conducted following the general guidelines suggested by Ritchie and Lewis (2012). The focus group discussions decided on the indicators to use on each dimension of sustainability including the threshold levels. For each production system, separate focus group discussions were held. The group discussions were comprised of the farmers, local extension officers and the researchers. A total of three focus group discussion meetings were held for the communal area production systems, one in each of the three different locations in the study area from where the farmers were drawn. For the other production systems, one discussion meeting was held for each system since few farmers were involved in all these cases.

5. Results

5.1 Establishing sustainability indicators

One of the initial steps in the framework (Fig. 3) was to choose indicators for the evaluation of cropping sustainability that would cover the three dimensions of sustainability already alluded to namely: economic, environment and social. The criteria for each sustainability dimension were defined, from which in turn the indicators were derived as shown in Table 1. A total of 16 indicators were selected from an initial large list compiled on the basis of literature review and discussions with the identified experts. Using this list of indicators (Table 1) and the grower survey data, the mean indicator values and range were calculated for each production system; they are summarised in Table 2.

5.2 Sustainability indicator values of the production systems

The average potato yield, produce price and the gross margin per dollar TVC were chosen as the sustainability indicators associated with land productivity. The grower survey showed that the average potato yield ranged from 8 t/ha in the A1 resettlement to 23 t/ha in the large scale commercial production system (Table 2). Within the different production systems, variations in yield were observed with the largest yield range of 37 t/ha being reported in the communal area system (Table 2). This wide yield range in the communal area cropping system suggests the existence of unsustainable yield levels by growers in the lower part of the range. The produce (farm gate) prices ranged from 0.4 to 0.8 US$/kg potato across all production systems, whereas the return per dollar invested ranged from 0.28 to 1.17 US$ (Table 2). Average production costs in each production system were computed using the general production practices and input use from the grower interviews. Using a blend farm gate price and the actual yield of each grower, the gross margin of each grower was calculated from which the return per dollar invested were derived.

Table 1. Overview of dimensions of sustainability and their respective criteria and indicators for assessing sustainability of Irish potato-based cropping systems in Nyanga district, Zimbabwe.

Sustainability dimension	Criteria	Indicators
Economic	Land productivity/profitability	Yield (t potato/ha)
		Produce price (US$/kg potato)
		GM/1 US$ TVC
Environment	GHG emission reduction	GHG emission (kg CO_2 eq./t potato)
		GHG emission (kg CO_2 eq./ha)
	Minimal use of natural resources	Yield (t potato/ha)
		Nitrogen use (g potato/g N)
		Phosphorus use (g potato/g P)
		Potassium use (g potato/g K)
		Irrigation water use (g potato/l)
	Environmental impact of biocides	Fungicide (kg potato/g a.i.)
		Insecticide (kg potato/g a.i.)
		Nematicide (kg potato/g a.i.)
		Herbicide (kg potato/g a.i.)
		Potato rotation (number of years)
Social	Farmer livelihood	GM/1 US$ TVC
	Farmer community participation	Field discussion days (number/year)
		Farmer training meetings (number/year)

Key: GM = Gross margin; TVC = Total variable cost; US$ = United States Dollar; CO_2 eq. = Carbon dioxide equivalent; a.i. = active ingredient; N = nitrogen; P = phosphorus; K = potassium.

Although the return was high in the smallholder A1 resettlement and communal area production systems, incomes remained low because of the low volumes of crop traded due to low yield levels.

The criteria for the environmental dimension of sustainability included GHG emission reduction, minimisation of extraction or use of natural resources and the impact of biocide use on the environment (van Asselt *et al*., 2014). The actual potato yields from the grower survey were used to calculate the indicator values of GHG emission, nutrients, biocides and water expressed as resource use efficiencies (Table 2). Mean GHG emission as estimated by the

Table 2. Farm characteristics, sustainability issues and indicators in Irish potato production derived from grower interviews in the different potato production systems in Nyanga district, Zimbabwe, in the period 2011 – 2014.

Sustainability issue	**Indicators**	**Production system**							
		LSC		**A2**		**A1**		**CA**	
		avg	range	avg	range	avg	range	avg	range
Farm characteristics									
Gross area [ha]		510	140 – 1000	98	12 – 220	na	na	na	na
Cropping area [ha]		183	50 – 400	46	7 – 120	4	2 – 6	3	1 – 7
Area irrigated [ha]		14	0 – 55	3	0 – 22	0.4	0 – 0.8	1	0 – 4
Area per planting [ha]		21	10 – 45	9	0.4 – 20	0.4	0.1 – 0.8	1	0.4 – 4
Land	Yield (t/ha)	23	12 – 35	19	12 – 32	8	7 – 13	17	8 – 45
	Rotation (years)	4	4 – 4	3	1 – 4	1	1 – 2	1	1 – 2
Economic/financial	Producer price (US$/kg)	0.5	0.4 – 0.8	0.5	0.4 – 0.8	0.5	0.4 – 0.8	0.5	0.4 – 0.8
	GM/1US$ TVC	0.48		0.28		0.89		1.17	
Mineral fertilisers	FUE_N (g potato/g N)	170	138 – 228	104	69 – 184	97	72 – 130	120	68 – 198
	FUE_P (g potato/g P)	46	38 – 60	41	21 – 75	46	22 – 59	41	22 – 63
	FUE_K (g potato/g K)	82	70 – 110	82	50 – 121	81	46 – 91	102	66 – 189
Biocides	BUEf (kg potato/g a.i.)	0.9	0.9 – 0.9	0.5	0.4 – 0.9	0.5	0.3 – 0.9	0.6	0.4 – 1.4
	BUEi (kg potato/g a.i.)	11	9 – 13	14	12 – 19	8	7 – 11	14	10 – 24
	BUEn (kg potato/g a.i.)	10	9 – 14	8	5 – 13	3	3 – 5	7	4 – 18
	BUEh (kg potato/g a.i.)	13	11 – 16	10	6 – 16	na	na	9	5 – 23
Irrigation water	WUEir (g potato/l)	9	9 – 9	4	3 – 4	5	2 – 6	2	1 – 6
Environment	kg CO_2 eq./t	228	143 – 372	277	99 – 479	240	180 – 297	216	62 – 331
	kg CO_2 eq./ha	4030	3549 – 4720	4139	2763 – 6819	1946	1217 – 2982	2868	1817 – 4005
Farmer training	Field discussion days (no./yr.)	2	1 – 3	2	1 – 3	3	2 – 4	4	3 – 5
	Training meetings (no./yr.)	1	1 – 2	1	1 – 2	4	3 – 6	5	4 – 7

Key: GM = Gross margin; TVC = Total variable cost; US$ = United States Dollar; CO_2 eq. = Carbon dioxide equivalent; BUE = Biocide use efficiency; a.i. = active ingredient; FUE = Fertiliser use efficiency; N = nitrogen; P = phosphorus; K = potassium; WUEir = Irrigation water use efficiency; f = fungicide; i = insecticide; n = nematicide; h = herbicide; na = not applicable; no./yr. = number per year; avg = average; LSC = Large scale commercial; A1 = A1 resettlement.; A2 = A 2 resettlement; CA = Communal area.

CFT-potato model ranged from 216 kg CO_2 eq./t potato in the communal area to 277 kg CO_2 eq./t potato in the A2 resettlement system (Table 2). Variations within the production systems were observed, and the highest was in the A2 resettlement system where it ranged from 99 to 479 kg CO_2 eq./t potato. Mean GHG emissions estimated in kg CO_2 eq./ha ranged from 1,946 kg CO_2 eq./ha in the A1 resettlement to 4,139 kg CO_2 eq./ha in the A2 resettlement system (Table 2). Variations within the production systems were similarly observed, and the highest was again in the A2 resettlement system where it ranged from 2,763 to 6,819 kg CO_2 eq./ha. Such a wide range suggests inefficient grower practices especially among growers in the upper part of the range. The major driver of the emissions were a combination of high N use (data not shown) and low potato yield. A wide variation in mineral fertiliser use efficiency among all the sample growers was observed and it ranged from 68–228 g potato/g N, 21–75 g potato/g P, and 46–189 g potato/g K (Table 2). High mineral fertiliser use was reported (data not shown) and this coupled with the correspondingly low yields suggest that not all fertiliser applied is utilised by the crop. The fertiliser not taken up by the crop has potentially detrimental effects on the environment. Biocide use in potato production in Zimbabwe is high, with fungicides being the most frequently used in terms of both the number of sprays and quantities applied during the crop growth cycle (Svubure *et al*., 2015). A wide variation in biocide use efficiency was similarly recorded among all the sample growers, and it ranged from complete non-use of herbicides in the A1 resettlement to 24 kg potato/g a.i. insecticide in the communal area production system (Table 2). Potato crop rotation was another important indicator under the environmental dimension of sustainable cropping. Growing potato continuously on the same piece of land leads to pests and disease inocula build-up that will require biocide spraying to control causing environmental concerns and increasing production costs. Potato rotation among the sample growers ranged from one to four years across all the production systems (Table 2). Minimisation of irrigation water extraction was another important criteria under the environmental dimension of sustainable cropping. The indicator water use efficiency was chosen to evaluate irrigation water use. A wide variation in irrigation water use efficiency was reported among the sample farmers ranging from 1 g potato/l in the communal area to 9 g potato/l in the large scale commercial production system (Table 2). The temperate climatic pattern with humid and high rainfall conditions experienced in the Nyanga Eastern Highlands decreases the need for supplemental irrigation (Fig. 2). However, unexpectedly high irrigation water use is reported in the Nyanga Eastern Highlands mainly because surface irrigation water is abundant and because the majority of the growers' irrigation systems are gravity-fed incurring no energy costs, hence the tendency to over-irrigate (Svubure *et al*., 2015). The over-application of irrigation water, coupled with the low yields obtained explains the generally low water use efficiencies observed.

The farmer's livelihood from potato cropping and participation in community farming-related activities were defined as the criteria for the social dimension of sustainable cropping. The gross margin per dollar TVC from potato cropping already alluded to, and the number of field discussion days and training meetings attended per year by any member of the farm family were chosen as the indicators of sustainable cropping under the social dimension. Field discussion days are arranged by farmer groups with coordination of the local agricultural extension officer. The host farmer showcases good agricultural practice for the community to learn from. Agro-chemical companies and potato buyers also participate in the field discussion days mainly as an opportunity to advertise their products and services. Attendance to such field discussion days varied among the sample farmers from once per year in the large scale commercial to five times per year per farmer in the communal area production system (Table 2).

Farmer training meetings followed a similar trend where attendance varied from one to seven times per year per farmer (Table 2). These training meetings are in most cases organised and conducted by the local agricultural extension officer. Facilitators from outside the area are sometimes invited to provide training on specific farming topics to the farmers. The highest number of farmer training meetings were recorded in the communal area system where an average of 5 training meetings were attended (Table 2). The government extension service is mainly focussed on the smallholder systems and less on the large-scale systems.

5.3 Proposed sustainability indicator thresholds

The mean indicator values and range within each production system were in most cases used as the basis to set the sustainability indicator thresholds. In most cases, indicator values below the average value within each production system were considered unsustainable, while the upper end (or maximum) values represented the best practice within each production system, and these were set as medium to long term minimum sustainable thresholds. Indicator values in-between the unsustainable and sustainable thresholds were regarded as transitionary and a grace period (usually 2 to 4 years) was set during which affected growers were expected to attain sustainable threshold values. In Zimbabwe, there is little or no data available on legal limits or policy targets in potato production that could have been easily used to set indicator thresholds.

Table 3 summarises the proposed sustainability indicator thresholds derived from farmer participation in the different potato production systems. Sustainable potato yield in the large scale commercial and A2 resettlement systems were set at greater than 35 and 32 t/ha, respectively, mainly because these systems are mechanised and use high input levels. The average potato yield in the large scale commercial and A2 resettlement systems were 23 and 19 t/ha, respectively, and these were considered the unsustainable indicator thresholds for the systems. However, these growers still lag behind their counterparts in neighbouring South Africa's Sandveld area whose average potato yield was reported as 45 t/ha, with a narrow range between 36 and 58 t/ha (Franke *et al*., 2011). Sustainable potato rotation was set at greater than 2 years in the smallholder A1 resettlement and communal area systems due to constraining cropping land area (Table 2). In Zimbabwe, effective potato crop rotation excludes other solanaceous crops, and agricultural extension generally recommends one potato crop in 4 years on the same piece of land. The recommendation was adopted as the sustainable potato rotation in the large scale commercial and to some extent in the A2 resettlement production systems where average cropping area was 183 and 46 ha respectively. Unsustainable nitrogen (N) use efficiency was set at less than 170, 120, 97 and 104 g potato/g N in the large scale commercial, communal area, A1 and A2 resettlement production systems respectively (Table 3). These values correspond well with those reported in studies in the Sandveld area in South Africa (Franke *et al*., 2011), and also with those reported by Battilani *et al*. (2008) in studies in some European countries.

On biocide thresholds, the practice of integrated pest management was also recommended because of its potential to improve the biocide use efficiency through lowering biocide application rates while maintaining or even improving yields. In the A1 resettlement production system, none of the sampled farmers use herbicides in potato production and this is a positive practice for the environment. Herbicide use may be unnecessary during potato production in Zimbabwe because two to three ridging operations carried out also serve as mechanical weed control measures (Svubure *et al*., 2015). Sustainable irrigation water use efficiencies were set at greater than 6 g potato/l for both A1 resettlement and communal area production systems (Table 3). For the large scale commercial and A2 resettlement systems, the sustainable irrigation water use efficiency thresholds were set at greater than 9 and 4 g potato/l respectively. These water use efficiency indicators compare very well with those

Table 3. Proposed sustainability indicator thresholds derived from farmer participation in the different potato production systems in Nyanga district, Zimbabwe, in the period 2011 – 2014.

Sustainability issue	**Indicators**	**Production system**							
		Large scale commercial		**A2 resettlement**		**A1 resettlement**		**Communal area**	
		Unsus thr (<)	Sus thr (>)	Unsus thr (<)	Sus thr (>)	Unsus thr (<)	Sus thr (>)	Unsus thr (<)	Sus thr (>)
Land	Yield (t/ha)	23	35	19	32	8	13	17	23
	Rotation (years)	4	4	3	3	2	2	2	2
Economic/financial	Producer price (US$ /kg)	0.5	0.7	0.5	0.7	0.5	0.7	0.5	0.7
	GM/1US$ TVC	0.20	0.3	0.20	0.3	0.20	0.3	0.20	0.3
Mineral fertilisers	FUE_N (g potato/g N)	170	228	104	184	97	130	120	198
	FUE_P (g potato/g P)	46	60	41	75	46	59	41	63
	FUE_K (g potato/g K)	82	110	82	121	81	91	102	189
Biocides	BUEf (kg potato/g a.i.)	0.9	0.9	0.5	0.9	0.5	0.9	0.6	1.4
	BUEi (kg potato/g a.i.)	11	13	14	19	8	11	14	24
	BUEn (kg potato/g a.i.)	10	14	8	13	3	5	7	18
	BUEh (kg potato/g a.i.)	13	16	10	16	na	na	9	23
Irrigation water	WUEir (g potato/l)	9	9	4	4	5	6	2	6
Environment	GHG per t (kg CO_2 eq./t)	> 228	< 143	> 277	< 100	> 240	< 180	> 216	< 62
	GHG per ha (kg CO_2 eq./ha)	> 4030	< 3549	> 4139	< 2763	> 1946	< 1217	> 2868	< 1817
Farmer training	Field discussion days (no./yr.)	1	2	1	2	2	3	3	4
	Training meetings (no./yr.)	1	2	1	2	3	4	4	5

Key: < = less than; > = greater than; GM = Gross margin; TVC = Total variable cost; US$ = United States Dollar; CO_2 eq. = Carbon dioxide equivalent; BUE = Biocide use efficiency; a.i. = active ingredient; FUE = Fertiliser use efficiency; N = nitrogen; P = phosphorus; K = potassium; K_2O = potash; P_2O_5 = phosphate; WUEir = Irrigation water use efficiency; f = fungicide; i = insecticide; n = nematicide; h = herbicide; na = not applicable, no./yr = number per year; Sus thr = sustainable threshold; Unsus thr = unsustainable threshold.

reported in similar studies in the Sandveld area in South Africa (Franke *et al*., 2011). The large variation in GHG emission among the sampled growers which ranged from 62 to 479 kg CO_2 eq./t indicates that possibilities of lowering emissions exist. Sustainable GHG emissions were set using the lowest emissions in each production system (Table 3). On the social dimension of sustainability, higher sustainable thresholds for farmer training were set for the smallholder systems than for the large scale production systems mainly because of the high training need in the former (Table 3). Smallholder growers are mainly dependant on the government extension agency (Agritex) for skills training and advisory services. Non-governmental organisations and agro-dealers sometimes chip in with training services for smallholder farmers. In the large scale commercial and A2 resettlement production systems, trained agricultural workers are employed.

While each system ended up with its own set of sustainable and unsustainable threshold values, this is not the ultimate objective of sustainability. Each system should be optimized for best performance.

6. Discussion

The proposed framework described in the study, while accounting for the three dimensions of sustainability (social, environment and economic), it does not aggregate the sustainability indicators into a single score or composite number as an evaluation of a cropping system. Rather it presents sustainable and unsustainable indicator thresholds from which end user stakeholders (farmers) choose which indicators to target for implementation. Advantages of this approach include maintaining process transparency, easy communication of evaluation results and easy implementation, monitoring and continuous evaluation. In a similar study, van Asselt *et al*. (2014) argued that although indicators can be quantified objectively, the overall sustainability assessment becomes subjective, as it depends on the weighting or importance apportioned to each of the indicators.

The framework proposed in this study was able to distinguish the four different potato-based cropping systems identified. For example, the large scale commercial production had higher indicator values in yield, potato rotation, N, P and water use efficiencies compared with the other production systems. On GHG emission, again the large scale commercial system was very competitive notwithstanding the high fertiliser input use and mechanisation. The application of the framework also showed a large variation in indicator values both between and within the production systems. This suggests that many farmers need to improve their performance in order to narrow the range between the indicator values. However, a grower who chooses to improve potato yield to sustainable levels will inadvertently be improving other indicators such as synthetic fertiliser, biocide and water use efficiencies as well.

The absence of legal limits and policy targets on many issues concerning potato production systems in Zimbabwe is a major limitation to the setting of sustainable and unsustainable indicator values in the framework. It is important to establish and publicise legal limits on such issues as groundwater extraction rates for different locations, permissible biocide and nutrient levels in soil, ground and surface water sources. While monitoring of farmers as they gradually improve their indicator values to sustainable levels is important, concurrent parallel monitoring of the legal limits in the ecosystem is necessary too to ensure sustainability. The government extension agency, Agritex, is best placed to evaluate and monitor farmer progress as they improve their threshold values towards the desired direction of sustainability. In many European countries, it is usually the industry that sets norms that are later legalized by the government, and industry out of competition ask more from growers than legal minimum (Haverkort, personal communication, 2014). This may also be a future driver of sustainability in Zimbabwe.

The participatory nature of the framework involving farmers and local extension officers secures the buy-in of key stakeholders important for operationalisation, monitoring and evaluation. The involvement of the farmers led to selection of indicators they viewed as important and this incentivises them to implement them. Monitoring of farmer progression towards sustainable indicator thresholds easily merge with the skills training and advisory services role of local agricultural extension officers.

7. Conclusions

This study offered a framework to establish objective quantitative indicators for evaluating the sustainability of cropping systems. The involvement of all relevant stakeholders is important to the implementation and monitoring of the sustainability assessment results. Once the indicator threshold values are set, it will be up to the growers and agricultural extension to improve crop management practices to shift unsustainable indicator values to the minimum sustainable thresholds and beyond.

Chapter 7

General discussion

O. Svubure

1. Introduction

Irish potato production systems in Zimbabwe include the A1 and A2 resettlement systems that emerged from the Fast Track Land Reform Programme (FTLRP) in 2000, the remaining large-scale commercial and the already existing communal area systems. These production systems are distinct in terms of land size ownership, mechanisation, input use, crop management and actual potato yield (*Chapter 2*). The application of grower survey data and the LINTUL-POTATO model which calculates potential dry matter production based on light use efficiency of intercepted light by the potato crop, showed that there is tremendous potential to increase potato production in the Highveld and Nyanga Eastern Highlands bio-physical environments in Zimbabwe (*Chapter 3*). Again the grower survey data was used as input to the 'Cool Farm Tool-Potato' model. This model calculates the contributions of various production operations to the total GHG emission. The carbon balance showed that all the production systems were inefficient (*Chapter 4*). The Irish potato value chain in Zimbabwe is a web of multiple pathways which potato can take from the field of production to the end users (*Chapter 5*). A total of nine stakeholder groups are connected. They include ware and seed potato producers, middlemen/transporters, wholesalers, urban fruit and vegetable open market retailers, supermarket retailers, processors, household and public consumers. Considerable levels of value-addition were observed with gross profit of at least 13% recorded at each linkage. In *Chapter 6*, this study proposes a framework that can be used to evaluate and communicate the sustainability of cropping systems. It is important to analyse the implications of these research findings in terms of the potential to sustainably increase Irish potato production in Zimbabwe to help ease the food security challenges of the country.

Research findings of this study have important implications on the Irish potato sector in Zimbabwe in terms of: (1) how eco-efficient potato production can be achieved, (2) in terms of the potential contribution of potato toward food security in the country, and (3) in terms of how the potato industry in general can navigate itself to the next level of growth. In this general discussion chapter, highlights of the research findings are discussed first, followed by their implications to the Irish potato sector in the country. The chapter concludes with recommendations for future research priorities in this sector.

2. Highlights of the study findings

The highlights of the findings of this study are here synthesised in a SWOT (strengths, weaknesses, opportunities, and threats) matrix. This analysis helps to understand the potential of the Irish potato sector to sustainably increase Irish potato production in Zimbabwe and to contribute to the food security of the country. The study of the characteristics of the different potato production systems in Zimbabwe (*Chapter 2*), their resource and carbon footprints (*Chapters 3 and 4*), and an analysis of the potato value chain (*Chapter 5*) gave an insight on the strength, weaknesses, threats and opportunities of the sector. Table 1 summarises the strengths, weaknesses, opportunities, and threats to the Irish potato sector in Zimbabwe.

Table 1. SWOT matrix of the Irish potato sector in Zimbabwe

Strength	**Weaknesses**
- abundant land resources - irrigation infrastructure - production throughout the year - good seed certification system - government policy support - a growing A2 resettlement production system	- low actual potato yield - low resource use efficiencies - high greenhouse gas costs for potato production - dysfunctional potato breeding programme - lack of credit - high production cost - lack of umbrella potato association - farmer and extension education
Opportunities	**Threats**
- rising potato consumption - sustainable value addition along the potato chain - high yield potential - high yield gap percent	- cheaper potato imports from South Africa - introduction of the potato cyst nematode - socio-economic and political challenges - poor road network infrastructure

2.1 Strengths

The main potato growing areas in Zimbabwe are the Highveld and the Nyanga Eastern Highlands regions. The former is an extensive area covering about 25 % of the country's total area of nearly 390,000 km^2, while the latter comprises less than 5 % of the country's total area. (*Chapter 2*). Sufficient land is therefore available should area expansion becomes an option to increase potato production. The Highveld experiences a variable climatic pattern characterized by mild winters from May to September and hot summers from November to March. Long term monthly average temperatures range from 15 °C in June/July to 23 °C in October/November. Precipitation mostly occurs in the summer months and averages around 750 to 900 mm. It is suitable for intensive farming systems based on crops and livestock production. The Nyanga Eastern Highlands, at high elevations greater than 1,800 m amsl (average mean sea level) experiences a characteristic temperate microclimate and vegetation. Precipitation is received in all months of the year, but the rainy season normally begins in October extending into April, making it the longest in the country. Annual precipitation exceeds 1,000 mm which is the country's heaviest. Average monthly mean temperature ranges from about 11 °C in July to 18 °C in October. The favourable temperature and rainfall pattern enables the region to practise specialised and diversified farming that includes forestry, tea and coffee plantations, horticultural crops, and intensive livestock production.

Investment in irrigation infrastructure is another strength of the potato production systems in Zimbabwe making production independent of the rainfall pattern. Unlike potato, the staple maize crop output follows the seasonal rainfall pattern, rising with good seasonal rainfall quality and dipping with poor seasonal rainfall quality (Phillips *et al*., 1998). The study found out that all the growers sampled from the large scale commercial and A2 resettlement production systems had irrigation facilities used for the early and late winter potato crop (*Chapter* 2). Karoi region was the exception with 33 % of the A2 resettlement growers interviewed lacking irrigation facilities. The irrigated area ranged from 8 to 180 ha and both pivot and semi-portable irrigation systems were available. In the Eastern Highlands Nyanga district, similarly all the large scale commercial and A2 resettlement growers interviewed had irrigation systems drawing water from surface water sources. The irrigated area ranged from 0.4 to 22 ha. In the A1 resettlement and communal area production systems, 89 and 94 % had irrigation facilities, respectively. Both production systems had semi-portable irrigation designs and all were gravity fed giving the growers a considerable saving on irrigation energy costs. In addition, the irrigation water is free as it runs off the steep mountain slopes and is easily channelled to the fields.

In both regions, irrigated potato is generally grown throughout the year. This is an advantage that makes the need for storage facilities unnecessary. Again with prudent planning, potato production can be scheduled to augment food production when a decrease in maize production is anticipated. Maize production in Zimbabwe is predominantly rain-fed and production is limited to the summer rainy season from November till March/April.

The potato sector enjoys government policy support. In 2010, the government banned the importation of ware potato primarily to protect the local growers against cheap South African potato (Chimoio, 2013). In addition, there is also the threat of introducing the potato cyst nematodes, *Globodera rostochiensis* and *Globodera pallida*, which are parasites of worldwide significance attacking the crop. These have not been reported yet in Zimbabwe, and will be very difficult to eradicate once they are introduced into the soils (Manzira, 2011). The government also declared Irish potato a national strategic food security crop on 18 May 2012 making the crop eligible for government initiated mechanisation and irrigation development support programmes (The Herald, 2012). The potato sector has a functional seed certification system in place. All seed potato sold in the country's formal seed sector is certified. The government Seed Services Institute oversees seed certification in the country. This mandate is enshrined under the Seeds Act [Chapter 19:13] of 1971 and its enabling regulations, the Seed Regulations (1971), and Seeds Certification Scheme Notice (2000). According to these regulations, registered seed potato companies are given the Certifying Agency status by the Seed Services Institute, the designated Certifying Authority. The seed potato company certifies the seed of its contracted growers under the monitoring and control of the Certifying Authority. The seed potato situation is varied in other African countries. For example, in neighbouring Mozambique, the demand for quality seed potato far outstrips the country's ability to produce it, resulting in shortages and a heavy reliance on imports (MoEA, 2014). The Mozambique national certified seed potato production including imports satisfy only 4 % of the national seed potato requirements of about 36,000 t, with the balance being met by the use of uncertified material (MoEA, 2014). This continuous recycling likely leads to loss of genetic vigour leading to increased susceptibility to diseases and low productivity. In Ethiopia, seed certification is poor and the informal seed system is dominant and low quality seed potato is extensively used (Hirpa *et al*., 2010). Similarly in Kenya, only 1 % of the annual seed potato requirements of about 165,000 t is certified leading to declining ware potato yields partly due to use of poor quality seed (Janssens *et al*., 2013).

2.2 Weaknesses

Irish potato yields in Zimbabwe are low. Low potato yields have been reported in other African countries as well. For example, in Mozambique, yields range from 10 to 30 t/ha

(MoEA, 2014). In Kenya, the national average yield has been reported at 8 t/ha (Janssens *et al*., 2013). The low potato yields have been attributed to poor agronomic practices such as low input use, use of uncertified seed, poor pest and disease control. Grower survey results in Zimbabwe show that the actual fresh tuber yield ranged from 8 t/ha in the A1 resettlement to 35 t/ha in the large scale commercial production systems (*Chapter 3*). The wide yield range suggests inefficiency in the potato production systems in Zimbabwe. Water use efficiencies were similarly low. For example, actual water use efficiency based on irrigation water and precipitation ranged from 2 to 6 g potato l^{-1}, while the simulated potential water use efficiency from irrigation and precipitation ranged from 9 to 17 g potato l^{-1}. This large gap observed between actual and potential water use efficiency shows the scope to improve crop management practices to increase actual yield and improve water use efficiency. Considering the synthetic nutrient footprint, the combination of high synthetic fertiliser use and the low potato actual yields realised clearly demonstrates the inefficient fertiliser use in the Zimbabwe potato case. The nutrient use efficiencies ranges were: 97–162 g potato g^{-1} N, 93–105 g potato g^{-1} P_2O_5 and 97–123 g potato g^{-1} K_2O. Unlike the case of potato, maize growers in Zimbabwe use very low synthetic fertiliser and mining of soil nutrient reserves has been reported (Twomlow *et al*., 2008). In the Irish potato case, the overdose of synthetic fertilisers and the low yields obtained suggest that not all of the applied nutrients are taken up by the potato hence there is concern over environmental consequences of excess fertiliser.

This study reports high greenhouse gas (GHG) costs for Irish potato, thereby threatening the sustainability of the potato production systems (*Chapter 4*). The individual grower carbon footprint calculated ranged from 99 to 479 kg CO_2 eq./t potato harvested (*Chapter 6*). The wide range of the CO_2 costs observed suggest that the potato production systems in Zimbabwe are inefficient in terms of their carbon balance. The major drivers of the GHG emissions were fertiliser production and soil-related field emissions, which together accounted for on average 56% of the total emissions across all the production systems.

Other weaknesses reported in the study included a dysfunctional national breeding programme, lack of credit for growers, high production cost, lack of umbrella association for the potato sector, and limited production knowledge by both farmers and extension. The potato cultivars used in the country are very old and were grown since the early 1980s (Joyce, 1988). The national potato breeding programme stopped since the turn of the millennium, mainly due to financial constraints and a high breeder staff turnover in government service. Though few growers provided details on the production costs, high costs of potato production were recorded, ranging from US$ 265 and US$ 344 per ton in the A1 resettlement and large-scale commercial systems, respectively (*Chapter 5*). Growers also raised lack of credit facilities to fund production, because they do not have collateral security asked by commercial lending institutions. In the past, farmland was used as collateral security. But the land reform nationalised land, hence it could no longer be used as collateral security for a loan. The majority of growers use savings, which is risky in the event of crop failure. Therefore, lack of private land ownership remains an important weakness of potato production in Zimbabwe.

2.3 Threats

The cyst nematode has been reported in neighbouring South Africa and there it is treated as a prohibited pest and any infection is not tolerated (Knoetze *et al*., 2006). Hence, Zimbabwe has very stringent requirements on importation of South African seed potato (Manzira, 2011). However, there are reports of smuggling of ware potato from South Africa risking the introduction of the cyst nematode into the country (Dube, 2013). Therefore, the threat of cyst nematode introduction into the country remains an important issue to sustainable production of the crop.

The socio-economic and political challenges the country has faced since the turn of the millennium has resulted in significant drop in investment and maintenance of infrastructure. For example, the poor state of the road network infrastructure has led to high transportation costs of both input and output in the potato value chain (*Chapter 5*).

2.4 Opportunities

The yield gap analysis on the potato production systems in Zimbabwe showed a yield gap of up to 77 % based on the yield of the best performing growers. This yield gap reflects a considerable potential and opportunity to increase potato production by closing the yield gap through improving actual yields. The average potential yield from the LINTUL-POTATO model simulations ranged from 88 t/ha in the Chinhoyi and Karoi areas of the Highveld to 96 t/ha in the Nyanga Eastern Highlands. The mean actual yield observed in the study therefore range from 8 to 35 % of the simulated potential yield, translating to a yield gap of 65 to 92 %. Again this shows a considerable potential and opportunity to increase potato production in these environments.

Increasing potato consumption is another opportunity to the potato industry in Zimbabwe. Potato consumption per capita was about 9 kg per year up from 2 kg per year in the early 1980s (Joyce, 1988). Though there is growth in potato consumption over the years, the amount still lags behind compared to that in emerging economies. Potato consumption in South Africa is about 32 kg per capita per annum, while for emerging economies it is estimated at 14 kg per capita per annum (PSA, 2010). In Kenya, the average annual potato consumption per capita was estimated at 29 kg in 2003 (Janssens *et al*., 2013).

The study found that each of the Irish potato value chains actor adds value to the product as the product passes from one actor to another. Value addition was considered as the difference in sales price and cost of inputs (raw materials) at each stage of the value chain. This reflects a health state and an opportunity which the industry should take advantage of. Figure 1 shows the distribution of value addition among some of the value chain actors in the Zimbabwe potato value chain. Growers added 26 % of the total value of ware potato, while the middlemen were responsible for 15 %, wholesalers 19 %, and the most value addition contribution was 40 % by the retailers (Fig. 1). The price differential between what the consumer pays and what the grower receives was 100 %. The highest profit margin was earned by retailers due to low operational scale and cost, while the middlemen and wholesalers have the smallest profit margin. However, the operational scale of the middlemen and wholesalers was high making them the dominant value chain actors.

3. Implications

3.1 Toward eco-efficient potato production in Zimbabwe

Efficient use of natural resources has been fundamental to agricultural practice for a very long time (Keating *et al*., 2010). In this study, efficiency was calculated simply as the level of output per unit of input, termed the partial factor productivity; it can easily be calculated for farmers who keep records of input use and crop yields obtained. The efficient use of ecological resources used as inputs, mainly land, nutrients, biocides and water, should be considered together with the economic, environmental and social impact on the ecosystem that agricultural practice positively or negatively influences.

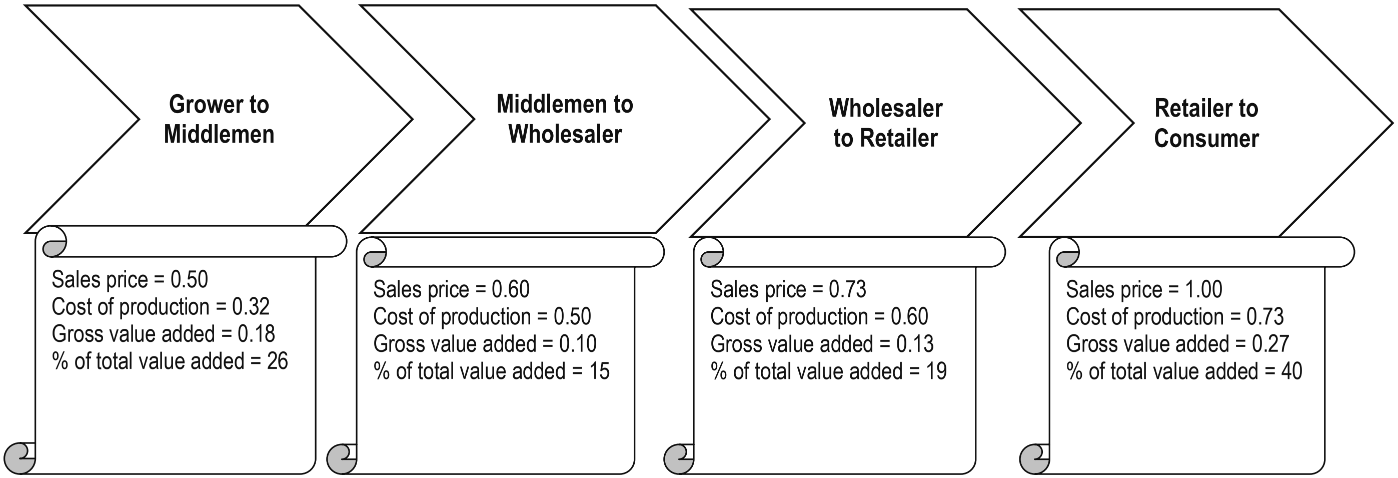

Fig. 1. Characteristic distribution of value addition (in US $ per kg potato) in the Irish potato value chain in Zimbabwe.

3.1.1 The production function concept and resource use efficiency

(a) The production scenarios

Optimal input–output combinations in crop production systems to achieve desirable economic and environmental outcomes are possible if the efficiency of input use such as fertilisers, water and biocides is improved (de Koeijer *et al*., 1999). Production functions relate different input–output combinations, and resources use efficiencies differ at different production levels as discussed by De Wit (1992). Figure 2, adapted from Keating *et al*. (2010), illustrates three production function scenarios relating the variation of agricultural output to input use that can help understand resource use efficiency in the Zimbabwe Irish potato case. The lowest production function scenario (Fig. 2) shows the mean current resource use efficiencies of grower practices in a given bio-physical environment. The second higher production function (Fig. 2) represents the attainable efficiencies through use of the best currently available technologies and cultural practices adapted for that biophysical environment. The efficiency gap between the two production functions is largely due to socio-economic differences between farming households that leads to correspondingly different approaches to agricultural practice. The important factors could be labour, remittance and access to a range of resources (Carter and Murwira, 1995). The highest production function (third uppermost curve, Fig. 2) is continually sought after. Movement toward it is shown by the arrows pointing upwards (Fig. 2). This production function can potentially be realised through successful agricultural research that includes improvement in nutrient, water, pest and disease management, and the provision of high yielding adapted cultivars.

(b) Shape of input-output process relationships

The generic product function, also called response function, relates the output of a crop to the inputs used to produce it (Dillon and Hardaker, 1993). Fig. 2 represents a generic single-variable input process, but realistically the output is a function of a multi-variable input process which indicates that yield is significantly determined by an array of factors that include fertilisers, water, biocides, seed and labour. The output of the generic single-variable input production function (Fig. 2) can be zero if none of the variable input is used. This shows that the variable input under consideration is essential to production. An example in cropping is seed. However, in most scenarios, the production curve intercepts the output axis above the origin, indicating that some output is obtained when nil variable input is used. This is, for example, the case for the input applied fertiliser in cropping. Three theoretical segments can be identified in the production function (Fig. 2) as the level of the variable input increases. Segment A shows the output rising with additional inputs at an increasing rate; in this segment, there is an increasing marginal return to the input. In the middle stage (segment B), an increase in input levels still increases the total output but at a decreasing rate, that is, the marginal product is positive but is decreasing. The final stage (segment C), shows that further increases in input levels results in a decrease in total output, that is, marginal product becomes negative.

In the potato production systems in Zimbabwe, available single-variable input production functions can be used to: (i) select potato production technologies that can shift the production function curves in the upward direction as shown by the upward pointing arrows in Fig. 2, and (ii) for optimisation of input levels (Dillon and Hardaker, 1993). Selection of technologies is often determined by the prevailing socio-economic conditions and budgeting out the costs and returns of the alternative technologies which growers can make a decision on (Dillon and Hardaker, 1993). Dillon and Hardaker (1993) further outlined the steps of applying the single-variable input production function graphical form for input optimisation.

3.1.2 Land use efficiency

Yield per unit land area is the most frequently used eco-efficiency measure for field crops. In this study, potato yield per unit land area was assessed on the four potato production systems in Zimbabwe. The potato yield was low ranging from 8 t/ha in the A1 resettlement to 35 t/ha in the large-scale commercial production systems. The lowest yield level (8 t/ha) are represented by the lowest production function (Fig. 2) which shows the mean current resource use efficiencies from the current grower practices. While the highest actual yield (35 t/ha) is represented by the second higher production function (Fig. 2) that represents the attainable efficiencies in a given bio-physical environment that can be measured in the most productive fields of resource endowed farmers in a community (Tittonell and Giller, 2013). Using the lowest actual yield (8 t/ha) and the highest attainable yield observed (35 t/ha), the calculated yield gap is up to 77 %, reflecting a tremendous potential to increase potato production in Zimbabwe (*Chapter 3*). Improving crop management aspects such as nutrients, water, pests and diseases, and the use of high yielding adapted cultivars will increase actual yields and narrow the yield gap. Theoretically yield could be as high as 88 to 96 t/ha in the Highveld and Nyanga Eastern Highlands, respectively, as determined by the LINTUL-POTATO simulated potential yields in these environments (*Chapter 3*). Compared to the simulated average potential yield, the mean actual yield observed ranged from 8 to 35 % of the simulated potential yield, translating to a yield gap of 65 to 92 %. Again this shows a considerable potential to increase potato production in these environments.

3.1.3 Nutrient use efficiency

Nutrient use efficiency, defined in this study as crop yield per unit of nutrient applied, varied widely both within and across all the production systems suggesting that some growers were inefficient. For example, the nitrogen (N) use efficiency ranged from 97 to 162 g potato g^{-1} N. In a similar study in South Africa's Sandveld area, higher nitrogen use efficiencies were reported, which ranged from 106 to 228 g potato g^{-1} N (Franke *et al.*, 2011). Potato growers in Zimbabwe have a tendency to apply nutrients at high rates (*Chapter* 2). Given the low yields observed, there is high risk that not all nutrients are taken up by the potato crop and nutrient losses through leaching, volatilization and denitrification are likely to occur and to damage the environment.

In the Zimbabwean potato production case, movement along each of the three production functions (Fig. 2) through further increases in fertiliser application, will result in minimal gains in output (actual potato yield) because of the already high synthetic fertiliser use and low potato yields observed (*Chapter 3*). Rather the upward movement (as shown with arrows in Fig. 2) is the desired direction not only for grower profitability and national food security, but also for cropping sustainability as discussed in *Chapter 6* of this thesis. For example nutrient use efficiency values below the average in each production system were considered unsustainable. Movement towards the highest production function (Fig. 2) can be achieved through increasing yield without increasing fertiliser application to achieve the desired sustainability direction for nutrient use. Table 2 shows the characteristic gross margin analysis per ha of Irish potato production in the different potato production systems in Zimbabwe, highlighting the estimated fertiliser cost and return on fertiliser investment. Gross margin is the difference between revenue and cost of production and can indicate the profitability of a cropping enterprise. In the smallholder systems, land preparation, planting,

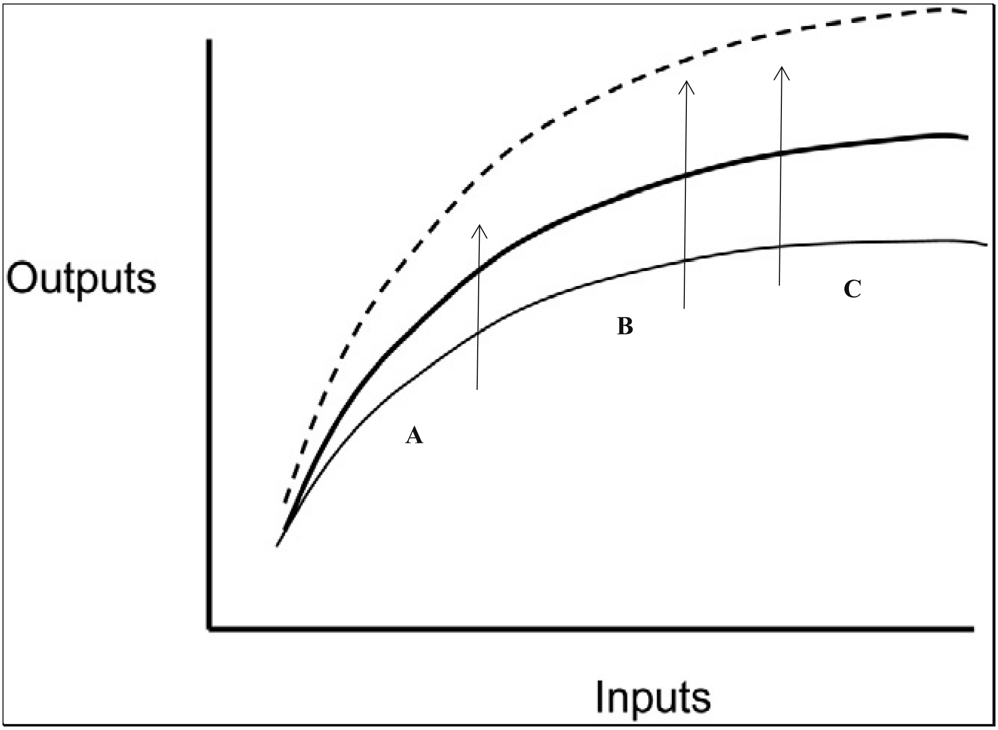

Fig. 2 Production functions that relate agricultural outputs to the level of inputs for observed farm performance (—), for current best technologies (**—**), and for foreseen new technologies (---) (adapted from Keating *et al*., 2010).

spraying, ridging and harvesting operations use animal draft power and were considered zero cost for simplicity although equipment wear and tear could have been estimated. Irrigation too was considered zero cost because it is gravity-fed and farmers do not pay for the free stream water. In most cases buyers purchase Irish potato on-farm, hence farmers do not directly incur produce transport costs. Similarly no costs were assigned to family labour. The best return on fertiliser investment was realised in the communal area (US$ 3.66 per 1 US$ fertiliser cost), and the least return was in the A2 resettlement production system (US$ 2.56 per 1 US$ fertiliser cost invested) (Table 2). Such an attempt to quantify the possible financial benefits to farmers of fertiliser investment can motivate them to enhance nutrient use efficiency. Fertiliser cost represents a high proportion of the total variable production costs of potato in Zimbabwe coming second only to seed costs. The fertiliser cost ranged from 22 % of the total production costs in the large-scale systems to 32 % in the communal area system (Table 2). Hence the need to reduce fertiliser cost while maintaining or even increasing yield is

Table 2. Characteristic gross margin analysis per ha of Irish potato production in the different potato production systems in Zimbabwe, in the period 2011 – 2014.

Item	A1 resettlement		Communal area		A2 resettlement		Large-scale commercial	
	Cost (US$)	% of TVC	Cost (US$)	% of TVC	Cost (US$)	% of TVC	Cost (US$)	% of TVC
Seed	990	47	1570	40	2200	30	2270	29
Fertiliser	**600**	**28**	**1250**	**32**	**1600**	**22**	**1700**	**22**
Biocide	350	16	750	19	950	13	1080	14
Transport (inputs to farm)	40	2	50	1	70	1	80	1
Land preparation	0	0	0	0	145	2	145	2
Planting	0	0	0	0	55	1	55	1
Spraying	0	0	0	0	250	3	250	3
Ridging	0	0	0	0	110	1	110	1
Irrigation	0	0	0	0	750	10	750	10
Harvesting	0	0	0	0	80	1	80	1
Packing materials	100	5	225	6	305	4	370	5
Transport (produce to market)	0	0	0	0	0	0	0	0
Labour	0	0	0	0	750	10	750	10
Sub-total	2080		3845		7265		7640	
Miscellaneous cost (2% of sub-total)	42		77		145		153	
TVC per ha (US$ ha^{-1})	2122		3922		7410		7793	
TVC per ton (US$ t^{-1})	265		231		390		339	
TVC per kg (US$ kg^{-1})	0.27		0.23		0.39		0.34	
Average yield (t ha^{-1})	8		17		23		28	
Blend selling price (US$ t^{-1})	500		500		500		500	
GI per ha (US$ ha^{-1})	4000		8500		11,500		14,000	
GM per ha (US$ ha^{-1})	1878		4578		4,090		6,207	
GM per ton (US$ t^{-1})	235		269		118		222	
GM per $1TVC	0.89		1.17		0.55		0.80	
GM per US$1 fertiliser cost	**3.13**		**3.66**		**2.56**		**3.65**	

Key: TVC = Total variable cost: GI = Gross income: GM = Gross margin: US$ = United States Dollar important. Recent experiences with maize in the United States as reported by Cassman *et al.* (2002) showed nitrogen (N) use efficiency increasing by 36%, from 42 kg maize kg^{-1} nitrogen in 1980 to 57 kg maize kg^{-1} nitrogen in 2000 with maize yields increased by 40 % during the same time. The drivers of this improvement appeared to be due to continuous increases in maize yield mediated by technological advances without increasing N fertilisation over fears of environmental consequences of excess N fertiliser in the ecosystem (Cassman *et al.*, 2002). Such technological advances included availing high yielding maize varieties to farmers and improvements in the fertiliser product quality. This includes use of nitrification inhibitors to reduce leaching and denitrification loss of N in many cropping systems (Fixen and West, 2002). In addition, farmers were encouraged to use slow release N fertilisers, such as polymer-coated urea, that are reported to increase N use efficiency and increase productivity of high value crops (Drost *et al.*, 2002). Particularly for the N nutrient, the potential for losses is greatest when the plant-available N pool exceeds crop uptake requirements, hence the need for greater synchrony between crop N demand and the N supply (Cassman *et al.*, 2002). Frequent soil testing and improved interpretation for science-based nutrient recommendations are critical for efficient nutrient use. This evidence clearly demonstrates that successful agricultural research can continually create new higher production functions (Fig. 2).

Quite opposite to the United States experiences with maize, and similar to the Zimbabwean Irish potato case is the problem of low eco-efficiency caused by excessive N fertiliser use on cereal crops in China (Ju *et al.*, 2009). Ju *et al.* (2009) reports 71 % increases in grain (from 283 to 483 million tonnes) in the period 1977 to 2005, while N fertiliser use increased by an incredible 271 % from 7.07 to 26.21 million tonnes during the same period. This translates to a fall in N fertiliser use efficiency of 40 kg grain kg^{-1} N in 1977 to 18 kg grain kg^{-1} N in 2005. Results of the study by Ju *et al.* (2009) also show that more efficient use of N fertiliser can reduce the current high application rates by 30 to 60 %, while maintaining grain yield and substantially reducing N losses to the environment. This was achieved through an integrated management package that included use of manure, crop residues, use of legume crops in rotations, and further reduction of synthetic N fertiliser use (Ju *et al.*, 2009). The management package also included removal of government subsidy on N fertiliser, introducing an N fertiliser tax, improving extension services, and farmer education on environmental awareness (Liu and Diamond, 2005; 2008). A similar strategy can be employed in the Irish potato case in Zimbabwe. First, research studies need to be conducted to account for inherent soil fertility especially increasing internal soil N cycling through crop residues, manures and including legumes in potato rotations. The research programme should recommend an integrated nutrient management strategy that accounts for organic nutrient sources as well as synthetic fertiliser use. Secondly, government policy on fertiliser pricing can be an instrument that can be employed to regulate fertiliser use. The government of Zimbabwe has long since moved from fertiliser price controls to supply and demand market forces in the 1990s, and this policy decision led to higher fertiliser prices now than prior to the removal of price controls (Rukuni *et al*., 2006). Although this is not a desirable outcome, the relatively high fertiliser prices have failed to reduce fertiliser use rates in potato production in Zimbabwe. This study on potato production in Zimbabwe confirmed that agricultural extension general synthetic fertiliser recommendations for potato production reported erred on the generous side. Awareness educational campaigns will be needed to educate extensionists and farmers on the integrated nutrient management strategy with reduced synthetic fertiliser use. Potato growers sampled in this study hardly have soil tests for nutrient correction. High application rates in the absence of soil tests often included an additional amount as kind of an 'insurance' to prevent yield reduction rather than matching the nutrient supply to crop demand. Traditionally, Irish potato has been regarded as a highly nutrient-demanding crop in Zimbabwe. Persuading farmers to reduce synthetic fertilisers will therefore be a challenge because of the long-established and strong opinion that higher potato yield will be obtained with more fertiliser. Consistent with the classical assertion by de Wit (1992), that the totality of resources are utilised most efficiently when their supplies are all close to yield-optimising levels, not only nutrient supply should be optimised but also the supply of other inputs. Poor management of water, weeds, pests, diseases, or wrong cultivar or population selection will most likely reduce anticipated yield and consequently nutrient use efficiency goes down (Fixen and West, 2002). Hence continuous improvement in cropping system management is important.

3.1.4 Water use efficiency

This study also analysed water use in potato production in Zimbabwe (*Chapter 3*). The water use efficiency based on actual fresh potato yield and available water from irrigation and rainfall, ranged from 2 to 6 g potato l^{-1}, while the potential (simulated) water use efficiency from irrigation and rainfall ranged from 9 to 20 g potato l^{-1}. The large gap observed between actual and potential water use efficiency shows the scope to improve crop management practices to increase both actual yield and water use efficiency. Since most growers are already using high nutrient input rates, the best pathway for these growers to increase production is to adopt new technologies that create a new higher production function frontier (Fig. 2), and improve water use efficiency.

Improved management of weeds, pests and disease problems, and the use of high yielding adapted cultivars will most likely increase yield and consequently improve water use efficiency. It was observed in the study that growers applied varying amounts of irrigation water across the different agro-ecological zones and production systems (*Chapter 3*). For example, using the 26 years long weather data from 1985 through 2010, Karoi area located in the Highveld had the highest mean monthly evapotranspiration of 245 mm indicating a high atmospheric evaporative demand. Consequently, Karoi area had the highest simulated irrigation need compared to the other parts in the study area. Predictably the lowest actual irrigation water applied was in the Nyanga Eastern Highlands (316 mm) because of the humid and high rainfall conditions experienced there thus decreasing the supplemental irrigation need. However, the high irrigation water use also observed (750 mm) in the Nyanga Eastern Highlands was unexpected; this was explained by the fact that the majority of the growers' irrigation systems are gravity-fed incurring no energy costs, hence the tendency to over-irrigate. Comparing with the simulated irrigation need, all growers generally over-apply water (*Chapter 3*). For example, the simulated irrigation need in the Nyanga Eastern Highlands was 141 mm but growers applied more than 5 times the water needed. Consequently, the lowest water use efficiency (2 g potato l^{-1}) was observed in the communal area system in the Nyanga Eastern Highlands where growers incurred no irrigation costs and the water running off the steep streams is free. However, over-applying water is likely to leach essential nutrients such as N hence farmer education is needed avoid this practice.

3.1.5 Biocide use efficiency

Another resource (input) analysed in the study was biocides. Early blight (*Alternaria solani*), because of the favourable climatic conditions for it, is more common and problematic than late blight (*Phytophthora infestans*) and other fungi (Manzira, 2011). According to Kromann *et al*. (2014), potato Integrated Pest Management (IPM) for disease management involves integrating the use of resistant cultivars, fungicides and grower training. In order for farmers to adopt new technologies, it is important for them to understand the economic, ecological and practical benefits of the technology (Kromann *et al*., 2014). Farmer training in Zimbabwe is the principal role of the government extension agency, Agritex. The low potato yields observed and the wide ranges of biocide use efficiencies among the sample farmers suggest that most growers were inefficient in biocide use (*Chapter 3*). Probably compounding this problem is that some growers could not practice the minimum one potato crop in 4 years rotation generally recommended for potato by the agricultural extension agency. This mostly likely led to pests and disease inocula build-up that will require biocide spraying to control causing environmental concerns and increasing production costs. Potato rotation among the sample growers ranged from one potato crop in one to four years across all the production systems in response to the limitations of cropping land available (*Chapter 3*). A possible intervention is the introduction of the IPM concept (Alptekin, 2011), as none of the growers sampled were applying it and lacked knowledge of the concept. This implies that both extensionist and grower education is needed on running IPM programmes. The biocide cost ranged from 13 % of the total production costs in the A2 resettlement systems to 19 % in the communal area system (Table 2). Hence the need to reduce biocide cost while maintaining or even increasing yield is important. The framework developed in this study to evaluate and communicate the sustainability of cropping systems (*Chapter 6*), set unsustainable biocide use efficiency thresholds as those values which were below the average. The framework development exercise involved the participation of farmers and agricultural extension officers increasing the likelihood of implementation. Farmers may be motivated to implement practices toward improving biocide use efficiency through working toward a targeted threshold unlike in the past. Besides, the possibility of cost reduction through adopting IPM strategies may induce additional motivation to improve biocide use efficiency.

3.1.6 The national potato breeding programme

Breeding has been a traditional route for the creation of new resource use efficiencies in agricultural production systems. Achieving the third uppermost curve (in Fig. 2) that represents the highest production function, will certainly require continuous breeding efforts for better adaptation to current and future climates (Keating *et al*., 2010). It is believed that future breakthrough innovations in agriculture will come from gene technology (Brookes and Barfoot, 2005). Reviewing literature on genetically modified crops, Brookes and Barfoot (2005) reported genetically modified insect-resistant cotton registering yield increases as high as 50 % in India. Findings of this study strongly suggest that potato farmers in Zimbabwe urgently need high yielding cultivars that are adapted to their biophysical environment in order to increase actual yields and improve resource use efficiencies. While the national breeding programme is currently dysfunctional, at least variety trials with imported materials can be conducted in the country for possible certification of superior yielding cultivars.

3.1.7 Input investment risk in potato production in Zimbabwe

Another noteworthy aspect from this study is the investment risk in potato production in Zimbabwe. Irish potato production in the country has been regarded as an irrigated high-fertiliser input crop. Consequently potato farmers invested in irrigation infrastructure and practice high synthetic fertiliser use. Besides, potato production has been limited to high rainfall areas (the Highveld and the Eastern Highlands) of the country. From this perspective, the question of adjusting the level of investment in crop production inputs in order to avoid either over-investing in crops with poor yield prospects or under-investing in crops with good yield prospects is fortunately unproblematic in the Zimbabwean potato case. This advantage enables potato farmers to adapt new technologies that improve resource use efficiency and generate higher production functions (Fig. 2). However, because of the absence of on-farm storage facilities (*Chapter 2*), the likely risk potato farmers may face is that of market failure where producer prices may fall reducing the farmer’s profits. A wide variation in potato producer prices of 0.4 to 0.8 US$ per kg potato was observed in this study (*Chapter 5*).The grain maize case in the country is quite opposite to the potato case in terms of investment risk. Grain maize production is predominantly dryland and in many areas it is subject to an extremely variable climate and consequently to extreme variation in both potential and actual grain production (Phillips, 1998; Richardson, 2007). Such climatic uncertainty reduces the farm’s capacity to plan for any given season.

3.2 Potential contribution of potato toward food security in Zimbabwe

3.2.1 Potential of potato to contribute to national food security

Food security is a state when “all people, at all times, have physical and economic access to sufficient, safe and nutritious food for a healthy and active life” (FAO, 2008). Globally, the estimates of food insecurity continues to indicate a downward trend according to the FAO when it reported an estimate of 805 million people as chronically undernourished in 2012/14, down more than 100 million over the last decade, and 209 million lower than in 1990/92 (FAO, 2014). The same report noted that Latin America and the Caribbean have made the greatest overall progress in increasing food security while in the sub-Saharan Africa region, progress has been modest. However, political commitment at the highest level to food security and nutrition has been strengthened in several countries of the sub-Saharan Africa region (FAO, 2014). In Zimbabwe, the government declared Irish potato a national strategic food security crop on 18 May 2012 adding to the staple maize crop (The Herald, 2012). The policy pronouncement is an important contribution to an enabling environment for food security and nutrition but the government needs to do more in terms of implementing this policy. Food security and nutrition involves both closing the yield gap and breakthrough technologies and practices to raise actual yield and increase resource use efficiency. This study found a large actual yield range among potato growers in the major growing regions that ranged from 8 to 35 t/ha representing a yield gap of over 77 % (*Chapter 3*). The implication is that there is great potential to increase potato production in the country through reducing this yield gap by improving actual yields and contribute toward national food security. In addition, the agro-ecology of the Highveld and Nyanga Eastern Highlands as described in *Chapter 3* of this thesis are conducive to year round potato growing. Average simulated potential yields are as high as 88 to 96 t/ha in the Highveld and Nyanga Eastern Highlands respectively, implying that there is potential to further increase actual yields. Covering an extensive area of more than 117,000 km^2, the Highveld and Nyanga Eastern Highlands provides sufficient area for potato production should area expansion becomes necessary. The window of year round production allows planning of potato plantings in response to the maize season rainfall quality to gap fill for anticipated shortfalls in maize production. Supplementary or full irrigation will be needed though for potato production that includes the dry season months.

The study also reports an ambitious plan by the potato industry in Zimbabwe to increase the potato planting area to 30,000 ha annually in the medium term (USAID-STAMP 2011; Ackerman, personal communication 2013). Achieving this plan will represent a huge contribution toward food security in the country. However, only 7 to 12 % global growth projection in food production was estimated to come from arable land area expansion over the 2000 to 2050 period (Fischer *et al*., 2005). Current arable land area is predicted as the major source of food production increase of the magnitude 75 % over the same period (Fischer *et al.*, 2005). Clearly therefore, yield gains will dominate the future prospects of global food security. The yield gap in potato production in Zimbabwe indicates the low eco-efficiency in the production systems, and gives a basis to compare with the desired improved eco-efficiency if farmers were operating close to the uppermost production function frontier as illustrated in Fig. 2. Potato farmers in Zimbabwe are well positioned to move to the next higher production function frontier if supplied with better technologies and practices because the majority have irrigation facilities and can afford higher fertiliser rates. For example over 70% of the sample growers use N fertiliser rates higher than the already high recommendations by extension (*Chapter 4*).

This study also carried out a value chain analysis of the Irish potato industry in Zimbabwe as described in *Chapter 5* of this thesis. The value chain analysis has demonstrated that the potato industry in Zimbabwe generates very considerable levels of value-addition, leading to profitable businesses at each stage of the value-chain. This is a positive signal that the value chain is competitive. *Chapter 5* lists several opportunities that chain players should exploit in order to enhance the potato value chain performance and increase its contribution to national food security and nutrition. For example, Irish potato is now a national strategic food security crop, hence stakeholders should take advantage of this, and implore government to give the crop the necessary support it deserves. Additionally, the government ban on ware potato imports gives the value chain the advantage of local supply monopoly.

3.2.2 Potential of potato for household food security in the smallholder production systems

Cropping systems in Nyanga district is based on Irish potato (*Chapter 6*). A grower survey in the Nyanga district communal area production system showed that the average actual potato yield was 17 t/ha and ranged from 8 to 45 t/ha (*Chapter 4*). The highest household potato consumption in the country was recorded in Nyanga district where potato is the staple food crop. The average communal area household size recorded was 5.6 people, and the average per capita consumption was 70.2 kg/yr and it ranged from 54 to 100 kg/yr (*Chapter 5*). An analysis of the potato production and utilisation shows that potato plays a major role in the communal area household economy in Nyanga district. Table 3 shows that on average about 2 % of the potato produced directly contributes to the food needs of the household while more than 88 % is sold to generate income to access other food items, meet social obligations or investment. About 9 % of the output is retained as seed for the next plantings. It was observed in the survey that smallholder potato growers often retain part of the first harvest for seed.

Table 3. Characteristic household potato production and utilisation in the communal areas of Zimbabwe: case of Nyanga district.

Item description	**Quantity**	
	[kg]	[%]
Household consumption	393	2.3
Seed (amount per ha)	1,573	9.3
Sold (amount per ha)	15,034	88.4
Total production (amount per ha)	17,000	100

Source: Computed from survey data (*Chapters 2, 4 and 5*).

3.3 Growth in the potato sector in Zimbabwe

The potato industry in Zimbabwe is still small. Experts estimate annual potato planting area at around 6,000 ha and annual production at nearly 120,000 t (Ackerman, personal communication 2013; Manzira, personal communication 2013). The Food and Agricultural Organisation of the United Nations estimates are even lower reporting a peak production of 58,000 t over a cropping area of 3,500 ha in 2013 (FAOSTAT, 2013). Leading countries in southern Africa in terms of annual production in the 2009–2013 period include Malawi with 3.9 million tonnes, South Africa with 2.1 million tonnes and Angola with 0.8 million tonnes (*Chapter 2*).

An umbrella association encompassing all stakeholders may be the antidote needed to build and grow a viable potato industry in the country. This study reported the Fresh Produce Marketing Association of Zimbabwe (FPMAZ) as an umbrella body representing most farmers, wholesalers and retailers involved in the formal marketing and production of fresh fruit and vegetables (*Chapter 5*). However, the majority of stakeholders in the potato sector were not aware of the existence of FPMAZ. The association could not promote the interests of the potato industry due to financial constraints to run its programmes, and also that it deals with all fresh produce. An association of stakeholders in the potato sector similar to Potatoes South Africa (PSA) in South Africa is therefore needed to serve, promote and protect the interests of the potato industry in Zimbabwe. With the primary goal to build and grow a viable potato industry in the country, the major roles of the association will include, conducting market research, running the national breeding programme, conducting technical research to improve yield and resource use efficiency, provide extension service and assist emerging farmers grow into fully fledged commercial potato producers. Currently provision of most of these essential services is absent or grossly inadequate. Levying of all the value chain actors may contribute to address the issue of funding of the proposed association.

Meanwhile, the provision of adequate agricultural infrastructure that delivers needed goods and services to growers by government, non-governmental organisations and the private sector will continue to be essential toward improving crop yield, resource use efficiency and food value chain systems. Such agricultural infrastructure includes manufacturing of quality fertilisers, availability of sufficient soil testing services, paved road network for efficient transportation of inputs and outputs, and provision of extension and grower education. Improving agricultural infrastructure will certainly contribute toward the growth of the potato sector in Zimbabwe.

4. Future research priorities

A number of future research challenges have emerged based on the findings of this study. First, plant breeding has been the traditional route to achieve yield gains and new efficiency frontiers in crop production. Irish potato yield levels in Zimbabwe are low. The urgent need for high performing potato varieties in Zimbabwe has already been emphasised in this study. Variety trials using imported materials to select superior performing varieties for certification and making them available to farmers as seed potato can be the initial phase while the national breeding programme is rebooted. The envisaged potato association as described in Section 7.3.3 should take charge of the national breeding programme along the same approach the country adopted on tobacco research. In 1950, the country established the Tobacco Research Board (TRB) under the Tobacco Research Act, Chapter 18:21 (1955), with the mandate to direct, control and carry out tobacco research in Zimbabwe. The TRB has exclusive rights to flue-cured research in Zimbabwe and its mission is to maximise economic value from sustainable and responsible tobacco production through the development and provision of elite varieties and innovative agro-based services and products. Similar privileges can be argued for Irish potato.

Second, work needs to be done toward improving eco-efficiency in potato production in Zimbabwe. Such research should develop optimum rate of application of all nutrients, and such attention to balanced nutrition is important to improve the use efficiency of all nutrients. Section 7.3.1 of this thesis has alluded to that integrated nutrient management strategy research output for recommendation to farmers. A likely partner for future research of this kind is the African Centre for Fertilizer Development (ACFD) of the African Union (AU) which has its headquarters in Harare (ACFD, 1987). The ACFD was formed after noting that agricultural production in Africa has declined significantly, and realising that fertilizers constitute one of the essential factors for increased agricultural production in Africa (ACFD, 1987). One of the specific objectives of the centre is to conduct and support research, develop, promote, and demonstrate the role that fertilizers must play for improved agriculture and fertilizer management practice.

Third, related to the integrated nutrient management strategy is the need for other agronomic trials for continued improvement in cropping systems management. For example suboptimal plant populations, poor management of weed, pest and disease reduce anticipated yields and consequently lead to reduced fertiliser use efficiency. There is need therefore for research to make recommendations on these agronomic practices to improve potato yield in Zimbabwe.

Fourth, through an iterative process, the developed framework on evaluating the sustainability of cropping systems (*Chapter 6*) needs continuous refinement for easier application. Future research can also explore other possible indicators viewed as more appropriate under the given different agro-ecological production conditions. The indicator thresholds provided can act as an incentive for famers to work toward achieving.

Finally, this study established the potato potential and water-limited potential yields and their variation with planting months in some areas within the leading (Highveld and Nyanga Eastern Highlands) growing regions of the country. It is worthwhile to expand this analysis throughout the country and explore what other new areas have potential to grow potato besides the present regions. Knowledge of potential areas for the crop in the country would among other things guide breeding programmes and the development of specific crop management strategies for the respective areas. In conclusion, the agricultural trajectory for the future has to be the eco-efficiency trajectory, with continuous growths in the efficiency with which scarce resources of land, water, nutrients, and energy are used. Attainment of the desired output and efficiency must be without further greenhouse gases emissions to mitigate climate change and its impact on agro-ecosystems.

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Summary

Irish potato is becoming an important food crop in Zimbabwe. Substantial growth in potato consumption has been realised. Currently it stands at about 9 kg/c/yr (kilogrammes per capita per year) up from only 2 kg/c/yr in 1984. The sector growth projections target an annual potato crop of about 30,000 ha in the short to medium term, an ambitious 5 times increase from the current estimates of about 6,000 ha. Faced with persistent food security challenges since the radical Fast Track Land Reform Programme (FTLRP) of 2000 and coupled with the growing interest in potato production and consumption, the government decided to deliberately support potato production in the country. On 18 May 2012, the government declared Irish potato a national strategic food security crop complementing the staple maize. This major policy pronouncement qualified Irish potato for government initiated farmer support initiatives such as mechanisation and irrigation capacity building. However, the land reform initiated in 2000 created a completely new agrarian landscape. By the end of 2010 when the FTLRP officially ended, about 96 % of the original 12.5 million ha of large-scale commercial farmland in 1980 was taken up for resettlement using two model settlement patterns. The A1 resettlement model adopted the communal area land allocation system in which each beneficiary household was allocated about 6 ha arable land for cropping while separate grazing land was communally owned. The A2 resettlement followed the former large-scale commercial model with ‘private’ land allocated for cropping, grazing, residential, woodlot use and any other purpose. However, the farm units were small to medium size and ranged from about 35 ha in the high rainfall regions to 300 ha in the drier parts of the country. It is now the responsibility of the two resettlement systems that emerged from the land reform, the few remaining large-scale commercial farms, and the already existing communal area systems to meet the rising demand for agricultural products for food, feed and fuel of a growing population and export market. This new agrarian landscape coupled with the national strategic food security importance of Irish potato is the scenario under which the investigation of the scope to increase potato production in Zimbabwe was mooted. Sustainable increase of potato production is necessary for the crop to indeed assert itself as a national strategic food security crop, and will help ease the food security challenges the country is grappling with.

The overall objective of the study was therefore to assess the potential to sustainably increase Irish potato production in Zimbabwe and to contribute to the food security of the country. First, the potato production systems that emerged from the land reform of 2000 were

distinguished and characterised in terms of resources used as inputs in potato production. Such resources included land, water, synthetic fertiliser, biocides, and infrastructure related to potato production. A desk study was done to identify regions active in potato production and stakeholders already interfacing with growers. Subsequently, a survey was conducted to collect data on grower practices in potato production. Soil samples were taken from the fallow potato fields in which the grower wanted to plant the next potato crop. The samples were analysed mainly for pH, texture and NPK. In order to increase the dependability of the data collected, only growers with a minimum of 5 years continuous potato growing experience were interviewed. The characterisation findings are presented in *Chapter 2*. Potato is grown mainly in the Highveld and Nyanga Eastern Highlands regions. The latter, situated at elevations above 1,800 m above mean sea level (amsl), experiences a temperate-like climatic pattern receiving the country's heaviest precipitation of more than 1,000 mm per annum. Average mean temperature in this region ranges from about 11 °C in July to 18 °C in October giving the best potato growing environment in the country. The Highveld region is a gently undulating plateau at altitudes above 1,200 m amsl. It experiences a highly variable climatic pattern characterized by mild winters from May to September and hot summers from November to March. Precipitation mostly occurs in the summer months and averages around 750 to 900 mm. The large-scale systems (i.e., the large-scale commercial and A2 resettlement) are high-input, mechanised production systems with the majority of growers having irrigation systems installed. In the large-scale commercial holdings, farm gross area ranged from 165 to 1,600 ha while the cropping area ranged from 17 to 900 ha. The average potato area per planting was 11 ha and ranged from 3 to 25 ha. In the A2 resettlement production system, gross farm and cropping area ranged from 31 to 390 ha and 16 to 313 ha, respectively. The average potato area per planting was 8 ha and ranged from 1 to 23 ha. High synthetic fertiliser use exceeding the general recommendations of 120, 123, and 149 – 199 kg/ha N, P, and K, respectively, for an average potato yield of 30 t/ha was recorded in the two large-scale systems. The average N, P and K use in the large-scale commercial system was 181, 125 and 250 kg/ha, respectively. Similarly high N, P and K use rates of 197, 119 and 181 kg/ha, respectively, were recorded in the A2 resettlement production system. In the smallholder (A1 resettlement and communal area) systems, cropping area averaged 4 and 3 ha in the A1 resettlement and communal area production systems, respectively; the average potato area per planting was 0.4 and 1.1 ha, respectively. Experienced smallholder growers were only identified in the Nyanga Eastern Highlands. In terms of irrigation infrastructure, surprisingly, 89 and 94 % of the growers in the A1 resettlement and communal area production systems had irrigation facilities, respectively. All the irrigation systems were gravity-fed due to the steep terrain in the Nyanga Eastern Highlands giving the growers considerable savings on irrigation energy costs. Both smallholder systems use animal-drawn equipment for potato production. Although both are low-input systems, the fertiliser use rate had an exceptionally wide variation and was unexpectedly on the high side. The N use rate for example, was in the range of 45 – 164 and 80 – 244 kg N/ha in the A1 resettlement and communal area systems, respectively. The risks of N loss through leaching are high and the wide variation among the growers suggested inefficient N use. In terms of biocide use, fungicides were the most frequently used biocides in potato production across all the production systems in Zimbabwe. An average of 35 kg active ingredient (a.i.) fungicide per ha and 2 kg a.i./ha insecticide were applied during the growing period of the crop across all the production systems. None of the sampled growers were aware of the concept of Integrated Pest Management (IPM). Another factor influencing biocide inputs could be the potato rotation practice among the sample growers. The potato rotation ranged from one potato crop in one to four years on the same piece of land across all the production systems. Extension recommends one potato crop in 4 years on the same piece of land while completely excluding other solanaceous crops in the rotation to reduce overwintering of inoculum. Hence there is scope to reduce fungicide use while maintaining or even improving yields through improved potato rotations and wider use of the IPM concept.

In *Chapter 3*, the potential to increase potato production in the country was explored through the use of the yield gap concept, grower survey data and the application of modelling. For each grower sampled, the survey data collected was used to calculate the respective resource footprints of land, water, biocides and nutrients based on the actual yield, Ya. Additionally, the Ya data were used to compute the yield gap, YG, based on the yield of the best performing growers, Yh, simulated yield potential, Yp, and water-limited potential yield, Yw, of the respective agro-ecological areas. For a particular crop cultivar, Yp represents the maximum attainable yield achieved when the crop is grown under non-limiting conditions of water and nutrient supply, with biotic stress effectively controlled. In rainfed systems, Yw of a particular crop cultivar is the maximum yield attainable and is only limited by plant available water. The yield gap, YG, is the difference between Ya and Yh, Yp or Yw. The yield gap therefore, is a measure of unexploited food production potential of an agro-ecological area. The greater the narrowing of the yield gap, the greater the increase in food production that can help address the challenges of food insecurity. The LINTUL-POTATO model was used to estimate Yp, Yw and the water need. This model simulates potential dry matter production based on a fraction of incident Photosynthetically Active Radiation, PAR (400–700 nm spectral range), intercepted by the crop and a radiation use efficiency to convert the intercepted light into dry matter. Grower survey results show that the actual tuber yield ranged from 8 t/ha in the A1 resettlement to 35 t/ha in the large scale commercial production systems. Using 35 t/ha as the Yh value, the calculated yield gap equals over 77%. This yield gap reflects a considerable potential to increase food production by closing the yield gap through improving actual yields. The average potential yield from the LINTUL-POTATO model simulations ranged from 88 t/ha in the Chinhoyi and Karoi areas of the Highveld to 96 t/ha in the Nyanga Eastern Highlands. Unlike the Highveld, the Nyanga Eastern Highlands experiences a cool temperate-like climate pattern leading to a long growing period that allows late maturing crops resulting in a high potential yield. Compared to the simulated average potential yield, the mean actual yield observed ranged from 8 to 35 % of the simulated potential yield, translating to a yield gap of 65 to 92 %. Again this shows a considerable potential to increase potato production in these environments. The source of the actual yield gap existing among the growers is likely due to the differences in potential yield and lack of important cultural practices such as use of certified seed, fertiliser type, irrigation water, pest and disease management. On water use efficiency, the average simulated water use efficiency based on potential evapotranspiration ranged from 10 g potato l^{-1} for winter plantings to 27 g potato l^{-1} for summer plantings. Warm summer temperatures accompanied by high radiation intensities resulted in high evapotranspiration to meet the high atmospheric evaporative demand. This high evapotranspiration was partly compensated for by the high potential yields. Simulated irrigation need ranged from 141 mm in the humid Nyanga Eastern Highlands to 545 mm in the Kaori area of the Highveld. The latter experienced the highest mean monthly evapotranspiration of 245 mm, indicating a high atmospheric evaporative demand hence had the highest simulated irrigation need in the study area. Unexpectedly, the highest irrigation application of 750 mm was observed in the Nyanga Eastern Highlands. These growers use gravity-fed irrigation systems incurring no energy costs, hence there is a tendency to over-irrigate. Actual water use efficiency based on irrigation water and precipitation ranged from 2 to 6 g potato l^{-1}, while the simulated potential water use efficiency from irrigation and precipitation ranged from 9 to 17 g potato l^{-1}. This large gap observed between actual and potential water use efficiency shows the scope to improve crop management practices to increase actual yield while lowering irrigation water when necessary. Considering the synthetic nutrient footprint, the combination of high fertiliser use and the low potato actual yields realised, the inefficient fertiliser use in the Zimbabwean case is apparent. The nutrient use efficiencies ranges were: 97–162 g potato g^{-1} N, 93–105 g potato g^{-1} P_2O_5 and 97–123 g potato g^{-1} K_2O. The study suggested a cocktail of options to improve nutrient use efficiency such as use of high yielding cultivars and using soil tests for nutrient correction. The case of the biocide resource footprint was similar to that of the nutrient use efficiencies in that the generally high biocide use observed in return for low potato yields leads to low calculated biocide use efficiencies. Calculated biocide use efficiencies ranged from 0.5 to 0.9 kg potato g^{-1} active ingredient (a.i.) fungicide, and 8 to 14 kg potato g^{-1} a.i. insecticide. As already mentioned, introducing Integrated Pest Management (IPM) may improve biocide use efficiency. Training though is needed for both extension and growers on IPM.

In *Chapter 4*, the grower survey data was used as input into another model, the 'Cool Farm Tool-Potato' model. The model further distinguishes and appraises the production systems in terms of actual potato yields, inputs and efficient use of energy as reflected in their CO_2 balances. It calculates the contributions of various production operations to the total greenhouse gas, GHG emission. Consequently, grower practices which had the highest contribution to the total GHG emission were identified and possible generic mitigation measures for each production system were suggested. This model is suitable to assess such differences in efficiency because all inputs and operations from the seed material through storage of the harvested potato product are dealt with. Besides, there is no need to measure actual energy use by farmers because the tool has been constructed from several sub-models and these are already embedded in it. By reporting a single figure calculation of GHG emission (e.g., kg CO_2 eq./t), it is immediately evident which system is most efficient. The average carbon footprint calculated was 251 kg CO_2 eq./t potato harvested, ranging from 216 to 286 kg CO_2 eq./t in the communal area and A2 resettlement production systems, respectively. The major drivers of the GHG emissions were fertiliser production and soil-related field emissions, which together accounted for on average 56 % of the total emissions across all production systems. Although mitigation options were not assessed, the model output displays the factors/farm operations and their respective emission estimates consequently allowing the grower to choose the inputs and operations to reduce the carbon footprint. Opportunities for benchmarking, as an incentive to improve emission performance, exist given the large variation in GHG emission among growers.

Rather than focusing on the production aspects only, the study also considered the performance of the entire Irish potato sector in the country, a sector to date not well understood. In *Chapter 5*, the main findings on the performance of the sector are discussed. The discussion centred on the identity of the main actors in the value chain and a mapping of the relationships among them, activities within each segment, opportunities and constraints faced. Suggestions were offered to enhance the competitiveness and profitability of the potato sector in the country. The study employed the value-chain analysis tool. First, a desk study was undertaken and stakeholders in the industry were identified. Quantitative data on the identified stakeholders were collected using structured questionnaires. Field observations, local knowledge, and expert elicitation were also used. Results show that the Irish potato value chain in Zimbabwe is a web of multiple pathways which potato can take from the field of production to the end users. A total of seven stakeholder groups are connected. They include ware and seed potato producers, middlemen/transporters, wholesalers, retailers, processors, household and public consumers. Over 65 % of potato production is processed as French fries and less than 35 % is for household fresh potato consumption. Considerable levels of value-addition were observed with gross profit of at least 13 % recorded at each linkage. The middlemen/transporters and the Mbare Musika group of wholesalers dominated the value chain and can influence potato pricing. The middlemen/transporters buy almost the entire crop of the smallholder growers, about 50 % of the A2 resettlement crop and less than 10% of the large-scale commercial crop and transport it to the Mbare Musika wholesale market. Mbare Musika, with more than 75 % of the wholesale market share, buys the bulk of the middlemen/transporters crop. While the sector enjoys government policy support, major factors impacting on the value-chain performance relate to high potato production costs, low yields, and lack of farmer training. The poor state of the road network hampers smooth transportation of both input and output. It is therefore recommended to lower production costs, supply high yielding cultivars, provide credit facilities, guarantee land ownership, and improve the country's road network.

With a rising demand for agricultural products for food, feed and fuel amid growing concerns on sustainability, protocols to assess the sustainability of agricultural systems are scarce, especially in the context of developing countries. Realising this dilemma and the important role of evaluation protocols, this study developed a framework that can be used to evaluate and communicate the sustainability of cropping systems. In *Chapter 6*, the approach

and the main findings of this study are discussed using the case of Irish potato-based cropping systems in southern Nyanga district of Zimbabwe. Nyanga district is a traditional potato growing area and hosts all the four different potato production systems in the country. The widely accepted social, economic and environmental dimensions of sustainability were covered using pre-defined criteria from which in turn the indicators were drawn. An initial large list of indicators was established based on literature review and expert opinion, and through a filtering process the list was reduced to about 16 representative core indicators. The grower survey data collected on potato production practices was used to calculate the sustainability indicators expressed as resource use efficiencies based on the actual potato yields. Further, the survey data also served as input into the CFT-Potato model to estimate greenhouse gas emissions from farm operations involved in potato production. Greenhouse gas emission was used as one of the indicators to assess environmental sustainability. With the help of local agricultural extension officers, focus group discussions were held with farmers of each production system to decide on the sustainable and unsustainable indicator threshold levels. This innovative approach of involving farmers and local extension officers secures the buy-in of key stakeholders important for operationalisation, monitoring and evaluation.

In conclusion, the use of grower survey data and the application of modelling have clearly demonstrated the inefficient use of resources used as inputs in Zimbabwe for potato production such as land, water, nutrients and biocides. Further, the large actual yield range among potato growers implied a tremendous potential to increase potato production and contribute toward national food security. Food security and nutrition involves closing this yield gap through the use of breakthrough technologies and agronomic practices to raise actual yield and increase resource use efficiency. Future research should focus on breeding for high performing potato varieties to increase yield, improving nutrient use efficiency in potato production, and exploring the possibilities of expanding the potato production frontiers in the country.

List of publications

Svubure O, Struik PC, Haverkort AJ, Steyn JM (2015) Yield gap analysis and resource footprints of Irish potato production systems in Zimbabwe, *Field Crops Research* **178**: 77–90, DOI: 10.1016/j.fcr.2015.04.002.

Svubure O, Struik PC, Haverkort AJ, Steyn JM (2015) Carbon footprinting of potato (*Solanum tuberosum* L.) production systems in Zimbabwe (submitted)

Svubure O, Struik PC, Haverkort AJ, Steyn JM (2015) Analysis of the potato (*Solanum tuberosum* L.) value chain in Zimbabwe post the Landmark Agrarian Reform (submitted)

Svubure O, Struik PC, Haverkort AJ, Steyn JM (2015) Comparative analysis of potato (*Solanum tuberosum* L.) production systems in Zimbabwe after the 2000 radical Land Reform (submitted)

Svubure O, Struik PC, Haverkort AJ, Steyn JM (2015) A quantitative framework for evaluating sustainability of potato (*Solanum tuberosum* L.) cropping systems post the landmark Agrarian Reform in Zimbabwe (submitted)

PE&RC Training and Education Statement

With the training and education activities listed below the PhD candidate has complied with the requirements set by the C.T. de Wit Graduate School for Production Ecology and Resource Conservation (PE&RC) which comprises of a minimum total of 32 ECTS (= 22 weeks of activities)

Review of literature (6 ECTS)

- Agronomic and environmental studies of potato (*Solanum tuberosum* L.) and analysis of its value chain in Zimbabwe (2011)

Writing of project proposal (4.5 ECTS)

- Agronomic and environmental studies of potato (*Solanum tuberosum* L.) and analysis of its value chain in Zimbabwe (2011)

Post-graduate courses (5.9 ECTS)

- Increasing photosynthesis in plants; EPS, PE&RC (2011)
- Geographic information systems and GPS training; SIRDC, Zimbabwe (2012)
- Bio-energy production from crop plants and algae; EPS (2014)
- Basic statistics; PE&RC (2014)

Laboratory training and working visits (1.2 ECTS)

- Seed potato company operations; Seed Potato Coop, Zimbabwe (2012)
- Seed certification; Seed Services Institute, Zimbabwe (2012)
- National potato breeding programme; Nyanga Experiment Station, Zimbabwe (2012)
- Potato processing into frozen French fries; Innscor Africa Limited, Zimbabwe (2012)

Invited review of (unpublished) journal manuscript (3 ECTS)

- Zimbabwe International Research Symposium: 3 papers: SM54-ZIRS15 / SM65-ZIRS15 / SM80-ZIRS15 (2015)

Deficiency, refresh, brush-up courses (1.5 ECTS)

- GenStat statistical analysis package (2012)
- IBM SPSS Statistics (2013)
-

Competence strengthening / skills courses (1.5 ECTS)

- Competence assessment (2011)
- Navigating complex socio-environmental processes: a serious but fun introduction to the basics of complexity (2011)
- Introduction to participatory socio-environmental games & simulations (2011)

PE&RC Annual meetings, seminars and the PE&RC weekend (2.4 ECTS)

- Potato soft rot workshop; Crop Science Department, University of Zimbabwe (2012)
- Critical thinking in higher education (2013)
- PE&RC Weekend (2014)
- PE&RC Day: optimization of science: pressure and pleasure; evolution of science in a changing world (2014)
- Convergence of sciences: strengthening agricultural innovation systems (CoS-SIS) in Benin, Ghana and Mali; seminar (2014)
- WGS PhD Workshop carousel (2015)

Discussion groups / local seminars / other scientific meetings (4.5 ECTS)

- School of Agricultural Sciences & Technology; Chinhoyi University of Technology, Zimbabwe (2012-2014)

International symposia, workshops and conferences (2.5 ECTS)

- Third global science conference on climate smart agriculture; Montpellier, France (2015)
- Chinhoyi University of Technology international research conference; Chinhoyi, Zimbabwe (2015)

Lecturing / supervision of practical's / tutorials (15 ECTS)

- Soil science (2012, 2013)
- Water resources management (2013)
- Crop production for engineers (2014)
- Research project (2014)

Curriculum vitae

Oniward Svubure was born in Ndanga, Masvingo province, in Zimbabwe on December 9, 1968. He did his primary education at Chimedza, Zaka and Mutamba primary schools all in Zaka district. He did his Ordinary Level secondary education at Saint Anthony's Musiso High School from 1982 till 1985. From 1986 to 1987, he did his Advanced Level education at Gokomere High School just outside Masvingo city. He then enrolled at the University of Zimbabwe where he studied for a BSc Honours degree in Agriculture, majoring in Soil Science from 1988 to 1990. From 1991 to 2003, he joined the Ministry of Lands and Agriculture in Zimbabwe working for the Department of Agricultural, Technical and Extension Services (Agritex) as a Provincial Agronomist for Mashonaland West Province. During that time, he was offered a Scholarship by the Biotechnology Trust of Zimbabwe (BTZ) in 1997 to undertake a Master of Philosophy (MPhil.) Research Study at the University of Zimbabwe's Faculty of Agriculture. He completed the MPhil. studies in 2000 with a thesis entitled, "*Contributions of Biological Nitrogen Fixation (BNF) by selected legumes to sustainability of the maize-based cropping systems in Communal Areas of Zimbabwe*". In the following year in 2001, he was awarded a Research and Extension Grant by the Agricultural Research Council of Zimbabwe (ARC) to revive the production of indigenous legume crops in rural communities (2001-2003). In 2003, he joined the Chinhoyi University of Technology (CUT) when it started as part of the pioneer lecturing staff. In 2005 to 2007, he studied for an MSc in Water Resources Management at UNESCO-IHE, Delft, The Netherlands courtesy of the Joint Japan/World Bank Graduate Scholarship Programme (JJ/WBGSP). His MSc thesis entitled, "*Participation and Institutional Reform in the Water Sector in Zimbabwe: Case of Smallholder Formal and Informal Irrigation in the Mzingwane Catchment*" got The World Bank Institute Award for outstanding research. In April 2011, he was offered a PhD sandwich programme fellowship by the Wageningen *Universiteit en Research Centrum* (WUR) Executive Board, Wageningen, the Netherlands. During his PhD study, he worked on the thesis, "Agronomic and environmental studies of potato (*Solanum tuberosum* L.) and analysis of its value chain in Zimbabwe" at the Centre for Crop Systems Analysis.

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