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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, Y_a, and the maximum (potential) yield, Y_p, achieved when a crop is grown under conditions of non-limiting water and nutrient supply with biotic stress effectively controlled; (2) the gap between Y_a and the water-limited yield, Y_w, which is the maximum yield attainable under rainfed systems; and (3) the gap between Y_a, and the highest yield, Y_h, 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 against the actual water use efficiency of 2–6 g potato/l 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 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.

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; Chamberlain et al., 2014). However, converting these potentially available croplands to cultivation could entail losing the inherent biodiversity under them. Some of

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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, Y_p, 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, Y_p 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, Y_w, which is equivalent to water-limited potential yield and is the maximum yield attainable in rainfed systems (Van Wart et al., 2013). Hence, Y_w 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 (Y_h) locally attained in a given agro-ecological area is another important benchmark. Y_h 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 Y_p or Y_w, characteristic of the prevailing climatic and soil conditions in the selected agro-ecological region. Surveying good growers can provide estimates of Y_h for a particular agro-ecological region of interest. Average actual yield, Y_a, 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, Y_G, is therefore the difference between Y_p, Y_w, or Y_h and Y_a. The formula $(1 - Y_a/Y_p)$, $(1 - Y_a/Y_w)$ or $(1 - Y_a/Y_h)$ is used to provide a relative value of the Y_G. Y_G can be a useful measure to assess the efficiency of land use for crop production. Besides identifying regions where Y_G 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 (Ministry of Lands and Rural Resettlement (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 (Ministry of Lands and Rural Resettlement (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, 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 Y_a 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 and calculation of resource footprints

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 (LSC) 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, 1982). It is responsible for the initial potato seed multiplications and only 21 out of the 27 growers in the area are active (Ackerman, 2012). A further 18 communal area (CA), 5 A1-resttlement and one of the four remaining LSC growers, all outside the Quarantine Area completed the Nyanga Eastern Highlands sample. AGRITEX officials in Nyanga estimated about 1000 CA and less than 100 A1-resettlement growers. A total of 11 LSC and 14 A2-resettlement growers were interviewed in the extensive Highveld agro-ecological zone. According to AGRITEX officials, the Highveld has less than 30 LSC growers and about 100 A2-resettlement growers, while a few A1-resettlement and CA 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 (Y_a) achieved. The data collected were used to calculate the resource footprints of land, water, biocides and nutrients based on the actual yields (Y_a). Further, Y_a data collected were used to calculate the YG based on the simulated Y_p and Y_w. In addition, the data was also used to understand the general Irish potato agronomic practices in Zimbabwe.

2.2. 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, Y_a, reported by the growers. Daily evapotranspiration (ET) for potato was calculated from the Penman–Monteith grass reference evapotranspiration (ET_o) (Smith et al., 1996) multiplied by a crop specific coefficient (K_c) according to the procedure recommended by Allen et al. (1996). The input parameters to calculate the daily ET_o 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 (Y_p and Y_w) 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 to 7 and 12 to 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.

2.3. 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).

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 1200 m amsl (above mean sea level), and the Eastern Highlands at higher elevations greater than 1800 m amsl. The Highveld covers about 25% of the country's total area of nearly 390,000 km^2. This region experiences a highly variable climatic pattern but is generally characterised 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 1000 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, 280 and 180–240 kg/ha of N, P_2O_5 and K_2O, respectively. A nematicide is also sprayed along the furrows. About 2 t/ha 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, 2013). The large-scale commercial production system has been the traditional potato growing system since the early 20th century in the country (Joyce, 1982), 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 (Ministry of Lands and Rural Resettlement (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

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)			WUEi (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^{*}	$<.001^{**}$	0.313ns	0.004^{*}	0.01^{*}	0.714ns	0.177ns	0.002^{*}
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, ns denotes non-significance at $p < 0.05$, mean values in the same column followed by the same letter are not significantly different.

[*] Denotes significant difference at $p < 0.05$.

[**] Denotes significance at $p < .001$.

ranged from 11 to 16 days, 28 to 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 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 (Fig. 4b–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

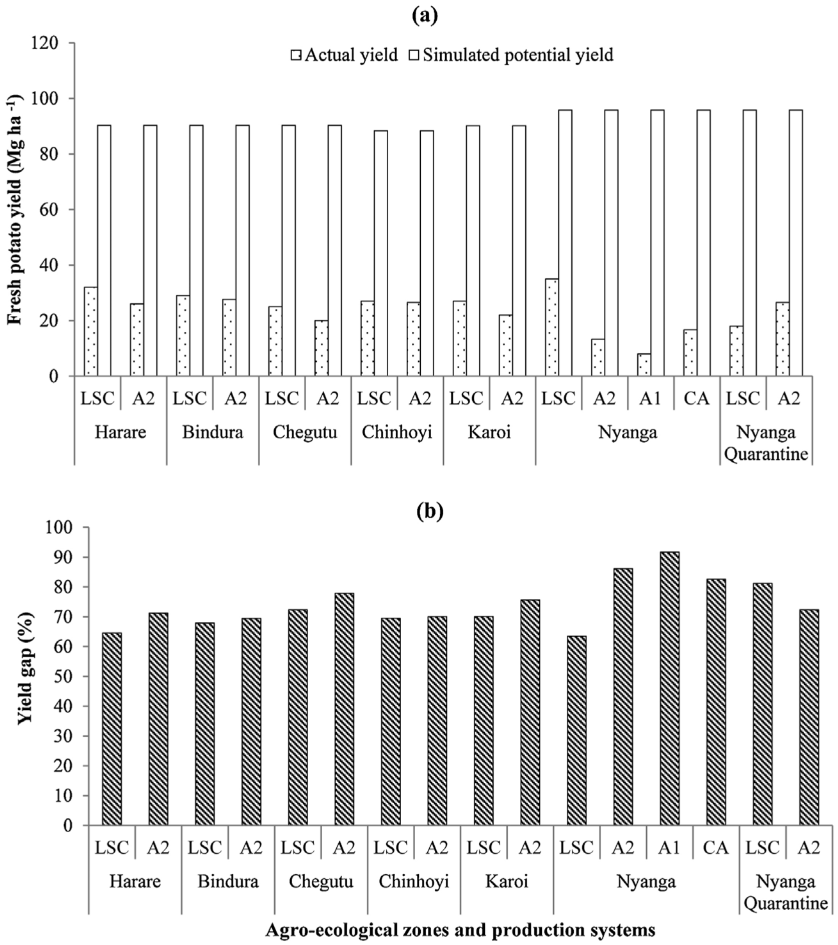

Fig. 1. Actual and average potential yield (simulated) (a) and yield gap percentage (b) of different agro-ecological zones and Irish potato production systems of Zimbabwe.

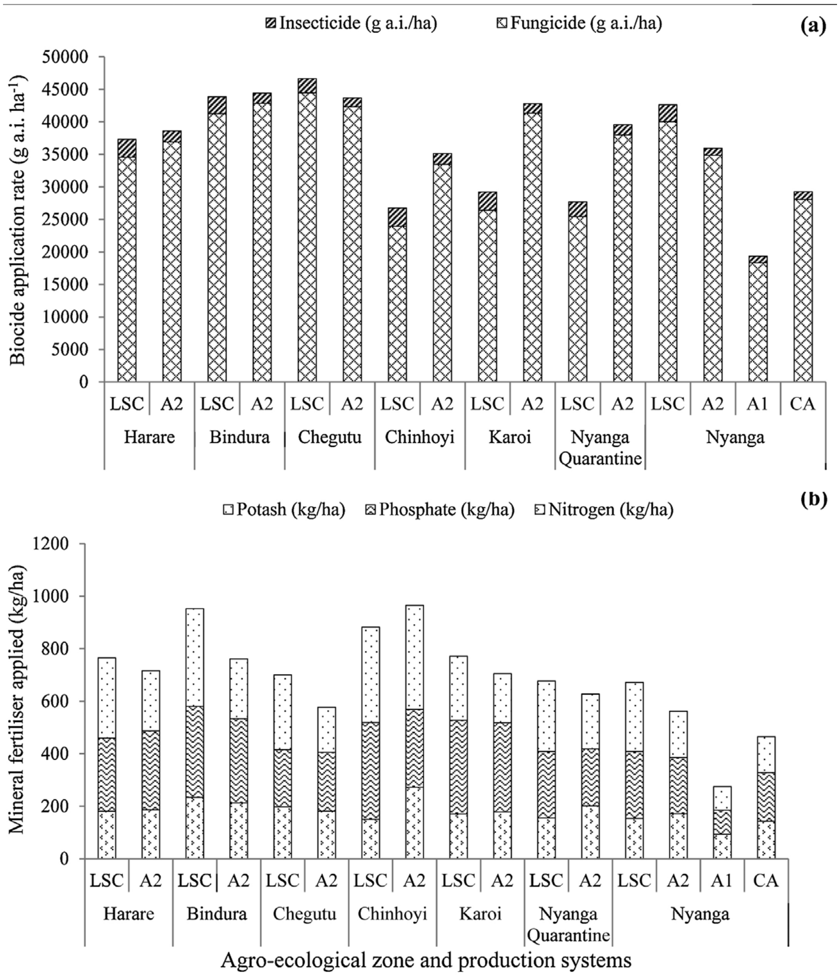

Fig. 2. Amount of biocides (a) and nitrogen (N), Phosphate (P_2O_5) and potash (K_2O) (b) applied to the potato crop in different agro-ecological zones and potato production systems in Zimbabwe.

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 (Fig. 4b–d). This is due to the decreasing average temperatures during the growing period in the months April through July (Fig. 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 (Fig. 4b–d).

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

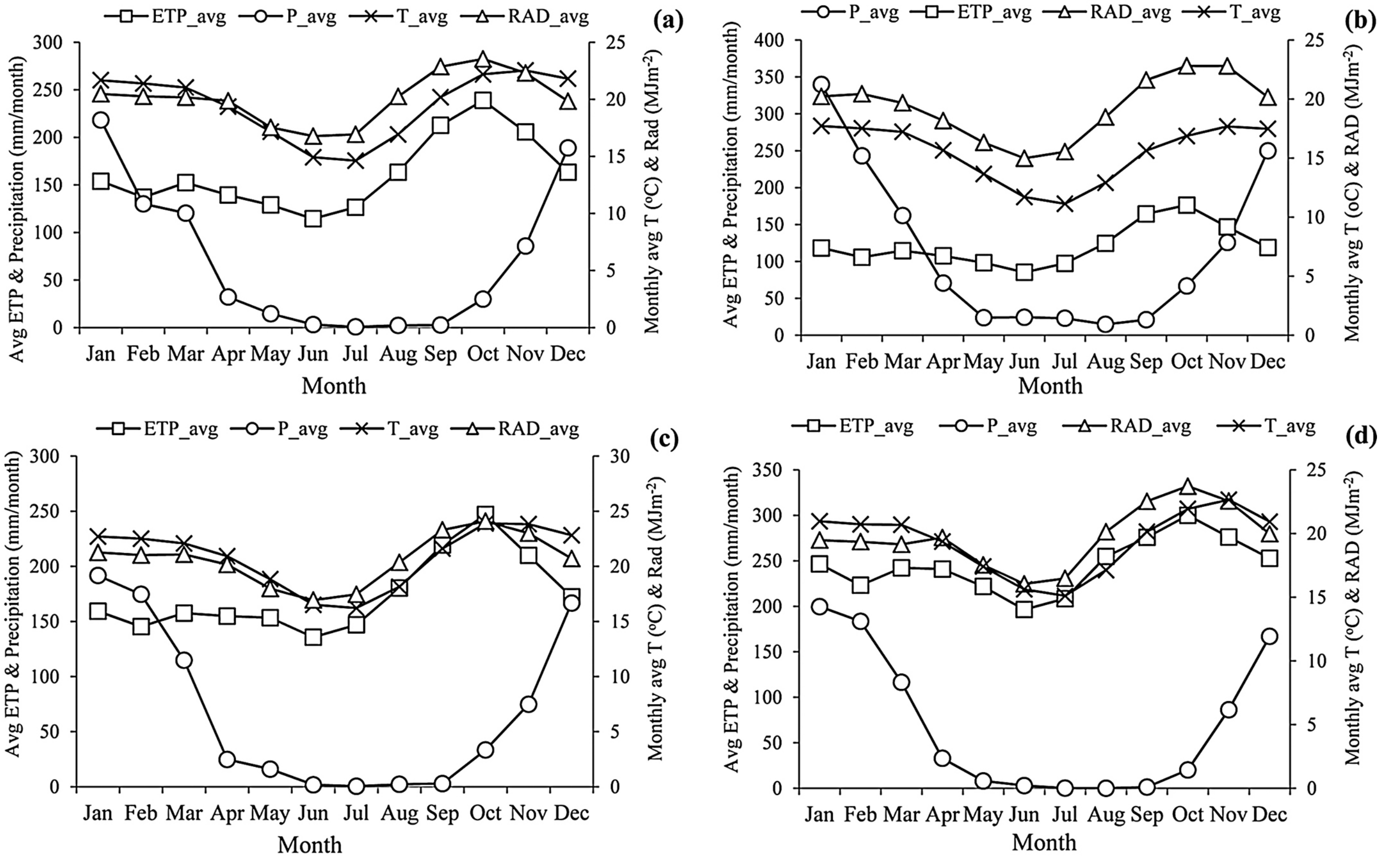

Fig. 3. Monthly average P (precipitation), ETP (evapotranspiration), T (temperature) and RAD (radiation) for (a) Harare, Bindura and Chegutu Highveld areas; (b) Nyanga Eastern Highlands; (c) Chinhoyi and (d) Karoi Highveld areas of Zimbabwe, using climatic data of the period 1985 to 2010.

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 ($p < 0.001$) 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 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 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 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 (Fig. 5b–d).

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 in August to 13.1 g potato/l 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). 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

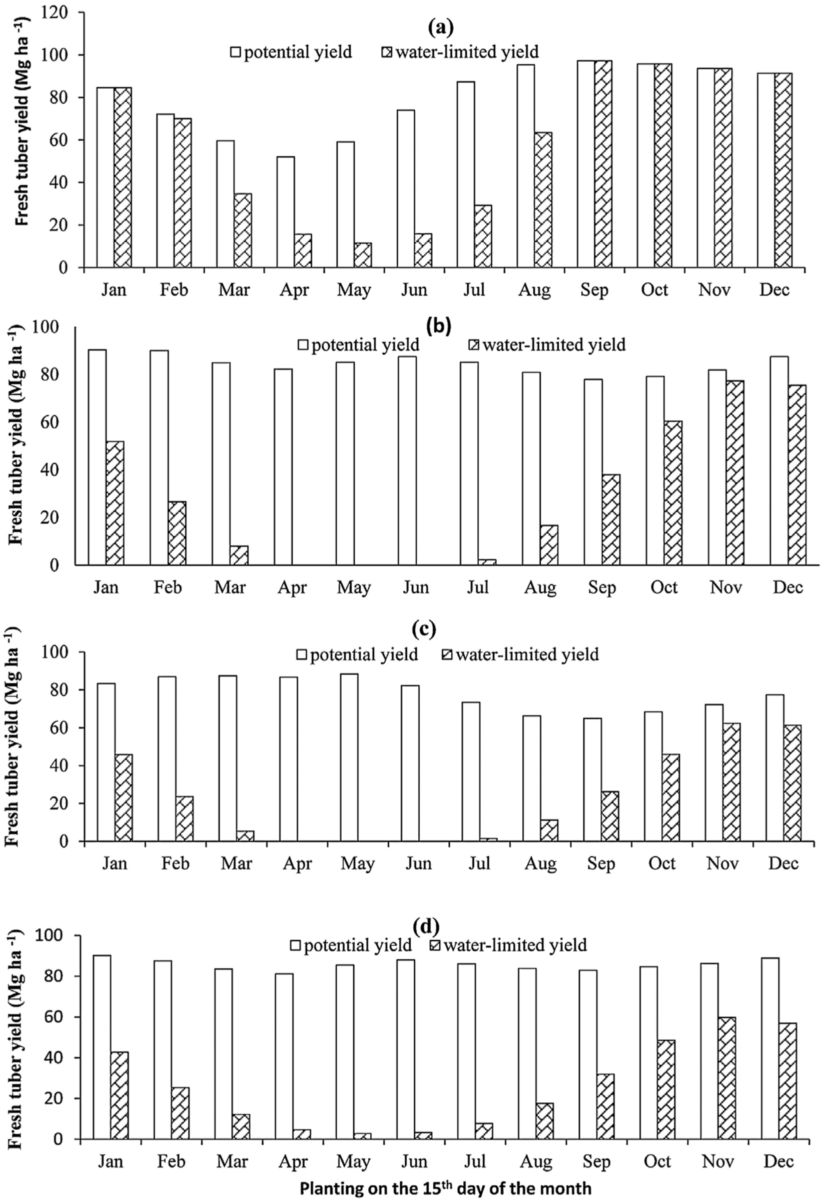

Fig. 4. Simulated potential and water-limited potato yield in Nyanga Eastern Highlands (a), Harare, Bindura and Chegutu (b), Chinhoyi (c), and Karoi (d) Highveld agro-ecological zones of Zimbabwe using average climatic data from 1985 to 2010.

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 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 (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 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.

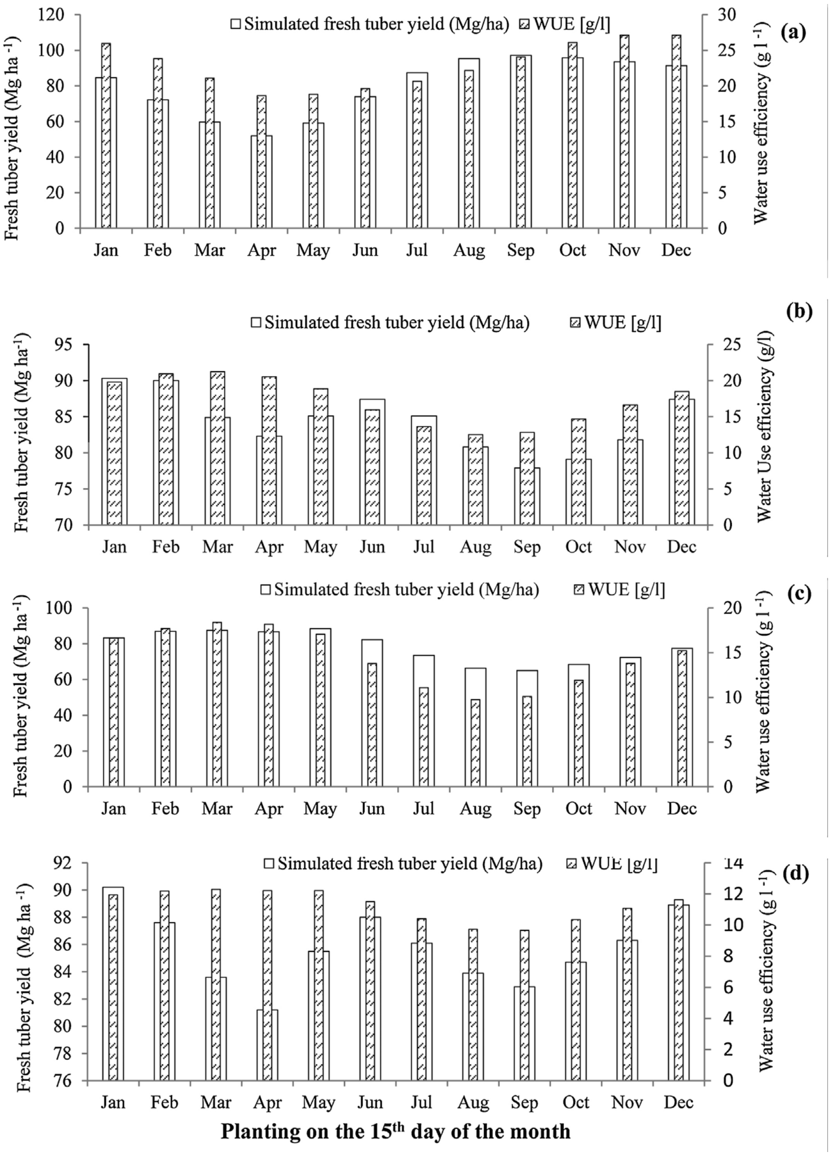

Fig. 5. Monthly simulated potato potential yield (left *y*-axis) and monthly water use efficiency (WUE) based on Evapotranspiration by the crop and soil (right *y*-axis) in Nyanga (a) Harare, Bindura and Chegutu (b) Chinhoyi (c) and Karoi (d) agro-ecological zones of Zimbabwe using average climatic data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

3.4. Nutrients footprint

A wide variation in mineral fertiliser application rate among all the sample growers was observed and it ranged from 94 to 272 kg N/ha, 91 to 369 kg P_2O_5/ha, and 90 to 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 N (Table 1). In a similar study in South Africa's Sandveld area, a nitrogen use efficiency range of 106–228 g potato/g 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 and a range between 36 and 58 Mg/ha (Franke et al., 2011), whereas in the Zimbabwean case, the potato actual yields averaged 19 Mg/ha and ranged from 8 to 28 Mg/ha (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 P_2O_5 and K use efficiency range was 97–123 g potato/g 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.

Predictably, all the nutrient (N, P_2O_5 and K_2O) use efficiencies in all the production systems were each positively related

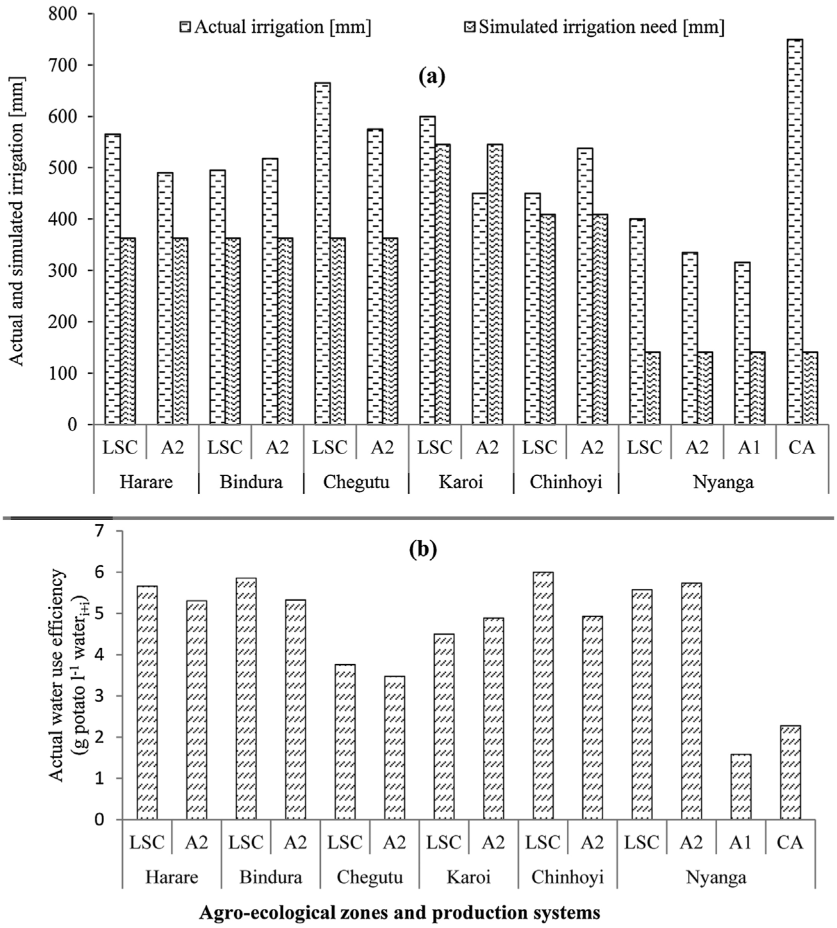

Fig. 6. Actual and simulated irrigation need (a) and actual water use efficiency (fresh yield/(irrigation + precipitation) (b) in different agro-ecological and potato production systems in Zimbabwe.

to the reported potato average actual yield (Fig. 7). All the actual yield-nutrient use efficiency linear relationships were significantly ($p < 0.05$) positive in all the production systems except in the A1-resettlement system (Fig. 7a–c). The A1-resettlement system recorded the least yield increase in response to increasing nutrient use efficiency (Fig. 7a–c), suggesting that other factors were more limiting. The other production systems recorded comparatively high yield increases in response to increasing nutrient use efficiency (Fig. 7a–c).

The communal area actual yield–nutrient use efficiency linear relationship (Fig. 7a–c) had the highest slope implying the largest yield increase per unit rise in nutrient use efficiency compared with the other systems. This suggests a more efficient fertiliser use in the communal area system compared with the other systems. The average actual potato yield in the communal area system of 17 t/ha (Table 1) is close 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 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. However, since all the growers (in the A2-resettlement, large-scale commercial and communal) production systems already use high fertiliser application rates (Fig. 2), it is advisable for them to employ other management interventions that increases efficiency of fertiliser use by the potato crop in order to increase yield. As already alluded to, these management practices could be improving water, pest and disease management and the use of certified seed. Especially important is the use of high-yielding cultivars with greater stress tolerance, improved management of other production factors besides N, and use of better fertilisers 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.

As anticipated, all the nutrient use efficiencies (N, P_2O_5 and K_2O) were negatively related to the respective nutrient application rate (Fig. 8a–c). The relationships were significant ($p < 0.05$) in all the production systems except in the A2-resettlement system (Fig. 8a–c). The slope of the nutrient rate-efficiency relationships under the A2-resettlement system was the least steep depicting increases in nutrient application that caused relatively small decreases in nutrient use efficiency. This implies that the A2-resettlement system growers use optimal or near optimal nutrient levels but with less efficient use of the fertiliser to cause yield benefits. Hence A2-resettlement growers must focus on the management of 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 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

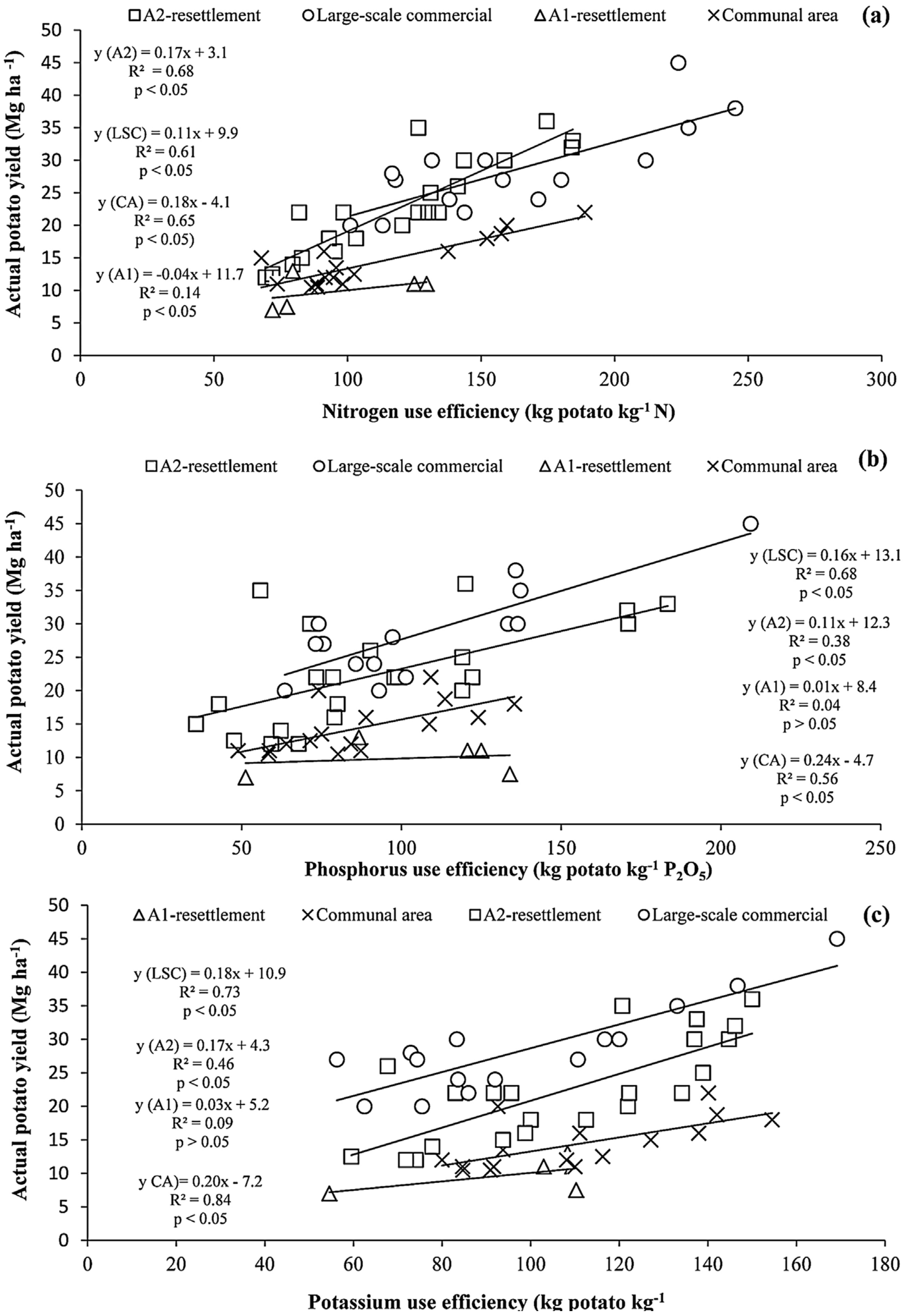

Fig. 7. Nutrient use efficiency and the average actual potato yield relationships in the different potato production systems in Zimbabwe.

to the environment. A similar case was reported by Cardberry et al. (2013) in the case of Chinese wheat farmers who used high N application rates. On the other hand, the slope of the nutrient rate-efficiency curve in the A1-resettlement production systems was the steepest (Fig. 8a–c). This implies that the growers have an opportunity for significant potato yield increases through improving both the level of nutrient application rate and the management of other needed production resources. 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 N 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).

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

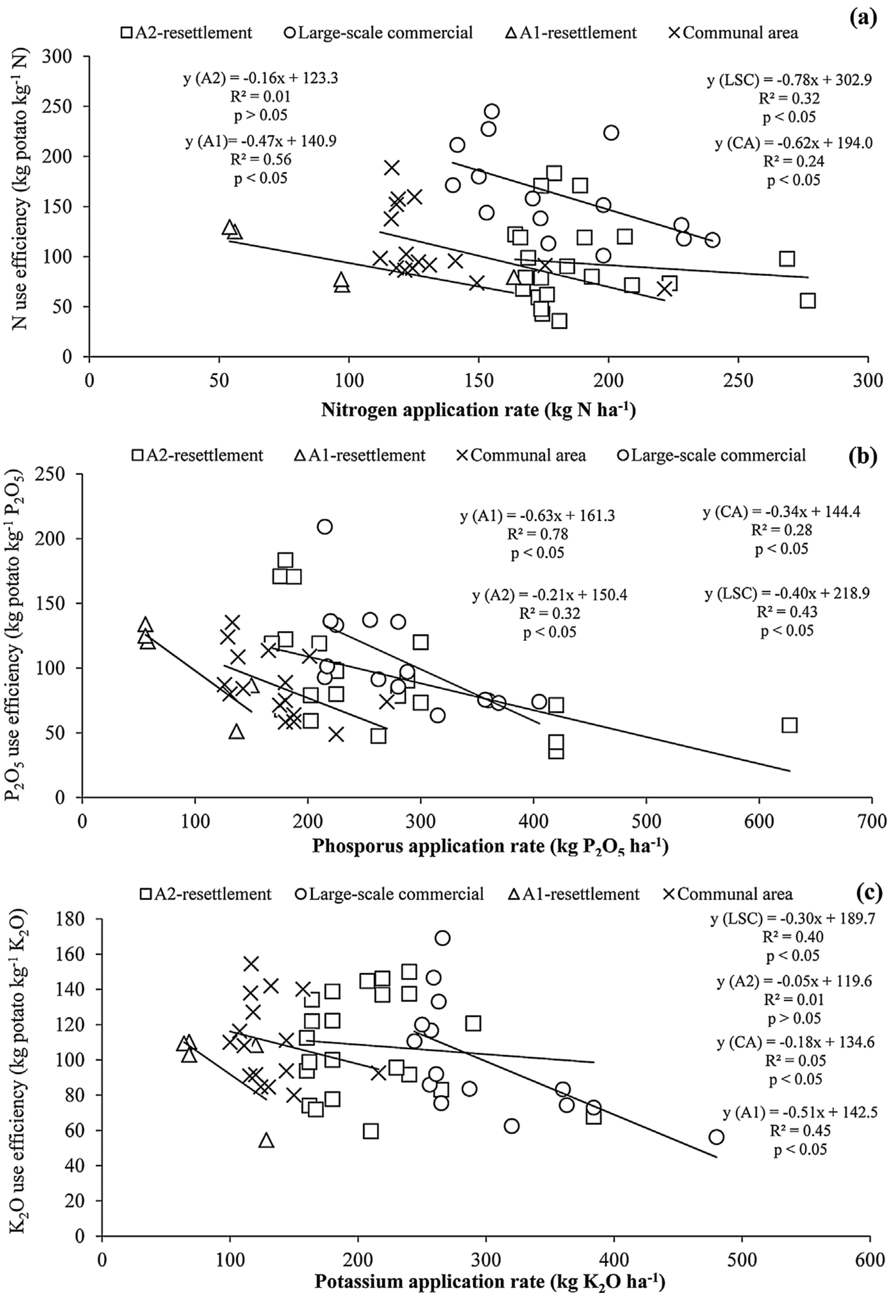

Fig. 8. Nutrient use efficiency and application rate relationships in Irish potato growing in the different potato production systems in Zimbabwe.

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. In the smallholder systems, cropping area averaged 4 and 3 ha in the A1-resettlement and communal area production system, respectively. 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). Fig. 9a shows a positive correlation between tuber yield and fungicide use efficiency. With the exception of the relationship in the A1-resettlement system which was not significant ($p > 0.05$), the relationship in the other production systems were significant ($p < 0.05$) (Fig. 9a). The slope of the mean tuber yield-fungicide efficiency curve was steepest for the communal area and A2-resettlement production systems (Fig. 9a), showing the scope to improve yield through increasing fungicide use efficiency. All the sampled growers were

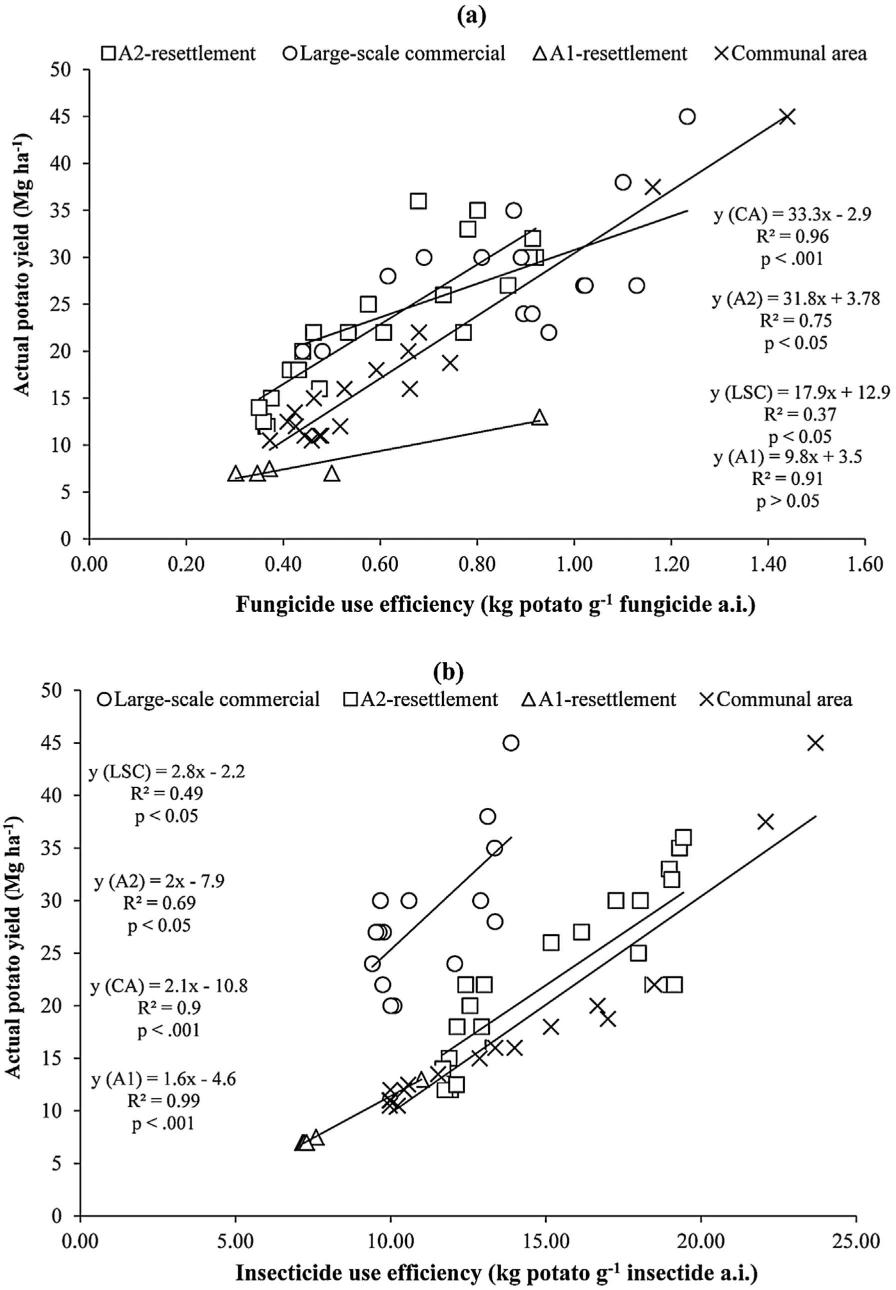

Fig. 9. Relationship between actual potato yield and fungicide use efficiency (a) and insecticide use efficiency (b) applied during the crop growth cycle in the potato production systems in Zimbabwe.

not aware of the concept of Integrated Pest Management (IPM). Hence there is scope to reduce fungicide application rates while maintaining or even improving yields and consequently the fungicide use efficiency through application of the IPM concept.

Strong positive relationships were found between tuber yield and insecticide use efficiencies in all the production systems (Fig. 9b). The slopes of the mean tuber yield-insecticide use efficiency lines were similar for all the potato production systems (Fig. 9b), indicating that equal opportunity to improve yield through increasing the respective insecticide use efficiencies exist in all the production systems.

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 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.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.fcr.2015.04.002

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